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Unified Secure Access Service Edge (SASE): Transforming Security for Hybrid Workforce and Multi-Cloud Environments

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Abstract— Organizations increasingly adopt hybrid cloud infrastructures and hybrid workforce models, creating a demand for secure and seamless networking solutions. Unified Secure Access Service Edge (SASE) is an integrated architecture that combines wide-area networking (WAN) functionality with advanced network security, offering a unified solution to address these challenges. This article explores the key components of Unified SASE and their effectiveness in handling the complexities of cloud infrastructure adoption and hybrid work environment integration. By embedding security capabilities into a cloud-based framework, Unified SASE ensures rapid responses to evolving threats and facilitates consistent security policies across on-premise data centres and multi-cloud environments. This article emphasizes the importance of adhering to industry standards in the development and deployment of Unified SASE, particularly regarding compatibility and interoperability. Ultimately, Unified SASE addresses the challenges of cloud environments and hybrid workforce models by integrating network security with access services, providing enterprises with a robust framework for secure, efficient, and scalable operations.

Keywords— Unified SASE, hybrid cloud infrastructure, SD-WAN, Cloud Access Security Broker, Zero Trust Network Access.

I. Introduction

The rapid increase of digital transformation, cloud adoption, and remote work has created an urgent need for a more advanced and comprehensive networking and security model. Unified Secure Access Service Edge (SASE) [1] came as a transformative solution that integrates networking and security functionalities into a cloud-native architecture. By using these capabilities, organizations can enhance performance, strengthen security, simplify network management, and reduce complexity.

Traditional network architectures and security models are increasingly insufficient to address the demands of today's dynamic and distributed workforce. The dependence on appliance-centric security measures and perimeter-based strategies—characterized by data backhauling and fixed network perimeters—fails to meet the needs of environments driven by cloud-first and remote-work models. Unified SASE addresses these challenges by combining advanced networking technologies, such as Software-Defined Wide Area Networking (SD-WAN) [2], with comprehensive security features, including Zero Trust Network Access (ZTNA) [3], secure web gateways, cloud access security brokers (CASBs) [4], and firewall-as-a-service (FWaaS) [1]. By using a cloud-native approach, SASE creates a robust and scalable architecture that supports digital transformation, adapts to the growing number of endpoint devices, and meets the needs of hybrid and remote workforces.

This study highlights how unified SASE simplifies network management by merging multiple security services into a single platform by integrating services like data loss prevention (DLP) [5], secure web gateways, and firewall-as-a-service, ensuring consistent security policies across the entire network architecture while lowering operational costs.

Another critical aspect of this study is investigating how unified SASE enhances user experience and overall network performance. By using SD-WAN capabilities, organizations can optimize bandwidth utilization, reduce latency, and intelligently route traffic based on application priorities. This ensures optimal performance for critical business applications and seamless user experiences, regardless of user location or device. Furthermore, unified SASE's ability to dynamically allocate bandwidth based on business requirements enables enterprises to achieve greater efficiency and reliability in their network operations.

II. Technical Background

A. Secure Access Service Edge (SASE) Architecture

Secure Access Service Edge (SASE) has emerged as a transformative solution to address the complexities of secure communication across diverse business landscapes. By integrating network and security functionalities into a

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unified, cloud-native platform, SASE provides organizations with the tools to enhance security, streamline operations, and reduce complexity. Some of these integrated solutions are shown in figure 1:

- **Software-Defined Wide Area Networking (SD-WAN):** which intelligently manages network traffic across multiple connections, ensuring consistent performance and reliability. This capability enables seamless collaboration for geographically detached teams and ensures uninterrupted access to critical applications.
- **The Cloud Access Security Broker (CASB):** it empowers organizations with visibility and control over cloud services, enforcing strict data security policies and regulatory compliance. CASB mitigates risks by proactively safeguarding sensitive information stored in cloud environments.
- **Zero Trust Network Access (ZTNA):** focuses on validating user identities and authorizing access based on context rather than location. This approach minimizes the attack surface by granting access solely to authorized applications, replacing traditional VPN-based models with a more secure methodology. Zero Trust frameworks divide networks into smaller, isolated segments to reduce lateral movement of attackers by implementing a concept known as micro-segmentation. This approach creates distinct zones within the network, where each zone is isolated and protected by its own set of security policies.
- **Secure Web Gateways (SWG):** protects users from web-based threats by filtering malicious content.
- **Data Loss Prevention (DLP):** prevents unauthorized access or disclosure of sensitive data by enforcing robust security policies.
- **Firewall-as-a-Service (FWaaS):** provides traffic filtering and shields against unauthorized access, fortifying the network against evolving cyber threats and vulnerabilities.

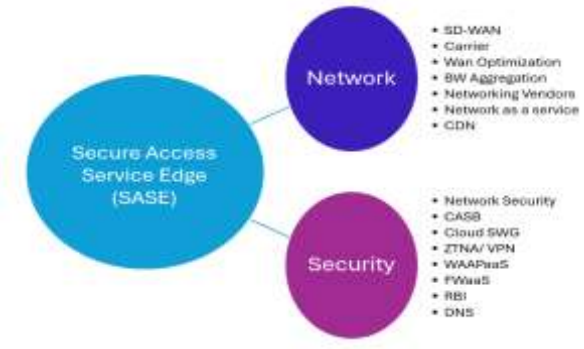

Fig 1. Technologies integrated in SASE

The adoption of SASE delivers many advantages, including simplified security management through the integration of multiple services into a unified platform that enables secure resource access from any location, improving user experiences and reducing costs by eliminating the need for disparate security solutions.

B. Unified Secure Access Service Edge (SASE)

Unified Secure Access Service Edge (Unified SASE) [6] improves SASE's foundational principles by combining security and networking functionalities into a single, streamlined cloud-based platform. This approach enhances operational efficiency and scalability, making it particularly valuable for enterprises with diverse and dynamic needs.

One of Unified SASE's core innovations is its single-pass scanning architecture, which inspects all network traffic only once. This design minimizes latency, reduces management complexity, and enhances performance while maintaining comprehensive visibility and control over network activities. This capability extends to advanced threat detection, including zero-day attacks and sophisticated malware. Figure 2 shows single pass parallel processing (SP3) architecture.

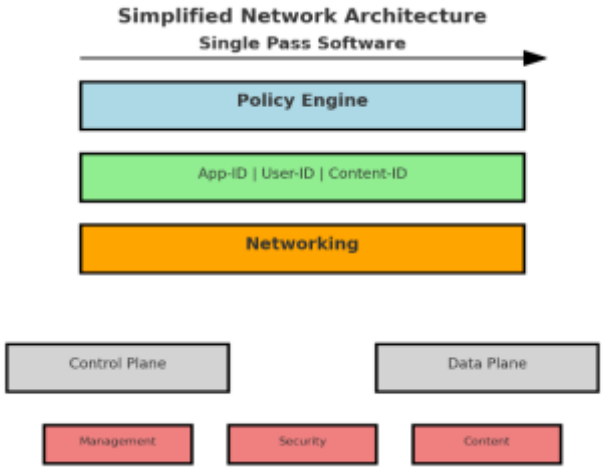

Fig 2. single pass parallel processing (SP3) architecture

A unified policy engine ensures consistent security policies across users, devices, and applications, regardless of their location. This reduces the administrative burden of managing disparate security systems. Additionally, centralized data storage in a unified data lake enables comprehensive insights into network activities, empowering organizations with real-time incident response and proactive security measures.

Unified SASE also provides a single solution for network management, simplifying operations, improving troubleshooting, and enhancing network health monitoring.

Table 1 shows a detailed comparison between SASE and Unified SASE.

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TABLE I
COMPARISON BETWEEN SASE AND UNIFIED SASE

Feature	SASE (Secure Access Service Edge)	Unified SASE
Definition	A framework that converges network and security services into a cloud-delivered model.	An enhanced and optimized version of SASE that integrates all components into a single architecture.
Core Components	- SD-WAN - ZTNA - CASB - SWG - FWaaS	All SASE components are unified into a single-pass architecture with optimized processing and management.
Architecture	Multi-vendor and fragmented deployment is common, often requiring separate platforms for network and security.	A single unified platform with integrated security and network functions managed centrally.
Data Processing	Security inspection may occur multiple times as data traverses different services (multi-pass inspection).	Single-pass inspection architecture processes traffic once for all security layers, reducing latency.
Policy Management	Policies are often spread across multiple systems, making management more complex.	Unified policy engine ensures consistent enforcement across all users, devices, and applications.
Deployment Flexibility	Often hybrid: mix of cloud-based and on-premise security solutions.	Fully cloud-native and scalable for global coverage with minimal dependency on on-premise hardware.
Scalability	Scalable but often limited by the multi-vendor approach.	Highly scalable due to unified architecture and centralized cloud-native platform.
Performance Optimization	SD-WAN optimizes traffic routing, but multi-pass inspection can cause performance issues.	Optimized traffic flow with single-pass scanning reduces latency and improves performance.
Visibility and Analytics	Disparate tools provide visibility; integrations may be required for holistic monitoring.	Unified data lake architecture provides centralized visibility and real-time analytics.
Threat Detection and Prevention	Each component handles threat detection individually, leading to inefficiencies.	Integrated threat intelligence, AI/ML-based analytics, and automated response enhance security.
Cost	Higher costs due to managing multiple solutions, vendors, and licenses.	Cost-efficient as it consolidates tools, and reduces hardware reliance.
Security Posture	Improved security but potentially inconsistent due to strict security services.	Enhanced security posture through integrated Zero Trust, consistent policies, and centralized controls.
Automation and AI Integration	Limited AI/ML usage across fragmented tools.	Advanced AI/ML capabilities enable automated threat detection, response, and optimization.
Vendor Lock-In	Can involve multiple vendors, reducing lock-in but increasing complexity.	Single-vendor solutions may increase lock-in but improve integration and support.

III. SASE IN HYBRID WORKFORCE ENVIRONMENTS

The shift to hybrid work environments, where employees operate across remote and on-premises locations, has introduced unique security challenges. Organizations now face the critical task of safeguarding sensitive data, providing secure access to resources, and maintaining consistent performance across distributed workforces. Traditional perimeter-based security models, which rely on fixed network boundaries, are no longer effective in addressing the complexities of hybrid work setups. Vulnerabilities such as unsecured public Wi-Fi networks, the widespread use of personal devices, and the challenge of maintaining regulatory compliance further complicate the landscape.

Secure Access Service Edge (SASE) can play an important role in addressing these challenges by offering a unified, cloud-native framework that combines networking and security capabilities. With features like Zero Trust Network Access (ZTNA), SASE ensures access to corporate resources is granted based on identity, context, and policy, minimizing the risk of unauthorized access. Cloud-native security services deliver centralized protection to users and devices, whether they are working remotely or on-premises. Additionally, tools like Secure Web Gateway (SWG) and Cloud Access Security Broker (CASB) protect web traffic and cloud applications, enabling secure and seamless access for employees across different devices and locations. SD-WAN further enhances connectivity by optimizing traffic flow and ensuring consistent application performance, delivering a superior user experience.

In real-world scenarios, SASE has proven instrumental in supporting hybrid workforces. For example, a global consulting firm implemented SASE to secure remote access for employees using collaboration tools like Microsoft Teams and Google Workspace, enhancing productivity while maintaining robust security. Similarly, a healthcare provider adopted SASE to ensure HIPAA compliance [7], enabling doctors to securely access patient records from remote locations with the help of Data Loss Prevention (DLP) and CASB tools. In the retail sector, SASE has been used to secure both in-store point-of-sale systems and remote employee devices, while SD-WAN ensures optimal connectivity between branch locations and headquarters. Universities have also leveraged SASE to provide secure remote learning environments for students and faculty, ensuring access to internal systems without compromising security.

By integrating networking and security into a single framework, SASE empowers organizations to effectively support hybrid work environments. It provides enhanced security, seamless access, and optimized performance, enabling employees to remain productive and protected

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regardless of their location. This holistic approach ensures that hybrid workforces can adapt to evolving demands while maintaining operational resilience and data integrity.

IV. Unified SASE Applications

Unified Secure Access Service Edge (SASE) delivers a cloud-based solution for network security and connectivity. Its adaptability and robust feature set allow it to meet the unique security challenges and operational needs of various industries [8]. This section explores how Unified SASE provides solutions to address sector-specific challenges.

A) Healthcare

The healthcare industry faces many challenges, including protecting sensitive patient data, ensuring compliance with strict regulations, and supporting a distributed workforce of medical professionals [9]. Unified SASE provides a comprehensive and layered solution to address these challenges effectively.

1. **Strengthened Data Security:** Unified SASE ensures compliance with regulations such as HIPAA by implementing advanced security protocols. Zero Trust Network Access (ZTNA) minimizes vulnerabilities by verifying user identity and device context before granting access, thereby reducing the attack surface.
2. **Integrated Data Loss Prevention (DLP):** Unified SASE prevents data breaches by identifying and stopping unauthorized transmission of sensitive information. This proactive approach safeguards electronic health records (EHRs) and patient confidentiality.
3. **Robust Remote Access:** Unified SASE enables secure and reliable access to applications and patient data from any location, supporting critical healthcare functions. It ensures the continuity of telemedicine services, allowing uninterrupted patient care during disruptions such as natural disasters or pandemics. Additionally, it facilitates seamless collaboration among medical staff, regardless of their geographical location, enabling effective communication and data sharing. By reducing business interruptions and enhancing operational continuity, Unified SASE helps healthcare organizations maintain consistent and high-quality care delivery in dynamic and challenging environments.
4. **Simplified Management and AI-Driven Security:** A unified management console streamlines security administration, reduces IT workload, and improves operational efficiency. Unified SASE also leverages AI-powered threat detection and automated responses to minimize downtime and mitigate real-time cyber threats.
5. **Cost Optimization:** By integrating multiple security systems into a single framework, Unified SASE significantly reduces hardware and software maintenance costs as well as IT operational expenses. This streamlined approach allows healthcare organizations to optimize resources while enhancing overall efficiency. For example, Unified SASE empowers healthcare providers to balance robust data protection, secure access, and operational efficiency in an increasingly complex and dynamic environment.

B) Finance

Financial institutions are prime targets for cyberattacks and must adhere to strict regulatory requirements while maintaining high standards of service. Unified SASE provides a robust and integrated defence to ensure security, compliance, and operational efficiency [9]:

1. **Comprehensive Security and Fraud Prevention:** Unified SASE integrates key security features to provide comprehensive protection against cyber threats. These include web filtering, firewalls, and intrusion detection/prevention systems (IDPS), which work together to prevent unauthorized access and defend against cyberattacks. Additionally, Unified SASE leverages real-time threat intelligence, proactively identifying and mitigating risks to ensure adaptability to evolving cyber threats and maintaining a robust security posture.
2. **Regulatory Compliance:** Unified SASE simplifies compliance with industry standards such as PCI DSS through rigorous audit capabilities, consistent policy enforcement, and advanced reporting tools.
3. **Enhanced Customer Experience:** Unified SASE ensures secure and seamless access to critical financial applications, including online banking and trading platforms. It offers faster and more user-friendly authentication processes while maintaining robust transaction security, which fosters customer confidence and trust. These enhancements not only improve the user experience but also strengthen consumer trust, a vital factor in maintaining brand loyalty and enhancing the institution's reputation in a competitive financial landscape.
4. **Operational Efficiency and Scalability:** by automating routine security tasks, significantly reducing the manual workload for IT teams. Its cloud-native architecture provides seamless scalability, enabling financial organizations to quickly adapt to changing operational demands. It streamlines network and security management while eliminating redundant security systems, leading to reduced costs for software, hardware, and maintenance. This integrated approach not only optimizes resource utilization but also ensures

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that organizations remain robust in a dynamic business environment.

C) *Manufacturing*

The manufacturing industry increasingly depends on interconnected systems such as Industrial IoT (IIoT), supply chain networks, and cloud platforms to drive operational efficiency and innovation. While these systems offer significant advantages, they also introduce vulnerabilities that require robust security measures. Unified SASE serves as an ideal solution by securing and optimizing these critical connections, ensuring seamless operation and data protection. Key Applications and Benefits:

1. **IIoT Security** [10]**:** Unified SASE provides comprehensive protection for smart factories and IoT devices, which are often the backbone of modern manufacturing processes. It safeguards these systems from cyber threats such as ransomware, unauthorized access, and network breaches. Features like Zero Trust Network Access (ZTNA) ensure that only authenticated users and devices can access IIoT networks, reducing the risk of malicious attacks.
2. **Supply Chain Visibility and Security:** Manufacturing organizations rely heavily on supply chain networks to manage logistics and inventory. Unified SASE secures access to cloud-based supply chain platforms, ensuring that data remains protected during transmission. This enables manufacturers to maintain real-time visibility into supply chain operations while safeguarding sensitive logistics information from cyber threats.
3. **Remote Monitoring and Maintenance:** With the increasing popularity of remote work, manufacturing engineers often need to access factory operations from remote locations. Unified SASE enables secure remote monitoring of machinery and processes, allowing engineers to diagnose issues, optimize workflows, and perform maintenance tasks without compromising security. This minimizes downtime and enhances overall productivity.
4. **Data Protection and Intellectual Property (IP) Security:** Unified SASE ensures the protection of sensitive data, including product designs, operational blueprints, and intellectual property (IP). Data Loss Prevention (DLP) features help prevent unauthorized sharing or exfiltration of critical information. By implementing centralized security policies, Unified SASE ensures consistent protection of valuable assets across distributed systems and locations.
5. **Performance Optimization:** Unified SASE's SD-WAN capabilities optimize network traffic, ensuring that critical applications such as IIoT platforms, analytics tools, and enterprise resource planning (ERP) systems receive priority bandwidth. This improves performance, reduces latency, and ensures smooth operation across distributed manufacturing sites.

Figure (3) summarize the applications of Unified SASE applications in different fields.

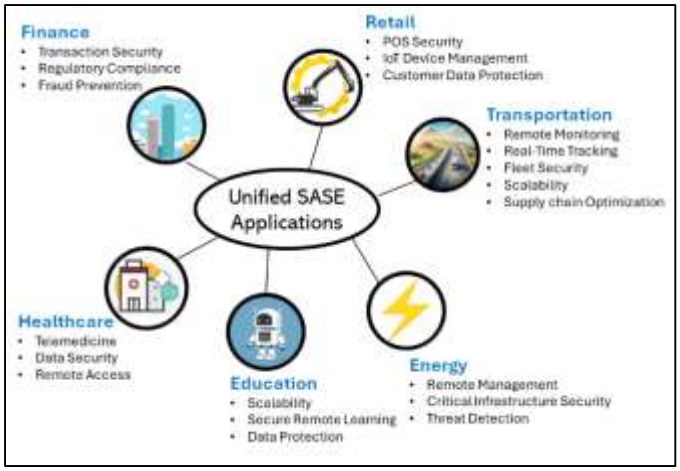

Fig 3. Unified SASE Applications

V. Challenges of Unified SASE Implementation

While Unified SASE provides many benefits, its implementation is not without challenges. Organizations, especially smaller ones, must carefully evaluate potential obstacles to ensure successful deployment and integration. Understanding these challenges is crucial for effective planning and execution.

One of the challenges lies in the significant initial investment required to adopt Unified SASE. For small and medium-sized enterprises, the transition to a cloud-native architecture may involve replacing or upgrading legacy infrastructure, subscribing to comprehensive SASE solutions, and selecting the appropriate vendor for their specific needs. While larger enterprises may find it easier to allocate resources, small enterprises often struggle to justify the costs, especially if their existing systems are still functional. The subscription-based pricing models of many SASE platforms further add to ongoing operational costs, making affordability a key concern for smaller organizations.

Organizations must also address technical challenges such as configuring legacy hardware to work with software-defined perimeters or ensuring that older applications can communicate effectively with centralized SASE frameworks. Additionally, migrating from legacy systems to SASE without disrupting ongoing operations can be a complex and resource-intensive process, requiring careful planning and phased implementation to mitigate risks.

The successful adoption of Unified SASE also depends heavily on the readiness of IT teams to manage its advanced features. Many organizations face a skills gap, as existing

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teams may not have expertise in managing components such as ZTNA, SWG, and centralized policy engines. Furthermore, adjusting to new workflows, such as monitoring and managing a single-pane-of-glass interface, can initially create operational inefficiencies. Without adequate preparation, there is a risk of misconfigurations, which can compromise the security and performance of the framework.

VI. Future Directions in Unified SASE Technology

The evolution of Unified SASE technology continues to redefine network security and connectivity, driven by emerging trends and advancements in AI/ML integration. One key trend is the shift towards greater automation and intelligence in SASE frameworks, where AI and machine learning (ML) are increasingly being utilized for predictive security [10]. Machine learning models are trained using large datasets comprising malware signatures, behavioural patterns, and network traffic anomalies. Supervised learning techniques are applied to identify specific attack patterns, while unsupervised learning detects anomalies that deviate from baseline behaviours.

TABLE III
TRAINING MACHINE LEARNING MODELS FOR THREAT DETECTION

	Supervised Learning	**Unsupervised Learning**	**Reinforcement Learning**
Purpose	Identifies specific attack patterns using labelled datasets of known threats.	Detects anomalies by analysing deviations from baseline behaviours.	Learns optimal responses to threats through trial-and-error and feedback.
Training Data	Requires labelled data with predefined categories (e.g., malicious vs. non-malicious).	Relies on unlabelled data to uncover hidden patterns and irregularities.	Uses real-time interaction data and rewards to refine decision-making.
Use Cases	Effective for detecting known threats (e.g., malware signatures).	Ideal for identifying zero-day exploits and previously unseen attack vectors.	Useful for dynamically adapting to evolving attack strategies over time.
Detection Mechanism	Matches inputs against pre-trained patterns or signatures.	Flags deviations from established normal behaviour as potential threats.	Develops policies to take proactive actions in uncertain environments.
Advantages	High accuracy for known threats; quick deployment if labelled data is available.	Capable of identifying new or emerging threats without prior knowledge.	Continuously improves detection capabilities in dynamic, real-world settings.
Challenges	Requires a large, labelled dataset; less effective for unknown threats.	May generate false positives due to lack of predefined attack patterns.	Requires significant computational resources and training time.

By analysing huge amounts of network data in real time, AI/ML algorithms can identify potential threats before they happen, enabling proactive responses and reducing the risk of breaches. This capability is particularly valuable in detecting sophisticated attacks such as zero-day exploits and advanced persistent threats (APTs). Table highlights different approaches to training machine learning models for threat detection.

Another significant direction is the growing emphasis on integrating Unified SASE with emerging network architectures such as 5G, edge computing, and hybrid cloud environments. These advancements demand scalable, low-latency solutions, which SASE is uniquely positioned to deliver through its unified and cloud-native framework. As organizations adopt distributed architectures, SASE will play a critical role in ensuring seamless connectivity and security across diverse endpoints and geographies.

Additionally, the evolution of security paradigms continues to influence SASE development. The adoption of Zero Trust principles, combined with enhanced policy enforcement capabilities, is expected to further strengthen organizational defences against evolving threats. The increasing reliance on decentralized workforces and IoT devices highlights the need for flexible, adaptable solutions like Unified SASE, which can dynamically adjust to changing environments without compromising performance.

VII. CONCLUSION

The Unified Secure Access Service Edge (Unified SASE) is a transformative solution for organizations adapting to hybrid cloud infrastructures and remote work models. By integrating wide-area network (WAN) functions with advanced network security features, Unified SASE addresses challenges associated with cloud adoption and hybrid work environments. Its focus on threat prevention, data protection, and secure user experiences ensures consistent security and productivity across various deployment scenarios. Unified SASE's scalability and adherence to industry standards ensure compatibility and interoperability, making it a robust framework for modern organizational needs. It empowers hybrid workforces, secures branch and retail locations, supports cloud and digital transformation initiatives, and enhances digital forensic readiness. These capabilities highlight its role in aligning security strategies with evolving operational demands. Overall, Unified SASE provides a robust and adaptive architecture that enables organizations to build resilient, future-proof networks, meeting the demands of today's dynamic corporate landscape.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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A Framework Combining YOLOv2 and Motion-Adaptive Inference with Multiple Data Splits for Waste Management in Smart Sustainable City

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Abstract— Sustainability is a key goal of the United Nations Sustainable Development Goals. Smart sustainable cities are futuristic urban centers expected to dominate the world in the future. Effective waste management is one of the critical indicators of a smart sustainable city. Previous studies have developed waste management models using AI algorithms, particularly convolutional neural networks. However, these studies often struggled with balancing detection speed and accuracy. This article proposes a framework that combines an optimized YOLOv2 model with motion-adaptive inference to achieve a balance between speed and accuracy in detecting organic and recycle materials. The proposed framework has been applied to detect organic and recycle materials alongside baseline algorithms, and it demonstrates improved performance in balancing speed and accuracy compared to the baselines. Making it suitable for adoption in smart sustainable cities. The proposed framework can be integrated into real-time systems to enhance waste disposal management in smart sustainable cities.

Keywords— Convolutional Neural Network; Sustainability; Waste Materials; Fast YOLO.

I. INTRODUCTION

The intersection of smart city and sustainability produces smart sustainable city with the aim developing a city without toxic impact on the environment and optimize the utilization of resources in the city [1-2]. One of the key indicators of environmental sustainability in achieving a smart sustainable city is effective waste disposal and material recycling, which should be integrated into the city planning for short, mid, and long-term urban projects [3]. Increase in population is increasing the challenges of waste management in smart cities [4]. Thus, effective waste management model or systems is required to solve the challenges. Studies were adopting algorithm requiring manual feature engineering for solving machine learning problem [5] including developing waste disposal management system [6] before finding effective solution with convolutional neural network (CNN) [7]. It was demonstrated that large-scale backpropagation networks, can processed images directly without the need for manual feature engineering (Figure 1). The network can learn from raw image data, paving the way for tackling problems involving large-scale, low-level information [8].

Since its inception, the CNN has received tremendous attention and has significantly evolved in the field of visual recognition [10]. It continues to be a leading approach for object detection, as evidenced by recent studies [11-16]. A combination of CNN with LSTM and transfer learning for the separation of organic and recycle waste images for sustainable environment was conducted in [17].

Fig. 1 Typical convolutional neural network with three filters [9].

The CNN has been intensively adopted for the identification of waste and recycle materials as evident in the survey covered by [18]. A CNN extract visual features for waste brand identification before feeding to KNN for prediction [19]. However, it is found that the CNN suffered from localization problem when solving problem regarding object detection. Girshick et al. [20] introduce region into CNN referred to as region with CNN (R-CNN) to solve the challenge of localization in the CNN. Ghadekar et al. [21] adopted R-CNN for the classification of waste from images having nine distinct categories such as plastic, glasses, metal objects, trash, cardboard, papers and more. A mask R-CNN and YOLOv8 were adopted for plastic waste sorting for the purposes of recycling [22]. Jain et al. [23] adopted Mask R-CNN for the detection of underwater waste in order to clean the water body.

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However, the bottleneck in fast R-CNN is the issue of convergence time associated with the region computation. To mitigate this challenge, region proposal network (Faster R– CNN) with capability of sharing full convolutional image features together with the network for detecting the object [24]. Nie et al. [25] uses fast R-CNN to detect garbage during sorting. Similarly, Jose & Sasipraba, [26] propose the use of dual faster RCNN to predict waste for effective waste management in cities. However, Despite the high accurate level recorded by Fast R-CNN, it still suffer from computational complexity especially when it is meant for integration into embedded system [27]. The computational complexity in R-CNN motivated the introduction of "*You only look once*" (YOLO) to reduce the computational complexity where computation of bounding box coordinates and probability of class are performed simultaneously [28]. Arulmozhi et al. [29] applied YOLO for the detection of garbage for waste management. The Single shot multibox detecton (SSD) is introduce to improve the computational speed of the single shot detectors (YOLO) including Faster R-CNN) and accuracy [27]. The SSD has been applied to waste disposal and management [30-33].

The issues with previous studies on waste management are that they primarily focus on either accuracy or computational complexity, with limited effort to explore the interplay between accuracy and computational complexity. To close this gap, the paper propose the adoption of fast YOLO combining optimized YOLOv2 with motion-adaptive inference that accelerate YOLOv2 object detection [34].

The other sections of the article include Section 2, which provides a detailed discussion of the methodology; Section 3, which presents the results and discussion; and finally, the article concludes with Section 4.

II. Waste Management in Smart Sustainable City

Typical waste management begins with the generation of waste from households, industries, streets, public facilities, retail businesses, and other sectors. The waste is then collected and transported by private, government, or informal waste collectors before undergoing sorting, dismantling, and processing. Subsequently, the waste is either recycled and reused in domestic markets, exported, converted into energy, or disposed of in landfills. The overview of the waste management lifecycle is shown in Fig. 2 [35].

The production of products and consumption has changed in the current "circular economy" regarded as environmentally friendly. The circular economy is built on the assumption that materials used will be recycled and reused. The recycling of materials have been typically conducted by humans to recover valuable materials. The manual approach is ineffective because of low productivity and increasing health risk [36]. The increasing amount of generated waste globally is triggering pollution, management of waste and recycling. Therefore, requires advance strategies such as AI to enhance waste management ecosystem [37]. One of the key functions of waste management is monitoring in view of the fact that it is required to ease waste management issues such as generation of the waste, collection, transporting, treatment and disposal processes. In achieving zero waste management, waste characterization is an effective step towards achieving the zero waste management [38].

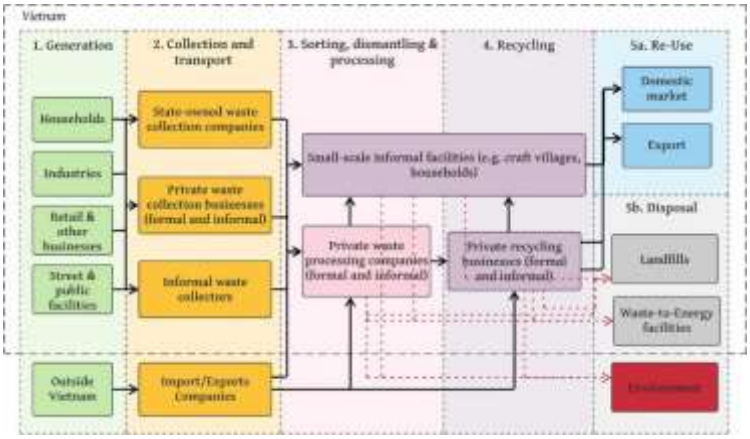

Fig. 2 The lifecycle of waste management value in Vietnam [35].

The future cities are expected to be shaped by the intersection of smart technologies and waste management because of urban landscape transformation. As such, produce a comprehensive approach to sustainable urban environments [39]. Waste management functionality in smart city is beyond its conventional role of disposing rubbish. The integration of state-of-the-art technologies and data driven models is paving a path to sustainable development and improving quality of life [40].

The adoption of AI in municipal waste management have the potential to enhance the effectiveness of collecting waste, processing and classification of the waste [37]. The classification of garbage is recommended strongly for use in solid waste management in municipal [36]. There are AI based technologies that enhance waste management such as smart garbage bins, robots and prediction models. The monitoring of garbage wirelessly enable the detection of waste bins, predict the collection of waste and optimize the waste processing facilities performance [37].

III. Methodology

This section provided the study detailed procedure of the methodology for easy understanding by the readers. The major component in the section is the datasets and the adopted framework.

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A. *Datasets*

The data used in this study contained images of waste involving organic and recycle materials, the sample of the data is presented in Fig. 3 The data is publicly available online through Kaggle as waste classification. The data has 25077 organic and recycle images [41].

Fig. 3 Sample of the waste comprising of organic and recycle materials

B. *Propose framework*

The Fast YOLO comprised of the optimized YOLOv2 and the motion-adaptive inference. Each of the frame is fed to 1D convolutional layer. The convolutional layer produces the motion probability map (see Figure 4). Subsequently, transmit it to motion-adaptive inference to find out if computation to updated class probability map requires deep inference. The deep inference is perform only when required to fasten the rate of object detection [34].

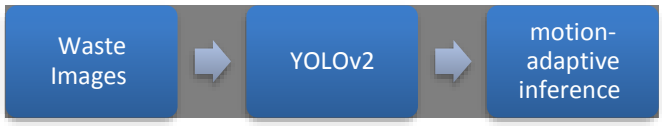

Fig. 4 Procedure for the Fast YOLO classification of organic and recycle materials

The platform used to run the experiment is Google Colab with free access to cloud-based CPUs and GPUs. The datasets described in Section A is splits multiple times: 50:50%; 70:30% and 60:40%. There is no universally accepted data partition ratio; most researchers rely on a single partition ratio, such as 80%-20%. However, such partitioning is often biased toward the pre-training data. To ensure fairness and robustness, this paper employs a multiple data splits technique. The datasets were divided into multiple splits to evaluate the robustness and consistency of the Fast YOLO in identifying organic and recyclable materials across different data splits. For the purpose of evaluation, similar algorithms like the CNN, R-CNN, Fast R-CNN, YOLO and SSD were applied to identify organic and recyclable materials across the different data splits. The performance metrics: Precision, Recall, F1 –score and accuracy were adopted for the study, those metrics are commonly adopted in the literature (e.g., [42-43]).

IV. Results and Discussion

The Tables I – III present the results obtained after running the algorithms to identify organic and recyclable materials from images of waste datasets described in Section III. Tables I–III present the results for multiple data partition ratios, including a 50:50 split, which creates a balance between the training and test datasets without bias.

TABLE I
ALGORITHMS FOR DETECTING ORGANIC AND RECYCLABLE MATERIALS WITH A 70:30 DATA PARTITION RATIO

Algorithm	Precision	Recall	Accuracy	F1 -score
CNN	85.67	84.34	84.79	84.87
R-CNN	86.56	88.45	87.11	90.34
Faster R-CNN	87.78	87.56	89.52	90.52
YOLO	92.43	92.38	92.91	92.29
SSD	91.68	92.96	91.24	92.34
Fast YOLO	**93.89**	**94.94**	**93.45**	**94.96**

TABLE II
ALGORITHMS FOR DETECTING ORGANIC AND RECYCLABLE MATERIALS WITH A 50:50 DATA PARTITION RATIO

Algorithm	Precision	Recall	Accuracy	F1 -score
CNN	70.51	71.61	74.81	74.83
R-CNN	72.06	73.39	77.57	77.74
Faster R-CNN	73.90	77.51	79.58	80.72
YOLO	80.85	82.93	83.88	85.94
SSD	79.51	82.04	85.72	86.19
Fast YOLO	**82.72**	**83.74**	**86.99**	**87.88**

TABLE III
ALGORITHMS FOR DETECTING ORGANIC AND RECYCLABLE MATERIALS WITH A 60:40 DATA PARTITION RATIO

Algorithm	Precision	Recall	Accuracy	F1 -score
CNN	81.49	81.99	82.79	82.85
R-CNN	83.34	83.91	85.61	85.91
Faster R-CNN	85.09	86.73	86.09	87.48
YOLO	88.43	**91.38**	90.31	90.31
SSD	87.84	89.23	89.41	90.09
Fast YOLO	**89.27**	90.94	**91.95**	**92.48**

Table I indicate that Fast YOLO outperforms the baseline algorithms with the best accuracy, followed by the YOLO and SSD. The CNN has recorded the lowest accuracy.

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Table II indicates that Fast YOLO maintains its position leading the accuracy measure, followed closely by SSD and YOLO. Table III, shows that Fast YOLO again leads the accuracy measure, while YOLO and SSD achieve second and third places, respectively.

Tables I – III clearly show that results demonstrate superiority of Fast YOLO consistently offering superior accuracy in varying data partition ratios. In terms of precision, its indicate that the Fast YOLO recorded the highest precision, meaning that it has the most reliable ability in minimizing false positives followed by YOLO and SSD with a strong precision. The CNN recorded the lowest precision, lagging behind. This suggest that the CNN misclassifies more non-target materials as organic or recyclable. Fast YOLO perform well in recall except in the case of 60:40 splits where YOLO standout, suggesting capacity to identify almost all organic and recycle materials. Again, Fast YOLO leads with the highest F1-score, indicating its exceptional balance between the precision and the recall. The possible reasons why the Fast YOLO outperform the other algorithms is likely because of its single step approach to detect object, simplified architecture that reduces computational complexity and ability to process images at high frame rates. Further observation on Tables I – III indicates that the baseline CNN is lagging behind on all the performance indicators. This is not surprising as the other algorithms were improvement over the baseline CNN.

The results in the tables reveal that accuracy reduces as the amount of training data decreases and vice versa, indicating that the accuracy of the algorithms is directly proportional to the size of the training data. This trend highlights the sensitivity of the algorithms to the size of training data available. As such, the lowest accuracy for all the algorithms is recorded at the 50:50 data partition, while the highest accuracy is achieved at the 70:30 data partition for all the algorithms. The Fast YOLO is more resilient to this changes compared to the other algorithms making it a reliable option in the situation where data is limited.

TABLE IV
COMPUTATIONAL SPEED OF THE ALGORITHMS IN IDENTIFYING ORGANIC AND RECYCLE MATERIALS

Algorithm	**70:30**		**50:50**		**60:40**	
	FPS	Time(m)	FPS	Time(m)	FPS	Time(m)
CNN	7	14.22	5	9.00	7.51	12.19
R-CNN	10	19.45	8	13.51	10.06	17.13
Faster R-CNN	15	28.17	13	23.00	13.00	22.53
YOLO	23	34.32	19	30.12	22.00	31.32
SSD	32	43.00	28	37.14	31.18	39.11
Fast YOLO	**48**	52.22	**45**	43.45	**48.23**	50.23

Table IV present frames identified per second (FPS) for the algorithms, it is found that the Fast YOLO achieved the best FPS across the data partition ratios among the compared algorithms suggesting fast processing times in detecting organic and recycle materials from the waste. It is established from Tables I – IV that Fast YOLO has better balance between computational speed and accuracy compared to the baseline algorithms.

The Fast YOLO is robust as suggested by the findings across multiple data partition ratios because of the consistent performance. The adaptability of the Fast YOLO makes it less sensitive to varying training data compared to the other algorithms. The high precision recoded by the Fast YOLO makes it an idle candidate algorithm for waste management systems in smart sustainable city requiring high precision in the identification of waste. The high accuracy archived by the Fast YOLO position it suitably for deployment in large-scale smart sustainable city where real-time waste identification and management is required. For example, the monitoring and optimization of waste collection routes. The quick and fast ability of the identification of organic and recycle waste is in line with the goal of sustainability in smart sustainable city by improving the process of recycling waste, reduction of dependence on landfill and ultimately reduces carbon dioxide footprint. The Fast YOLO outstanding performance with limited training data (50:50) makes it fit for smart sustainable cities in early stages of digitization process aiming at developing waste management systems.

The high precision and computational speed achieved by Fast YOLO is advantageous in practical applications because it has the ability to minimize misidentification of waste ensuring fast accurate sorting and recycling in the smart sustainable cities. The Fast YOLO with highest recall is valuable in waste management systems where ensuring maximum detection of recyclable materials is critical for sustainability goals. However, YOLO is the idle candidate algorithm ahead of Fast YOLO if the slits is 60:40 because the YOLO has a better recall in this case, it is the only case where Fast YOLO lag behind. The Fast YOLO F1-score demonstrates the Fast YOLO reliability and robustness to achieve high detection accuracy across almost all relevant metrics, making the Fast YOLO suitable for integration into real-time smart sustainable city waste management systems. The findings in the study emphasize the critical role of advanced waste detection algorithms in triumphing the objectives of a smart sustainable city.

V. CONCLUSIONS

The study proposes the adoption of optimized YOLOv2 with motion-adaptive inference for waste management systems to contribute in achieving environmental

sustainability goal in smart sustainable city. Comparison with baseline algorithms suggest the robustness, effectiveness and efficiency of the Fast YOLO, making it an ideal candidate algorithm for developing effective waste disposal and material recycling management system in smart sustainable city. As this is initial work, the project intend to integrate Fast YOLO with vision transformer combining Internet of Things sensors and urban analytics for broader smart sustainable city platforms to develop holistic waste disposal and recycling materials management system.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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LUNA: Bridging Communication with Sign Language Translation

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Abstract— This paper presents Learn, Unite, Network and Assist (LUNA) App, an assistive Internet of Things (IoT) system designed to facilitate two-way communication between individuals with hearing and speech impairments and the general public. The LUNA system integrates a smart glove embedded with flex sensors and an MPU6050 accelerometer to recognize hand gestures and translate them into real-time text displayed via a mobile application developed using Flutter. Beyond gesture recognition, LUNA includes a sign language learning module, GPS-based emergency location tracking, and video call functionality via WebRTC, enabling enhanced communication and user safety. Developed using the Scrum methodology, the system combines ESP32 microcontroller-based hardware with Firebase for real-time data handling. Experimental results demonstrate that LUNA achieves high accuracy and responsiveness, with gesture recognition response times ranging from 850 to 1200 milliseconds. This project represents a step toward inclusive communication by promoting mutual understanding and interaction between the disabled and non-disabled communities.

Keywords— Sign language, smart glove, IoT, gesture recognition, inclusive technology.

I. INTRODUCTION

Most people with disabilities such as hearing and speech impairment rely solely on sign language as their main mode of communication in public settings. These people are forced to limit their chance to show off their true skills in job interviews or workplace discussion [1]. Moreover, communicating with those who do not understand sign language can be challenging for sign language users as methods such as scribbling on their note or type on the phone might be time consuming. Thus, people with impairment and general communities need solutions to help them communicate with one another. Existing solutions only focus on how disabled parties can communicate with general parties without realising that both parties should make effort to communicate with one another.

Essentially, Learn, Unite, Network and Assist (LUNA) LUNA App aims to bridge the communication gaps between those both parties by integrating a smart glove that can translate sign language gestures into textual output through the smartphone application.

Objectives of the system include:

1. To enable two ways communication between speech and hearing impairment and public communities.
2. To translate sign language gestures into text in real-time.
3. To create a new solution by improving the existing system.

The smart glove monitors hand orientation using an MPU-6050 accelerometer and detects fingers motion using 2.2 inch flex sensors. Both hardware send data to the ESP32 microcontroller where it processes specific gestures then transmits them via WiFi into the LUNA App. We intend to go beyond the basic functionalities of existing glove-app systems.

Firstly, our LUNA app has a sign language learning module that was created to make it easier for non-disabled users to learn sign language. This module offers interactive instructions to facilitate learning to those who are interested in learning sign language. Additionally, the app's GPS integration allows users with impairments and their family members or caregivers to communicate their location in real time. This function enhances user safety by allowing caretakers to track the impaired user's exact location in case of an emergency. Those features not only help disabled people to communicate with non-disabled but also vice versa.

II. REVIEW OF PREVIOUS WORK

In this section, we analyze and differentiate those past works based on a few aspects such as accuracy, language support, advantage and disadvantage for improvement. This difference is for examining the existing gap to determine the most effective solution and provide a solid foundation for our project.

A. Smart Glove for Arabic Hijaiyah Detection for Quran Citation

Based on the review of existing systems, it is evident that while they share the common goal of improving the lives of individuals with hearing and speech impairments, they differ in scope. For instance, Smart Glove for Arabic Hijaiyah

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Detection for Quran Citation system is designed to recognize Arabic letters used in Quranic recitation, as shown in Figure 1 [2]. This system was developed in response to the challenges faced in the learning process and the lack of qualified Islamic educators proficient in teaching the Quran using sign language. By integrating technology into Quran recitation through sign language, members of the deaf Muslim community are empowered to fully engage with and embrace their faith [2].

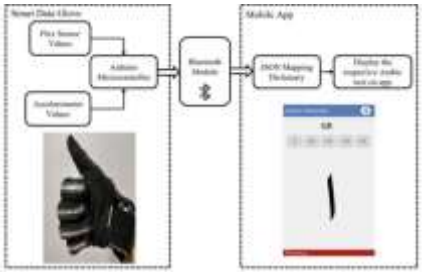

Fig. 1: Hijaiyah detection [2]

B. Sign Language Translation (SLT) Application

Ambar et.al. [1] created a wearable sensor glove to facilitate communication between a deaf person and normal community. They underline that communication between these two individuals is extremely impossible without the assistance of an interpreter. Aside from sign language, there is another technique to help deaf people: hearing aids. However, after wearing this instrument for an extended period of time, the user reported experiencing discomfort. In order to address people's everyday communication requirements, this project focuses on the fact that most people use smartphones and aims to investigate new possibilities by integrating sign language translation into smartphones, shown in Figure 2 [1].

Fig. 2: SLT "Assalamualaikum" detection [1]

C. Smart glove for ASL translation

Abougarair and Arebi [3] discussed how very few people are fluent in sign language. As a result, persons who rely primarily on sign language for communication may find it difficult to converse with others or simply express their opinions. In this rapidly evolving technological era, there are numerous different solutions available, including behind-the-ear, in-the-ear, and canal aids. Despite their usefulness, these devices make the user uncomfortable and allow them to hear background noise. This project intends to create wearable technology that allows the general public and the deaf population to interact while taking user comfort into account, as depicted in Figure 3.

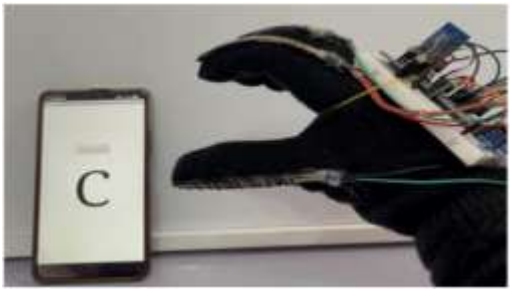

Fig. 3: ASL "C" output in display [3]

D. E-Voice Smart Glove

Amin et al asserts that communication barriers often arise when interacting with individuals with disabilities that limit their ability to engage with the general public [4]. This project addresses such challenges by proposing the development of a portable assistive device that reduces the reliance on others to learn sign language, highlighting one of the glove's principal features. Specifically, the project involves the design of an E-Voice Glove capable of translating hand gestures associated with sign language into alphanumeric text, while concurrently generating voice output through an integrated speaker, illustrated in Figure 4. The primary objective of this initiative is to establish seamless communication between individuals by developing a system that is highly accurate, cost-effective, and functionally independent.

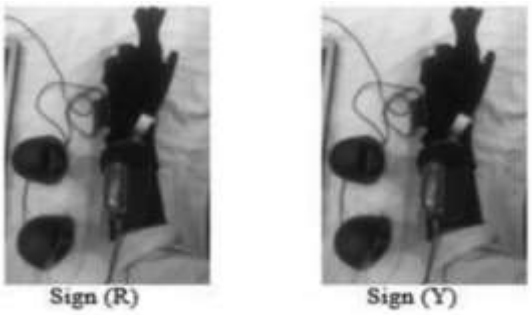

Fig. 4: Sign R and Y[4]

E. Malaysian Sign Language (MSL) Translator

Through the creation of a glove that can convert simple speech signals into images, text, and voice, this system

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seeks to enhance communication for the mute and deaf people in Malaysia [5]. Additionally, Mohamad & Lias optimized the flex sensor capability for the data glove application and created an app that can translate hand motions. In the absence of a workable solution, deaf and mute persons could find it difficult to interact with others, as shown in Figure 5.

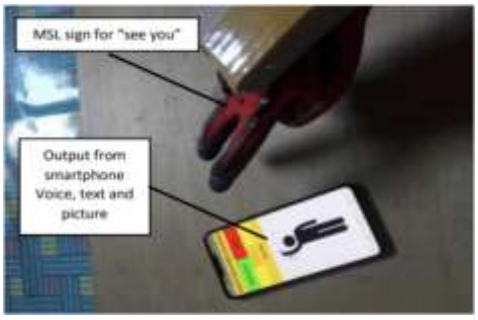

Fig. 5: MSL output from smartphone [5]

Most existing systems employ similar hardware components—namely flex sensors, accelerometers, and Bluetooth module in the development of smart gloves. While the majority of these systems utilize Arduino as the primary microcontroller, this particular project opts for the ESP32. The rationale for selecting ESP32 lies in its integrated Bluetooth and Wi-Fi capabilities, eliminating the need for external Bluetooth modules as observed in previous implementations [3]. Projects that favor Arduino typically do so due to its simplicity, which makes it a suitable choice for small-scale projects and for individuals new to embedded systems. Moreover, Arduino remains a popular microcontroller due to its affordability and versatility, offering significant advantages for educators, students, and hobbyists when compared to other microcontrollers used in similar applications [4].

Furthermore, based on our review of existing systems, there are 3 systems that use MIT App Inventor [1][3][5] and 1 system uses Flutter SDK [2] to develop their application. The MIT App Inventor is block-based tools that are designed for beginners as it enables developers to learn fundamental coding without additional assistance. Mohamad and Lias explained that using MIT App converter supports debugging and real time testing of the application [5]. This app also helps developers to see how the application behaves when they connect the software to their smartphone. Elshareif et al developed their software module using Flutter SDK using the same language as the Arduino microcontroller which is C++ [2]. However, most existing solutions focus solely on gesture recognition and displaying text results within the app. While this is helpful for one-way communication, it lacks the ability to enable two-way interaction or provide support in emergency situations.

The LUNA system addresses these limitations by integrating multiple modules into a single application. It not only recognizes basic hand gestures using a smart glove embedded with flex sensors and an MPU6050 accelerometer, but also allows users to:

- Display gesture outputs on LUNA mobile application.
- Learn gesture languages from photo and video provided
- Initiate one-to-one video calls with a linked emergency contact using WebRTC
- View and share real-time location data using Firebase and OpenStreetMap,

Unlike prior systems, LUNA aims to facilitate mutual communication between two communities which are the hearing-impaired and the general public by combining assistive gesture recognition with communication and emergency support features. This project adopts an IoT-based architecture using ESP32, MQTT, and Firebase, alongside Flutter for the mobile front end. The final goal is to offer a reliable, scalable, and user-friendly communication aid that supports users in both daily interaction and emergency contexts.

III. METHODOLOGY

Generally, methodology describes how the development approach is employed, the methodologies used to collect information and create system requirements, an overview of the pre-production phase, and the prototype activities carried out prior to full-scale development.

A. Development Methodology

In order to ensure an efficient and organized process, we adopted Scrum as a development approach for our project. Scrum is an iterative method for frequent changes, reduced risk and fast delivery to develop a software project [6]. Most software companies use Scrum and it has a positive effect on their software project management [6]

The adopted Scrum process is illustrated in Figure 6, which outlines the flow from product backlog to sprint completion. The team functioned in focused development cycles that allowed for iterative progress and reflection. which outlines the flow from product backlog to sprint completion. The team functioned in focused development cycles that allowed for iterative progress and reflection [7].

Each sprint lasted approximately 4 weeks, depending on task complexity and integration needs. This longer sprint cycle was necessary due to the dual development of hardware and software. The process involved maintaining a product backlog of core features such as gesture recognition, video call and map location, holding a sprint planning meeting to choose sprint goals, executing tasks through development, testing and integration, and ending with a sprint review and retrospective to access results and refine the next sprint [8].

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Fig. 6 : The Scrum Development Process Flow [7]

B. System Design and Tools

The Use Case Diagram shown in Figure 7 outlines the key functionalities available to the user in the LUNA system. These include actions such as signing up, editing the user profile, using the learning module, viewing the home page, changing the language, and triggering the SOS video call feature[9]. The diagram also shows interaction with the emergency contact, who can receive location data and video calls during emergencies. This helps define the system's scope and the responsibilities of each actor.

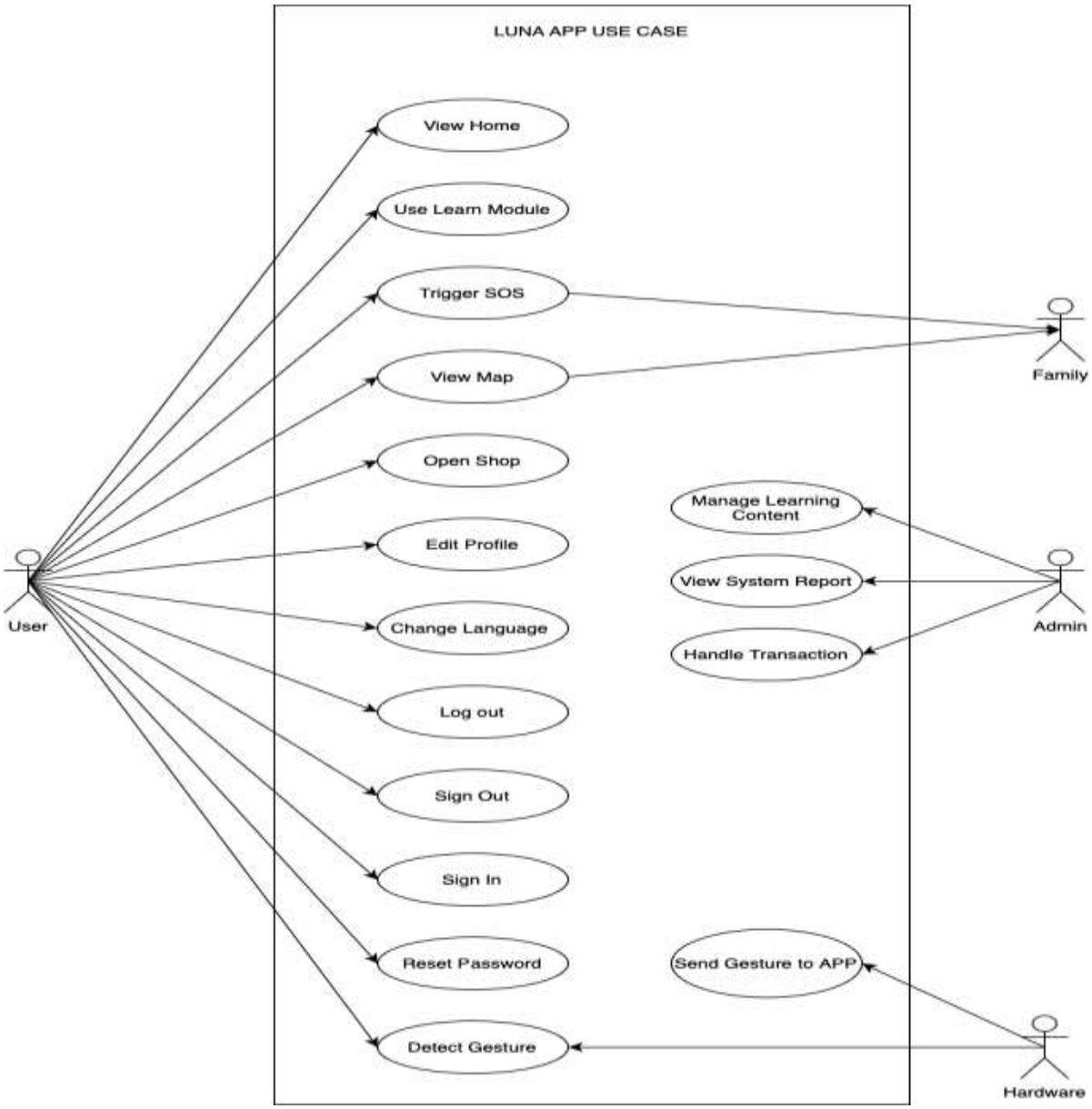

Fig. 7 Use Case Diagram

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The Sequence Diagram in Figure 8 shows the process flow involved in detecting and displaying a hand gesture. It starts with the user performing a gesture, which is detected by the smart glove. The glove sends sensor data to the ESP32, which processes and translates the gesture before transmitting the result to the mobile app. The app then displays the translated text output to the user in real time. This diagram is essential for understanding the interaction between hardware and software components in the system.

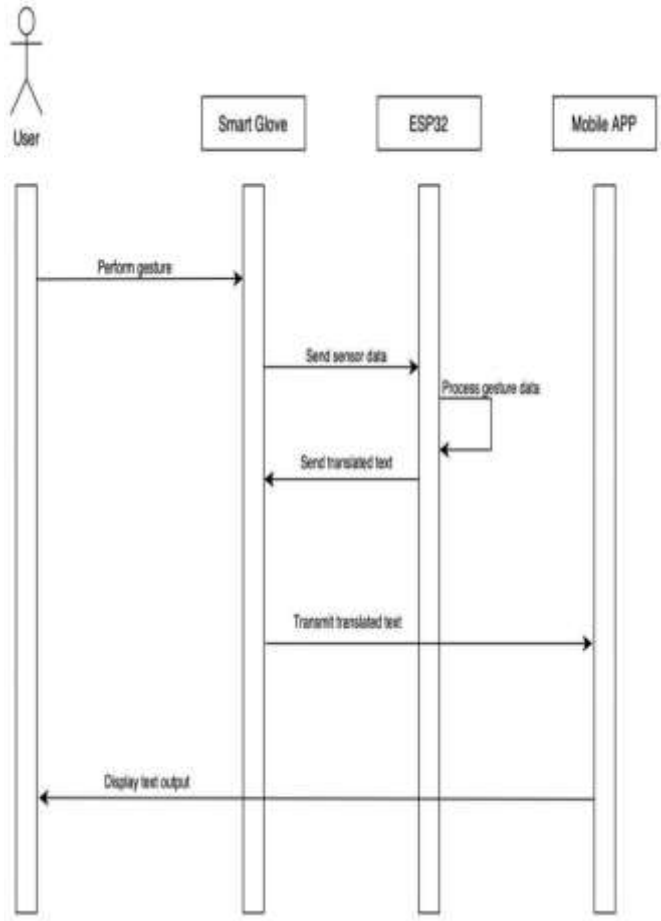

Fig. 8 Sequence Diagram

The Sequence Diagram shows the process flow involved in detecting and displaying a hand gesture. It starts with the user performing a gesture, which is detected by the smart glove. The glove sends sensor data to the ESP32, which processes and translates the gesture before transmitting the result to the mobile app. The app then displays the translated text output to the user in real time. This diagram is essential for understanding the interaction between hardware and software components in the system.

Table 1 shows all the tools that we used to develop the system for both LUNA Apps and Smart Glove:

TABLE 1
SOFTWARE AND HARDWARE TOOLS USED

Category	Tool/Technology
Programming Language	Dart (Flutter) , C++ (Arduino)
Frameworks	Flutter
Backend	Firebase Firestore, Realtime Database
Communication Protocol	MQTT (PubSubClient)
Location & Map Services	geolocator, flutter_map, OpenStreetMap, latlong2
Hardware	ESP32 (TTGO), 2.2 Inch Flex Sensors, MPU6050
Development Tools	Visual Studio Code, Arduino IDE

IV. RESULTS

The LUNA system successfully integrates a smart glove with a Flutter mobile application, offering the following functionalities: The LUNA system is capable of detecting basic hand gestures using a smart glove equipped with flex sensors and an MPU6050 motion sensor. gestures are displayed in real time both within the Flutter mobile application and on the TTGO display. During testing, gesture outputs were shown almost immediately, with an average response time ranging from 850 to 1200 milliseconds.

Users can also link a trusted emergency contact by entering their email address. Once linked, this contact will appear as the default option for emergency video calls and location tracking. If location sharing is enabled, the app retrieves and displays the emergency contact's last known location on an interactive map.

Additionally, the system supports direct one-to-one video calling between the user and their emergency contact. This feature is implemented using WebRTC, allowing real-time audio and video communication with proper camera and microphone permission handling across platforms [10].

A. System Testing Results

We conducted functional and performance testing on the mobile application to verify that all key features worked as intended. In addition, we performed performance testing on the glove integration to measure gesture detection threshold, average response time and pass rate, and the results are shown in Table 2.

All core features of the LUNA application successfully passed functional testing, as shown in Table 2. This is largely due to the fact that the app is relatively lightweight, with a focused set of features tailored specifically for gesture recognition, emergency communication, and basic user interaction. Unlike larger mobile applications that may involve complex navigation, multimedia processing, or high resource usage, LUNA was designed with simplicity and efficiency in mind. As a result, its features performed

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smoothly with no major issues across devices. The streamlined architecture contributes to overall system stability and responsiveness during testing. The response time thresholds differ between gestures due to the hardware limitations and sensor configurations of the current glove setup. The "Peace" gesture relies on flex sensors attached to the index and middle fingers, allowing for fast and accurate detection. As a result, a threshold of 1000 ms is sufficient, and testing showed a pass rate of 100% for this gesture under that threshold. In contrast, the "Hello" gesture is recognized using only the MPU6050 motion sensor, without any flex sensor input

TABLE II
APPLICATION FEATURE TESTING

Pages	**Test Data**	**Test Condition**	**Expected Result**	**Actual Result**
Sign up	Full Name, Email and Password	Tap "Sign Up" button	New user's account successfully registered	Pass
Sign in	Registered Email and Password	Tap "Sign In" button	Existing authorized user can navigate to Home page	Pass
Reset Password	Registered email	Tap "Send Reset Link"	Reset password link is sent to user's email	Pass
Learn	N/A	Tap all categories (Alphabets A-Z, Numbers 1-10 etc..)	Relevant videos and visuals load correctly	Pass
SOS	Camera and microphone access, emergency linked user	Tap "SOS" button	Video call is triggered to emergency contact	Pass
Map	Location access, emergency linked user	Tap "Map" button	User's and family location shown	Pass
Shop	N/A	Tap "Buy Now" button	User will navigate to whatsapp app to order the smart glove	Pass
Translation	Paired glove	Perform hello gesture	"Hello" text displayed on screen	Pass
Family Contact	Registered email of family	Add contact & toggle location sharing	Contact linked	Pass

This type of detection depends on hand movement patterns, which require slightly more time to stabilize. Therefore, a higher threshold of 1100 milliseconds is used for "Hello" to improve reliability, achieving a pass rate of approximately 90%. These variations in threshold values help balance gesture detection speed and accuracy based on the sensors involved.

TABLE III
PERFORMANCE TESTING

Gesture	T Total	Passes	Fails	Threshol	Average Respons Time	Pass Rate
Peace	10	10	0	≤ 1000	873 ms	100%
Hello	10	9	1	≤ 1100	1019 ms	90%

The Gesture Recognition test was conducted to evaluate the accuracy and response time of the glove in recognizing the predefined sign gestures. This testing is executed to ensure the smart glove consistently detects gestures and displays the correct output within an acceptable time.

Each gesture was tested 10 times under the same environment. The system was programmed to record the time when a gesture was detected and the time when the output (text) was displayed on the serial monitor. The difference between these timestamps represents the response time in milliseconds. The Arduino function millis() was used to capture timestamps, and each gesture detection was confirmed through Serial Monitor output.

The accuracy was calculated based on the number of successful detections over the total trials using the following formula:

$$Accuracy\ (\%) = (Pasess\ /\ Total\ Trials) \times 100$$

The core features of the LUNA application are shown in Figure 9. These screenshots include the Welcome Page, the Home Page, and the Side Drawer. These screens illustrate how users navigate the app, initiate gesture recognition, and access emergency features.

The Gesture Result Page displays the output of the hand gesture detected by the smart glove, as shown in Figure 10. Once the user performs a gesture, the sensor data is processed by the ESP32 and transmitted to the mobile application. The app then shows the recognized gesture inside a dedicated output box on the screen.

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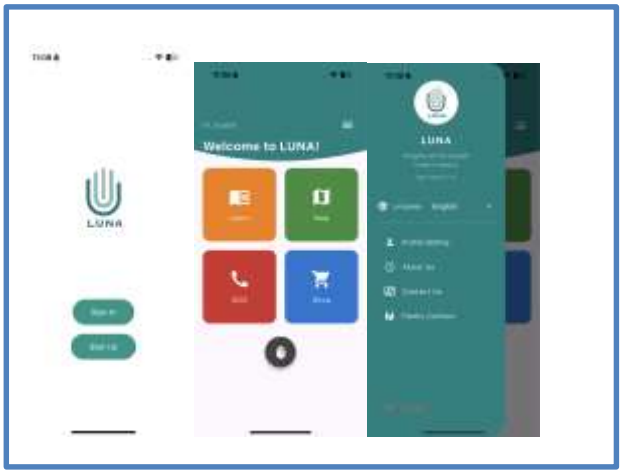

Fig. 9 LUNA App Features

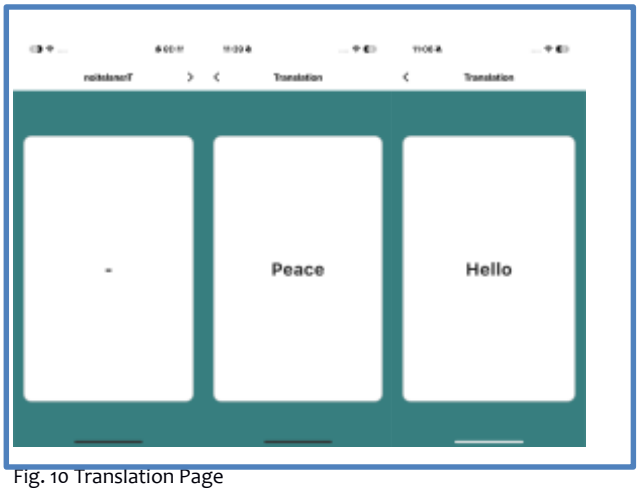

Fig. 10 Translation Page

IV. DISCUSSIONS

The primary goals of the LUNA system was to enable two ways communication between speech and hearing impairment and public communities through gesture recognition and emergency support features. Based on the final implementation and testing the system can:

- enable users to express basic phrases through hand gestures using a smart glove,
- display gesture results in a mobile app in real time,
- allow emergency communication via video calls and location sharing with a family contact.

A. Strength

The LUNA system demonstrates a number of key strengths that contribute to its overall effectiveness, usability, and social value. One of its most notable strengths is the ability to perform real-time gesture recognition using a smart glove embedded with flex sensors and an MPU6050 accelerometer. This allows users to receive immediate visual text output on the mobile application that enhances confidence and communication clarity [11]. The system also offers emergency contact integration, enabling users to link a trusted individual who can receive both SOS video calls and real-time location updates. This is a significant improvement over many existing solutions, which typically focus only on gesture output and lack direct emergency response features.

Furthermore, the LUNA application is designed to be lightweight, intuitive, and focused, with minimal clutter and a clean user interface that supports smooth performance even on low-spec devices. Unlike larger or more complex applications, LUNA provides a targeted set of features that address specific communication challenges. Lastly, one of the most impactful strengths of the system is its commitment to inclusive interaction. Unlike traditional assistive tools that focus only on the user with a disability, LUNA supports two-way communication between the hearing-impaired and the general public, promoting mutual understanding and empowering both sides of the conversation.

B. Limitation and Challenges

While the LUNA system successfully met its core objectives, several limitations were observed during development and testing. One of the limitation for our system is only two fingers are supported. The current glove prototype only detects gestures involving two fingers (index and middle). This limitation arose due to a change in communication method. Initially, the glove was designed and fully soldered for Bluetooth Low Energy (BLE) communication. However, due to BLE instability and time constraints during integration, the team switched to MQTT over Wi-Fi. As a result, only two flex sensor pins were reassigned and functional in the new configuration, while the rest remained tied to the original BLE circuit. Modifying the hardware setup further was not feasible within the available time frame.

Additionally, while the system displays the emergency contact's last known location, real-time tracking is not continuous. Location updates rely on manual toggles or re-opening the app, which may delay response during emergencies.

Furthermore, the glove's communication with the mobile app is fully dependent on a stable Wi-Fi connection. Since MQTT operates over Wi-Fi, the system cannot function in offline mode or via mobile data unless specific configurations are changed. This may limit usability in certain environments without reliable connectivity.

V. CONCLUSION AND FUTURE WORK

The LUNA system successfully achieves its goal of supporting real-time, two-way communication between individuals with hearing and speech impairments and the

general public. Through integration of gesture recognition, emergency response features, and sign language learning modules, LUNA offers a comprehensive and user-friendly solution. Functional testing confirms that all major features perform reliably across devices, while performance testing validates the system's ability to detect gestures within acceptable response times. Despite current hardware limitations, such as partial flex sensor support and reliance on Wi-Fi connectivity, LUNA demonstrates significant potential as an inclusive communication tool. Future enhancements will focus on extending gesture recognition to all five fingers, enabling continuous emergency tracking, and incorporating customizable gesture libraries and AI-based recognition for more robust and adaptive user interaction.

For future work, we aim to redesign the glove to support all five flex sensors using a stable Wi-Fi-based connection. This will allow a broader range of gestures to be recognized, increasing communication flexibility. Currently, only the last known location of the emergency contact is displayed. Future versions should implement continuous background location tracking with real-time updates, improving emergency responsiveness. Moreover, we also plan to implement a user-defined gesture library that has the ability for users to add, manage, and personalize their own gesture library. This feature would allow individuals to map custom gestures to phrases or commands, making the app more adaptable to different languages, dialects, or personal communication needs.

In addition, more tests will be conducted, such as effectiveness, usability and robustness test. The detailed testing will enhance the quality of the app and gloves.

Furthermore, future upgrades can integrate artificial intelligence (AI) to automatically detect sign language gestures (via camera or glove sensors) and generate live captions during video calls. This would enhance mutual understanding during real-time communication, especially when one party does not know sign language.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Automated Classification of Celestial Objects Using Machine Learning

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Abstract— The swift expansion of astronomical data requires the automated classification of celestial objects for practical use. Because of its manual and monotonous nature, classification is more prone to errors and is rapidly losing its viability. This study performs the classification of stars, galaxies, and quasars from SDSS (Sloan Digital Sky Survey) data using the Random Forest, XGBoost, Decision Tree, Gradient Boosting, Linear SVM, KNN, and Logistic Regression. In order to fix the imbalance in the data, the SMOTE algorithm was used, making the model more robust. Random Forest topped the models with their accuracy and reliability across many multiple data releases, hitting an astonishing 99.12% accuracy in SDSS DR18. This work shows how much machine deep learning can change astronomical surveys, providing readily available, precise techniques that are much more effective than manual approaches. The results add towards the development of astrophysics while simultaneously meeting Sustainable Development Goal 9 on fostering innovation through the need for infrastructure.

Keywords— SDSS, Astronomy, Machine Learning, Random Forest, Classification.

I. Introduction

Due to mobility, professional astronomers encounter many challenges because of the exponential growth in astronomical data, especially in the area of classification of objects in the sky. The process of identifying celestial objects using conventional methods, such as human identification and classification methods based on the observable characteristics, is becoming extremely difficult and unfeasible due to the vast amount of data captured by modern telescopes such as the Sloan Digital Sky Survey (SDSS). Through multiple SDSS data release, including DR12, DR14, DR16, DR17 and DR18, had supplied us with extensive spectroscopic and photometric datasets, with over 400,000 celestial objects recorded across these data releases. All of the datasets releases offered detail and rich datasets. This enables researchers to analyze the structure, motion and composition of astronomical entities with greater accuracy and efficiency [23], [26]-[29]. However, these manual classification approaches are not only labour intensive but are also prone to human error. This will make it harder for professional astronomers to effectively gain valuable insights from the available data for more scientific discoveries and advancement [1][9].

Today, the amount of data is growing rapidly, which causes the traditional classification method used by astronomers to become insufficient due to the slow process of classification and high probability of making errors [1][9]. There is a requirement for designing and implementing the automated classification systems to fulfil the requirements of astronomers in analysis and classification of very large data accurately [7][8]. This matter should be addressed as soon as possible because it slows down the developments in astronomical science and creation of new inventions [3],[11].

The aim of this work is to design a reliable machine learning model capable of classifying objects such as galaxies, QSOs, or stars. The goal of the research is to train classifier capable of handling the rich nature of astronomical information by using large dataset of SDSS from several data release. This type of model is important to construct because of the drawbacks of conventional classification methods and it will make it easier for astronomers to manage and evaluate a large amount of data.

The research also focuses on assessing and comparing different classifiers that are used to design the machine learning models. Each classifier must be evaluated by the metrics like precision, accuracy, f1-score and recall because to unearth out the most efficient classifier for classifying the astronomical objects.

In the assessment of SDSS, the study deploys the data source to build and test a variety of machine learning models for classifying a variety of astronomical objects. The stages include data preparation, model developing and model assessment that ensure the proper application of classification methods. The algorithms are presented and compared in a detailed yet concise manner, taking into

account a variety of evaluation metrics, including precision, recall, accuracy, and F1 score.

The main audience of this project is astronomers and academic researchers because they are always active in researching and analysing objects in space using the data they obtain. This study will also benefit institutions related to astronomical research because they always take data and pictures of objects in space using their modern telescopes.

Python language will be used because of its strong support for data science and machine learning where the various libraries available are Scikit-learn, Pandas, Numpy, Matplotlib among others. The computationally demanding experiments will be conducted on good performance computing that is capable of handling large datasets.

This research can enhance the progress of astronomical research because it is able to provide a more effective technique in classifying celestial objects as well as helping astronomers to improve their knowledge and understanding of nature more deeply. This initiative to create a classification model will help the advancement of this field of astronomy.

Furthermore, this initiative will significantly enhance research efficiency by facilitating quick analysis and processing of large amounts of astronomical data. Conventional classification techniques are inadequate due to the rapid increase in data collected by present-day telescopes. The use of machine learning in classifying celestial objects can speed up the classification process as well as save time and resources and give astronomers the opportunity to focus on more complex studies that require more effort. This will increase their productivity and facilitate their process of making new discoveries in the astronomy field.

II. LITERATURE REVIEW

The proposed study builds insights and methods from the reviewed literature to create an effective framework for classifying celestial objects into stars, quasars, and galaxies (see Appendix 1 and 2). Key adaptations and improvements have been made at various steps of the process to enhance performance and address limitations identified in prior studies. They make the study both reliable and efficient in terms of the methodology to be used in the study.

This dataset was sourced from the Sloan Digital Sky Survey as used by a number of authors such as Solorio-Ramirez et al. [5] and Er and Bilgin [33]. The selection is further supported by Zeraatgari et al. [35], who, together with the ALLWISE catalog data, managed to combine it successfully for classification purposes. Furthermore, Cruz et al. [32] reported SDSS is a good reference for spectral classification and accuracy of over 94 percent were carried out using Random Forest and Neural Networks.

Preprocessing remained a key focus as the data had to be prepared to give optimal results before analysis. This was done in order to manage missing data, remove duplicates, and ensure equitable distribution of cases and controls. Following the Hassina [7] and Zhang [34] methodologies, class imbalance was addressed by the application of SMOTE as the primary step of the class balancing which is essential for accurate prediction on the datasets with severely imbalanced categories. This point has been captured further by Er and Bilgin [33] who demonstrated that class balancing improved the accuracy of the predictive model from 87.71% to 94.67%, which is a substantial increase.

Increased efficiency in computation and improvement in model parameters was achieved through selective feature choices. Such conclusions are backed by Sharma and Sharma [9] as well as Vavilova et al. [1] who discussed the significance of making work with the model more effective through feature reduction and irrelevant features removal. Zhang [34] added to this information showing that the narrowing of focus during feature selection particularly to redshift and photometric features boosted the accuracy to 99.39% with XGBoost.

Because all features were expected to contribute to learning, data was normalized following Yoshino et al. [8] and Zeraatgari et al. [35]. Such normalization avoided algorithms, such as SVM, from struggling because of sensitivity to input scale. Exploratory analysis was done to understand the data, align with patterns, trends, or outliers like Smita et al. [11] did.

As quoted by Ashai et al. [2], the dataset was SMOTE oversampled to balance it out. This not only enhanced the model's performance but also provided artificial data for the minority categories which has been approved by Er and Bilgin [33], who did a systematic review on supervised machine learning techniques. These methods allowed for precision modeling with fairly evenly distributed data sets, especially for the more seldom detected quasars and other minority classes.

A set of algorithms were implemented for machine learning to facilitate building a complex classification system. The Random Forest algorithm was included because it is known to be effective with noisy and mixed data [5], [32]. Gradient boosting and XGBoost were selected because of their multi-stage error reducing method [3], [34]. SVM was applied to classify data with large dimensionality [9], [1]. K-Nearest Neighbors (KNN) was chosen because it is effective in classification problems of this sort [2]. Another set of algorithms for classifying cases is based on Decision Trees because they are easy to use, and easy to understand [10]. At last, the Logistic Regression model was employed because, traditionally, it is very effective in classification problems whether binary or multi-class, and it is able to

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provide reliable midpoints in the cases of the galaxy morphological types and could appropriate high levels of accuracy [1].

Although the introduction of Neural Networks (NNs) have successfully accomplished complex tasks, but for the scope of the research conducted in this case, NNs were not the recommended choice. Primarily, NNs will not perform to their best capabilities without ample amounts of data, which greatly exceeds the availability of the SDSS dataset. Secondly, even without considering NNs, models such as Random Forest and XGBoost already claimed remarkable results on previously conducted astronomical classification studies, thus eliminating the requirement of more advanced models [5], [8]. Furthermore, the vast majority of NNs are not as easily interpretable compared to regression trees which was a major concern for this research when it came to analysis of feature importance.

As for focusing on ensemble methods, Random Forest, XGBoost, and Gradient Boosting were selected because they have addressed multilevel class imbalances effectively as the literature review showed (See Appendix 1). AdaBoost and Extra Trees, on the other hand, were not selected because those models will simply serve to add redundancy, and are based on the same ideas as the selected models without outperforming them in other relevant researches [3], [7]. The requirements did not set any constraints and instead concentrated on the relative aspects of interpretability, efficiency of computation, and precision of classification provided by single robust algorithms, which can easily be accomplished through the existing benchmarks in the field.

III. METHODOLOGY

The dataset comes from the images that have been previously taken by the SDSS cameras, and then the pre-processed data was shared on Kaggle. This study focuses on classifying the data into three categories: galaxies, QSOs, and stars.

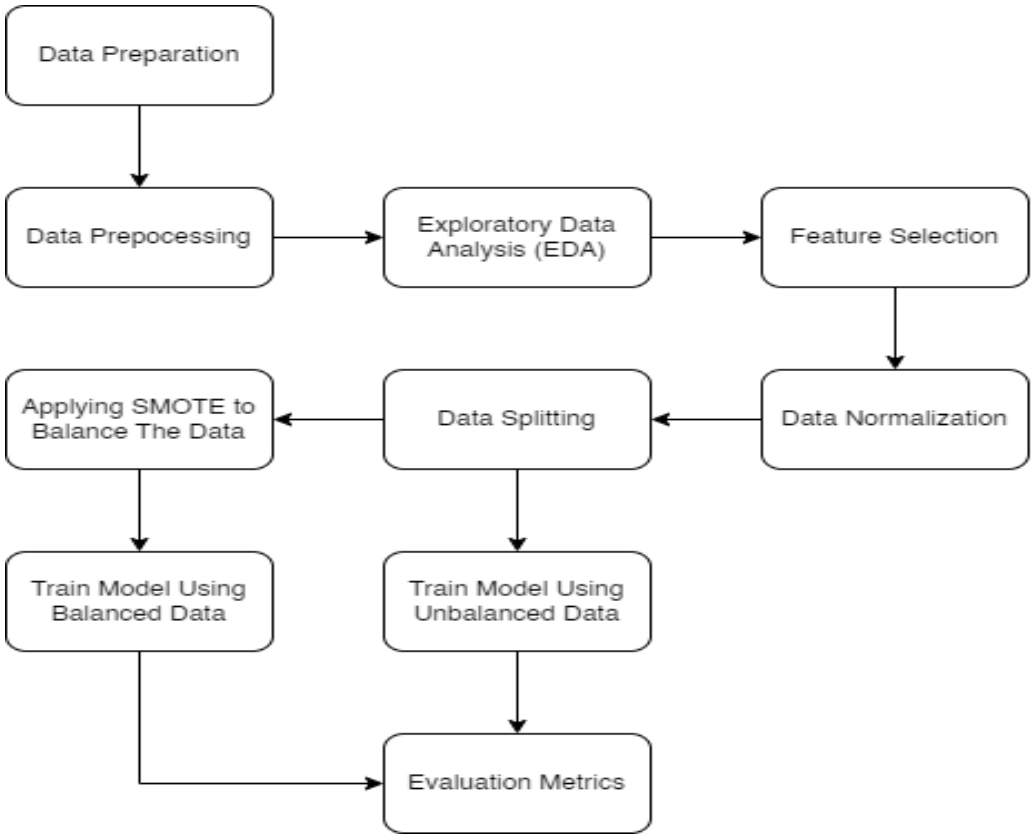

Fig. 1 The process flow of methodology

A. *Tools: Python and Pycharm*

The tools applied to this project were selected in order to implement the intended system for formation of celestial objects classification using machine learning. Python was the primary coding language due to variety and availability of numerous valuable libraries for data science and machine learning streams. Dealing with the dataset was facilitated by Pandas while NumPy was used for operations such as operation on the arrays and matrices. A package, Matplotlib,

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was used for the plotting and visualizing of data, as a way of making sense of patterns into the data generated.

B. *Dataset*

This dataset for this project was obtained from the Sloan Digital Sky Survey (SDSS) Data Releases 12, 14, 16, 17, and 18 and includes 418,070 rows of spectroscopic and photometric data concerning celestial objects. SDSS is a large-scale survey conducted at the Apache Point Observatory in New Mexico, using a specialized 2.5-meter-wide angle optical telescope. This survey has collected data on millions of celestial objects, providing deep, multicolour photographs that cover one-third of the sky [24].

This project focused on three types of celestial objects: galaxies, stars, and quasars. These were chosen because they emit their own light, making them easier to observe compared to objects like planets, gases, or black holes that rely on external light sources to be visible. By narrowing the scope to these three categories, the dataset became more manageable and relevant for building and evaluating machine learning models. The richness and detail of the SDSS dataset made it an ideal choice for this research, providing a strong foundation for accurate and meaningful classification [1].

C. *Data Preprocessing*

Data preprocessing was started with the first step, which is loading the dataset into a Pandas DataFrame. First, it was done to gain insight into the structure of the obtained data set. The researcher adopted the use of the command df.head() to get a preview of the content in a DataFrame. Thus, df.dtypes was used to check if each of the columns contained integer, floats, string or object values. In order to learn about the structure of the dataset containing integers, floats, strings or objects, the command df.shape was used.

The next challenge was how to handle missing values, which are detrimental to many machine learning models. These were detected using df.isnull().sum() command, on the data frame and then they were excluded by using the statement df.dropna(inplace=True). Rows were repeated which could bring a bias and redundancy, this was sorted out using df.duplicated() and removed using df.drop_duplicates(inplace=True). The target variable was basically in the form of categorical attributes where distributions and objects were classified as 'GALAXY,' 'STAR,' and 'QSO.' For machine learning purposes, numerical labels were given to each of these categories. In particular, 'GALAXY' was equated with '0,' 'STAR' with '1' and 'QSO' with '2.' Preprocessing steps have made the clean and effective preparation of dataset suitable for training the machine learning algorithm.

D. *Exploratory Data Analysis (EDA)*

Exploratory Data Analysis (EDA) was carried out to better understand the dataset and visualize the relationships between features. The main steps included:

1. Feature Distributions:
- Histograms were created to show how the values of each feature are spread across the dataset for different data releases.
- Boxplots were used to detect outliers and understand the range of each feature, helping to determine if outliers were meaningful or caused by errors.

2. Pairwise Relationships:
- Pair plots were generated to show the relationships between features. These plots helped us see how features like photometric bands and redshift are related and whether there are clusters or patterns in the data.

3. Correlation Matrix:
- Numerical features' association strength checking was based on the use of a correlation matrix. This assisted in detecting features whose relation is high and 'broadly' similar to the correlations identified between certain photometric bands (like r and i) and redshift adds additional information.

Such steps allowed receiving useful information about the given dataset and selecting features which are more significant for classification of celestial objects. This analysis was useful in the process of building this model and enhancing the outcomes of the research as well.

E. *Feature Selection*

Feature selection is a critical step in machine learning process and plays an enormous role in the improvement of input signals. The following is because, it saves time for computation, it is less likely to over-fit, and it is suitable for other unseen data. To reduce the dimensionality of the data set a process of feature selection was conducted to remove unneeded columns and features with variance of zero and the final dataset only contained features that were meaningful for classification of celestial objects.

The first operation performed was to detect features with feature variance equal to zero and then eliminate them. Variance can be defined as statistical measure of dispersion that quantifies how far apart from the mean of a feature values are. Features that have variance of zero have the same value for all observation which makes them unhelpful when doing predictive modelling. The features were flagged as comprising two variables: objid and rerun; these were excluded from the data set.

Other columns that were dropped since they contributed little to the classification of astronomical objects include

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features with zero variance. Often, these columns included miscellaneous information or ID's, etc., that excluded from the observation layer; in other words, the column could be less relevant during the classification process. The following features were excluded from the dataset:

- specobjid: Spectroscopic object identifier
- ra: Right ascension of the object
- dec: Declination of the object
- run: SDSS imaging run identifier
- camcol: Camera column
- field: Field number
- plate: Plate number
- mjd: Modified Julian Date
- fiberid: Fiber ID

Id-depending information and observational meta-information and extra information on the photometric or morphological aspect were taken out of the dataset to classify the feature space as simple as possible. The last subset of features chosen for the model is redshift together with u, g, r, i, z photometric bands. This was done to counter the observed variability in feature selection found in the current literature. However, these specific features such as redshift and photometric bands were applied persistently in many studies [3], [5], [7], [8]. While other features were selected, the justification for doing so was not always comprehensible, and the same can apply to the repeated use of this strategy. These theses prove the significance of these features for the classification of celestial objects. Redshift gives important data about distance and velocities of objects and with photometric bands that give information about the spectrum energy distribution which help to distinguish between stars, galaxies and quasars.

F. *Data Normalization*

In this study, all numerical features, other than the target variable class, were normalized using the StandardScaler function from the sklearn.preprocessing library. This method made each feature to have mean equal to zero and the standard deviation equal to one [25]. The cases include algorithms like Support Vector Machines (SVM) where standardization must be performed due to its scale of input data. It also stops feature with large value dominating features with small value, thus all numerical features are given an equal input into making the model.

G. Data Splitting

The data was split into two parts: X and y. The variable X was a combination of all features after normalization except the class and y was the target variable class which contained the labels for celestial objects. Using the function in sklearn. model_selection which is train_test_split, the data was split into train data at 70% and test data at 30%. Another configuration for the state of each component was a purely random choice of 42 in order to achieve a reproducible result. This split created four parts: These are; X_train (training features), y_train (training target), X_test (testing features), and y_test (testing target).

The 70/30 split is widely used in machine learning as it is effective in balancing between the need for a sufficient training data to optimize model and to adequate testing data to evaluate its performance. Empirical studies shown that by allocating 20 – 30% of data for testing provides the best trade off between minimizing approximation errors and also maximizing the validity of the model results. So, this ensures that the model generalizes well to unseen data while avoiding overfitting, as highlighted in [30].

K-fold cross validation provides a more robust approach as it uses the entire dataset for training and validating in multiple iterations. However, it can be computationally expensive especially for the large datasets like the one used for this study. So, the 70/30 split is computationally efficient and suitable for this project after considering the size of SDSS dataset and the available computational resources.

H. *Applying Synthetic Minority Over-Sampling Technique (SMOTE)*

Using Synthetic Minority Over-Sampling Technique (SMOTE) to handle imbalanced dataset, where one class has the most number or frequency compared to other class. In this study, SMOTE was applied using the imblearn library. The fit_resample method was used on the training data (X_train and y_train) to generate new data for the minority class, making the dataset balanced.

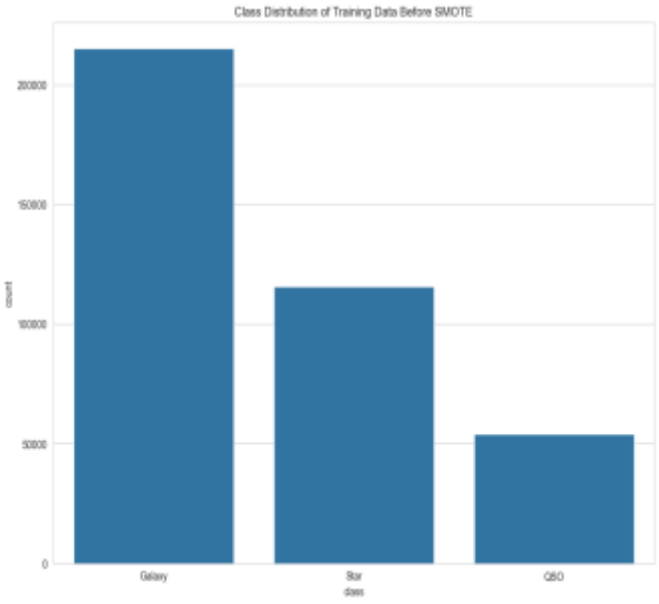

Fig. 2 Class distribution of training data before SMOTE

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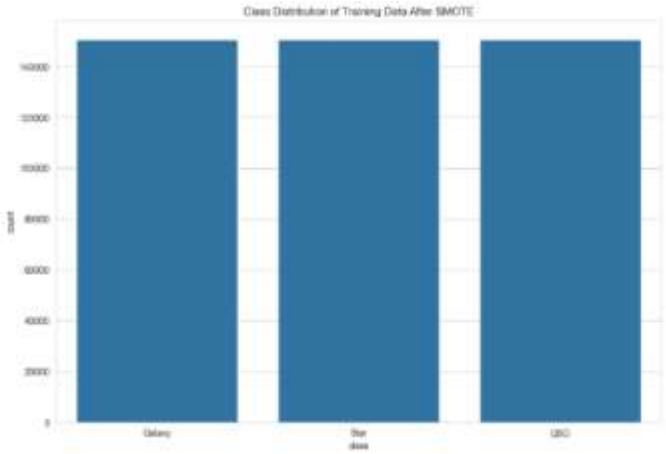

Fig. 3 Class distribution of training data after SMOTE

I. *Modelling*

The model was trained using seven different machine learning algorithms on raw and balanced data to assess and understand their behaviour under different data conditions, each with its own approach to classification:

- Gradient Boosting builds models iteratively, with each new model minimizing the errors of the previous one, combining them into a strong learner [16].
- XGBoost is an optimized version of Gradient Boosting designed for speed and efficiency, using ensemble learning to improve predictions [14][15].
- Decision Tree uses a tree-like structure where nodes represent decisions, branches represent outcomes, and leaves represent predictions, splitting the data based on selected features [13].
- Linear SVM finds the optimal decision boundary (hyperplane) that separates data points into different classes in feature space [19].
- Random Forest creates multiple decision trees using subsets of data and combines their outputs for a final prediction [18].
- K-Nearest Neighbours (KNN) predicts the label of a data point by analysing the labels of its closest K neighbours based on distance [17].
- Logistic Regression models the relationship between variables to calculate the probability of a data point belonging to a specific class [12].

Although the introduction of Neural Networks (NNs) have successfully accomplished complex tasks, but for the scope of the research conducted in this case, NNs were not the recommended choice. Primarily, NNs will not perform to their best capabilities without ample amounts of data, which greatly exceeds the availability of the SDSS dataset. Secondly, even without considering NNs, models such as Random Forest and XGBoost already claimed remarkable results on previously conducted astronomical classification studies, thus eliminating the requirement of more advanced models [5][8]. Furthermore, the vast majority of NNs are not as easily interpretable compared to regression trees which was a major concern for this research when it came to analysis of feature importance.

As for focusing on ensemble methods, Random Forest, XGBoost, and Gradient Boosting were selected because they have addressed multilevel class imbalances effectively as the literature review showed (Appendix I). AdaBoost and Extra Trees, on the other hand, were not selected because those models will simply serve to add redundancy, and are based on the same ideas as the selected models without outperforming them in other relevant researches [3][7]. The requirements did not set any constraints and instead concentrated on the relative aspects of interpretability, efficiency of computation, and precision of classification provided by single robust algorithms, which can easily be accomplished through the existing benchmarks in the field.

J. *Model Evaluation*

The evaluation of the machine learning models was performed using several key metrics to ensure a comprehensive understanding of their performance:

1) Accuracy: This metric represents the overall correctness of the model by calculating the ratio of correctly predicted instances to the total number of instances in the dataset. Accuracy is particularly useful for providing a general understanding of model performance but can be misleading in the presence of class imbalance.
2) Precision: Precision measures the ratio of true positive predictions to the total number of predicted positives. This metric is particularly important in cases where minimizing false positives is crucial, such as identifying quasars from other celestial objects.
3) Recall: Recall, also known as sensitivity, calculates the ratio of true positive predictions to the total actual positives. This metric is crucial for understanding how well the model identifies all instances of a particular class, especially for rare classes like quasars in the dataset.

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4) F1-Score: The F1-score is the harmonic mean of precision and recall, providing a balanced measure that is particularly useful when there is a significant class imbalance in the dataset. This metric ensures that both precision and recall are considered equally in the evaluation.

5) Confusion Matrix: A confusion matrix was generated to provide a detailed view of the model's performance across each class. It shows the counts of true positives, false positives, true negatives, and false negatives for each class (galaxies, stars, and QSOs). This matrix is essential for understanding the specific misclassification patterns and identifying areas where the model could be improved.

The evaluation was conducted on both the raw and balanced datasets, ensuring that the impact of class balancing techniques, such as SMOTE, was considered in the analysis. The metrics were calculated for each of the three classes—galaxies, stars, and quasars—individually to evaluate the model's performance across different celestial object categories comprehensively. This multi-metric evaluation approach ensured a robust comparison of the models and helped in identifying the best-performing algorithms for the classification of celestial objects using the SDSS data.

K. *Statistical Analysis*

Stastical analysis were conducted in order to validate the performance comparisons between each machine learning models. The analysis was done according to a detailed statistical framework. This framework combined parametric and non-parametric statistical test to validate the comparative performance of the models acrross multiple datasets of data release. The analysis was guided by the framework outlined by Chatzi and Doody [31] which emphasizes testing assumptions before choosing the appropriate statistical methods.

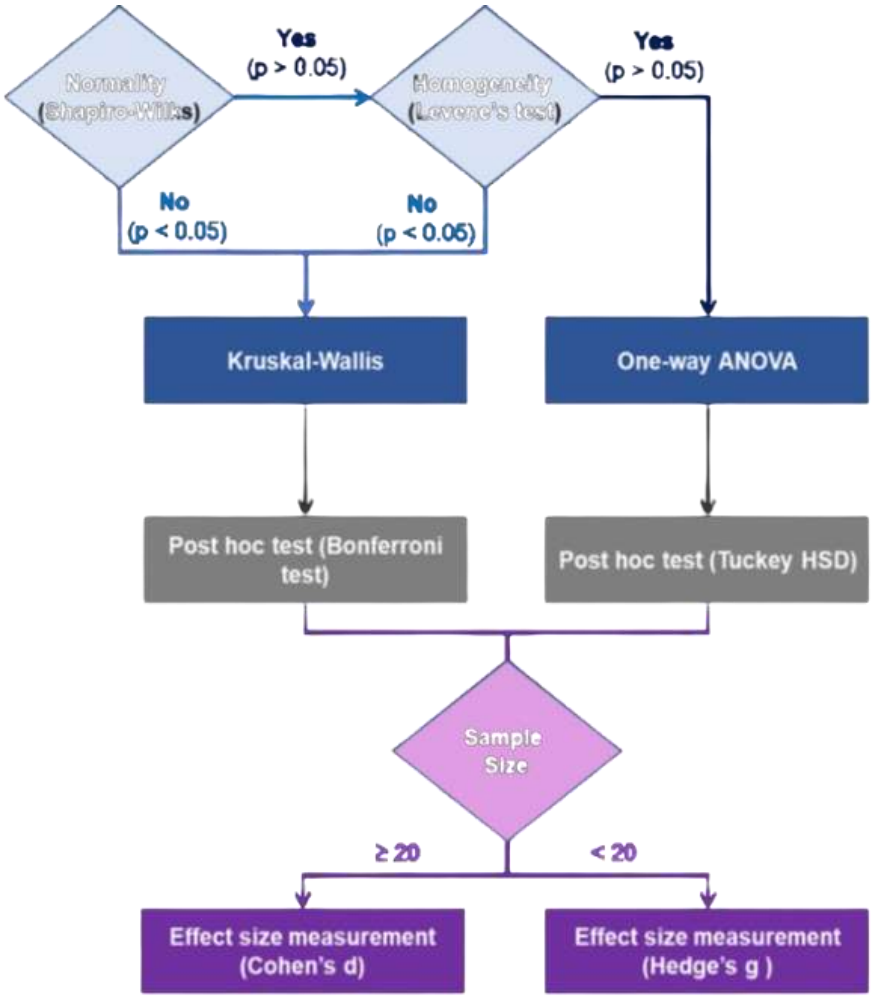

Fig. 4 Framework for selecting statistical analysis methods. Adapted from [31].

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1) Normality Assessment

The distributions of accuracy for each machine learning models were examined using the Shapiro-Wilk's test. A threshold of 0.05 was used to determine whether the data was significantly distributed and thus normal. Models that had a p value less than or equal to 0.05 were considered as having non-normal distributions. The findings clearly demonstrated that all models did not exhibit normality and some of them particularly Gradient Boosting and KNN did not satisfy the normality assumption. As discussed [31], this normality testing was important in deciding whether to use a parametric or a non-parametric test.

2) Homogeneity of Variance

Levene's test was performed to assess the equality of variances among the models' accuracies. The test results ($p \geq 0.05$) confirmed that homogeneity of variance. This fulfilled one of the criteria to allow the application of parametric. Variance homogeneity is one of the key assumption for parametric tests such as Analysis of Variance (ANOVA) and was addressed to ensure accurate comparison, consistent with [31]. However, if the normality assumption fails then, then analysis can only proceed to non-parametric tests.

3) Group Comparisons

- This test was done to check the differences of mean accuracy value across models when both normality and homogeneity assumptions are satisfied. According to [31], ANOVA is perfectly able to compare more than two means at one time and eliminates Type I error.
- Kruskal-Wallis Test:
  For those models which did not meet normality assumptions, the Kruskal-Wallis non-parametric test was used to detect any deviation from median accuracy. The p-value for this test was set at 0.05. Such results indicate that at least one model did not agree with the rest. This concurs with [31] warnings on the use of non-parametric methods where assumptions are known to fail.

4) Post-Hoc Analysis

Post hoc analysis aims to pinpoint the model which has impacted the research in question the most. [31] suggested that for Kruskal-Wallace test, Dunn's test with Bonferroni correction should be made for pairwise difference decision to eliminate Type 1 error. For ANOVA, the difference of means HSD test will assist in figuring out pairwise differences between models.

IV. RESULTS

A. *Comparative Performance Across SDSS Data Releases*

Figure 5 depicts the comparative performance of various machine learning algorithms—Random Forest, XGBoost, Gradient Boosting, Decision Tree, Linear SVM, KNN, and Logistic Regression—across multiple Sloan Digital Sky Survey (SDSS) data releases (DR12 to DR18). The results presented offer a comprehensive analysis of the models' accuracies under varying dataset complexities, shedding light on their adaptability and robustness.

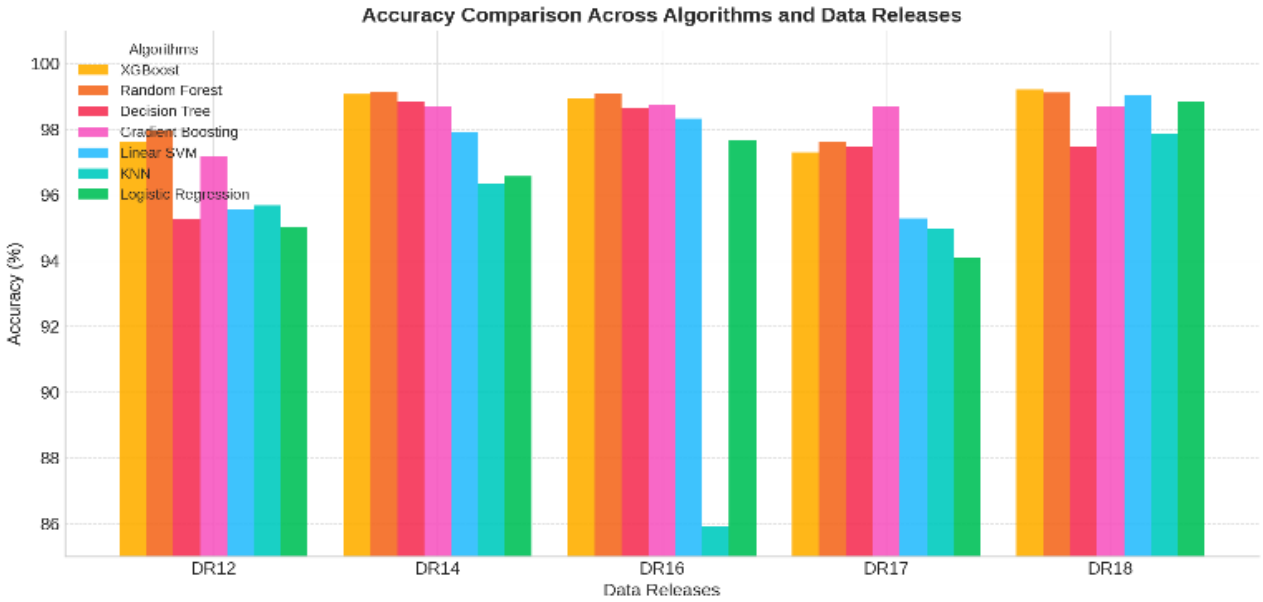

Fig. 5 Comparison of Accuracy Across Different Machine Learning Algorithms (e.g., Random Forest, XGBoost) for Classifying Celestial Objects Across SDSS Data Releases (DR12 to DR18)

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Random Forest consistently excels across all data releases and emerges as the most dependable algorithm. Its peak performance of 99.12% on DR18 validates its robustness and highlights its scalability to handle complex and diverse datasets. Its reliability in earlier datasets like DR12 (97.95%) further underscores its consistency. These findings corroborate previous research, such as [5], emphasizing the algorithm's capability to manage noisy, imbalanced data environments.

XGBoost, closely trailing Random Forest, demonstrates exceptional capability in minimizing misclassifications and managing high-dimensional datasets. Its peak accuracy in DR18 with 99.21% accuracy and competitive performance across earlier releases reinforce its versatility. The algorithm's strong adaptability to different celestial object classes suggests its potential as an alternative when precision is crucial, especially in classifying stars and galaxies.

Gradient Boosting, while achieving an accuracy of 98.69% in DR18, illustrates a trade-off between accuracy and interpretability. Its limitations become apparent in datasets with overlapping spectral features, such as DR16, where minor declines in accuracy were noted. Despite these drawbacks, its balanced performance across multiple datasets makes it a viable option for tasks requiring a compromise between transparency and performance.

Although decision Tree models are efficient for straightforward tasks like star classification, they face challenges in handling complex boundaries, such as those required for quasars. Their reduced F1 scores and accuracy dips in DR17 and DR18 highlight these limitations. Nevertheless, Decision Trees can serve as foundational elements in ensemble methods, offering simplicity and interpretability.

Linear SVM, with accuracies consistently exceeding 94%, struggles to address non-linear separability. This limitation, particularly evident in the classification of quasars, calls for kernel-based enhancements or feature transformations to boost its effectiveness.

Logistic Regression, maintaining a baseline accuracy above 94% across all data releases, highlights its simplicity and reliability for less complex tasks. However, its inability to handle intricate datasets underscores the need for more sophisticated models in applications involving substantial feature overlap.

K-Nearest Neighbors (KNN) recorded the lowest performance among the evaluated algorithms, which underscores its sensitivity to high-dimensional spaces and feature overlap. This trend is most apparent in DR16, where noticeable accuracy drops were observed. These findings emphasize KNN's limitations for large-scale and complex datasets, such as those in SDSS.

The results reveal practical implications for astronomical classification tasks:

1. Ensemble Methods: Random Forest and XGBoost are ideal candidates for automated classification pipelines in large astronomical surveys due to their scalability and robustness.
2. Simpler Models for Benchmarking: Logistic Regression and Decision Trees, while less suitable for complex classifications, serve as valuable benchmarks for evaluating advanced algorithms.
3. Dataset Characteristics Matter: The consistently superior accuracy in DR18 suggests that improved data quality and volume significantly enhance model performance. This underscores the importance of well-curated datasets in achieving optimal results.

Figure 15 confirms that ensemble methods like Random Forest and XGBoost dominate in performance, meeting the study's objectives by providing reliable and efficient solutions for celestial object classification. Meanwhile, the limitations of simpler models like KNN and Logistic Regression reinforce the necessity of advanced techniques for managing the complexities of astronomical data. These findings not only validate the research's approach but also provide a clear roadmap for future explorations in automated astronomical data analysis.

B. *Robustness and Variability of Model Accuracy*

Figure 6 provides a complete breakdown of how each machine learning algorithms' accuracy differed with respect to the SDSS data versions under consideration. This particular analysis demonstrates parallels and inconsistencies of algorithm efficiency, thus revealing how each model reacts to the varying datasets.

Random Forest: The IQR of Random Forest is narrow suggesting that it is consistent with achieving high accuracy score in all of the data versions. In addition, its lack of variability means that it is quite resilient to changes in data. It is worth mentioning that the usage of random outliers is almost non-existent. This attribute of random forest enhances its generalization capabilities on different sets of astronomical data.

K-Nearest Neighbors: Judging by KNN, the narrowest IQR implies that all other algorithms exhibit much broader outliers. This means that KNN is highly dependent on the feature overlaps or class imbalances in the dataset. The presence of multiple outliers in the controlled experimentation means the algorithm is performing inconsistently at bestangement pointing towards the proximity based classifiers for larger matrices that are highly dimensional like SDSS ones has their disadvantages.

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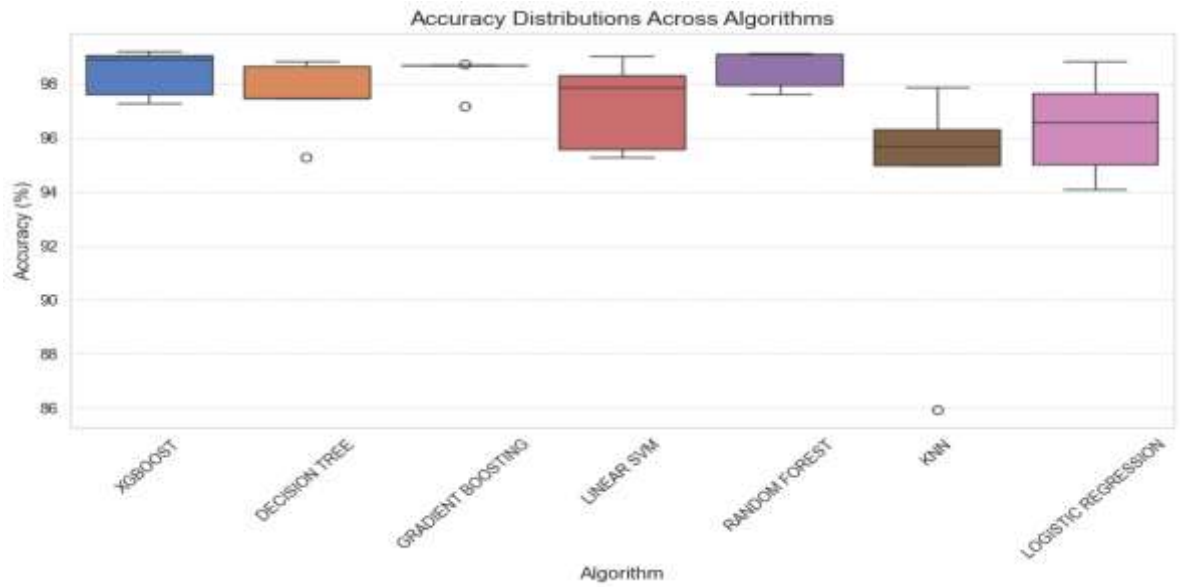

Fig. 6 Accuracy Distributions Across Machine Learning Algorithms

Logistic Regression: KNN is captured by the least variability against the other algorithms. Logistic Regression maintains a moderate median accuracy score while exhibiting central measures variability. This assumption stems from the model's linear structure.

C. *Statistical Validation of Performance Differences*

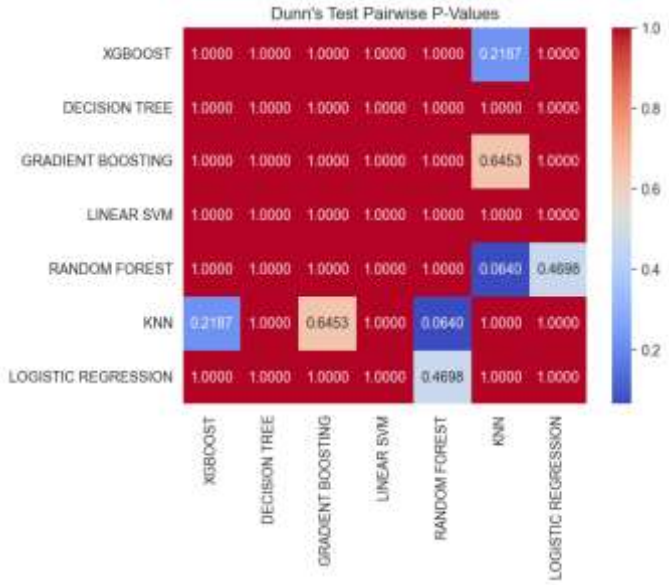

Fig. 7 Dunn's Test Pairwise P-Values Heatmap

Dunn's test results in Figure 7 elucidate the alignment and differences in the accuracy outcomes of different machine learning algorithms. As can be seen from the Random Forest's results, it's performance is quite different when analyzed through the use of K-Nearest Neighbors (KNN) thus showcasing its effectiveness and ability to generalize more robustly. This correlates with the results aim of finding a model that can classify celestial objects accurately and with great certainty.

Practically speaking, this study illustrates that Random Forest is optimal with respect to the processing of large volumes of astronomical data where the dimensionality and sparsity of the dataset is particularly high. The lack of significant differences between the XGBoost and the other algorithms results indicates that Decision Tree and Gradient Boosting may also be adopted as other reasonable methods depending on the nature of the data to be analyzed or the available computational power.

These results highlight the utilization of advanced statistical techniques such as Dunn's post-hoc test in measuring differences in the performance of various algorithms. As stated earlier, this helps ensure the conclusions reached have both statistical and practical value and sets the stage for further research into ensemble techniques and hybrids that would benefit from different algorithms. In so doing, this particular study provides powerful closure to the insights gained by melding these statistical results with the core objectives of the study. This, in turn, culminates to enhancing the techniques employed in automated classification of celestial objects.

The statistical analysis was done following a strict multi-level approach in order to ensure reliability and validity of results with the claims made:

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1) Normality Testing (Figure 18):

As shown in figure 8, the Normality of the accuracy distributions for each machine learning technique was carried out with Shapiro-Wilk test. This was necessary for deciding the use of parametric or non-parametric statistical techniques in the next phases of analysis. From the results, the assumption of normality was not uniformly met by the algorithms.

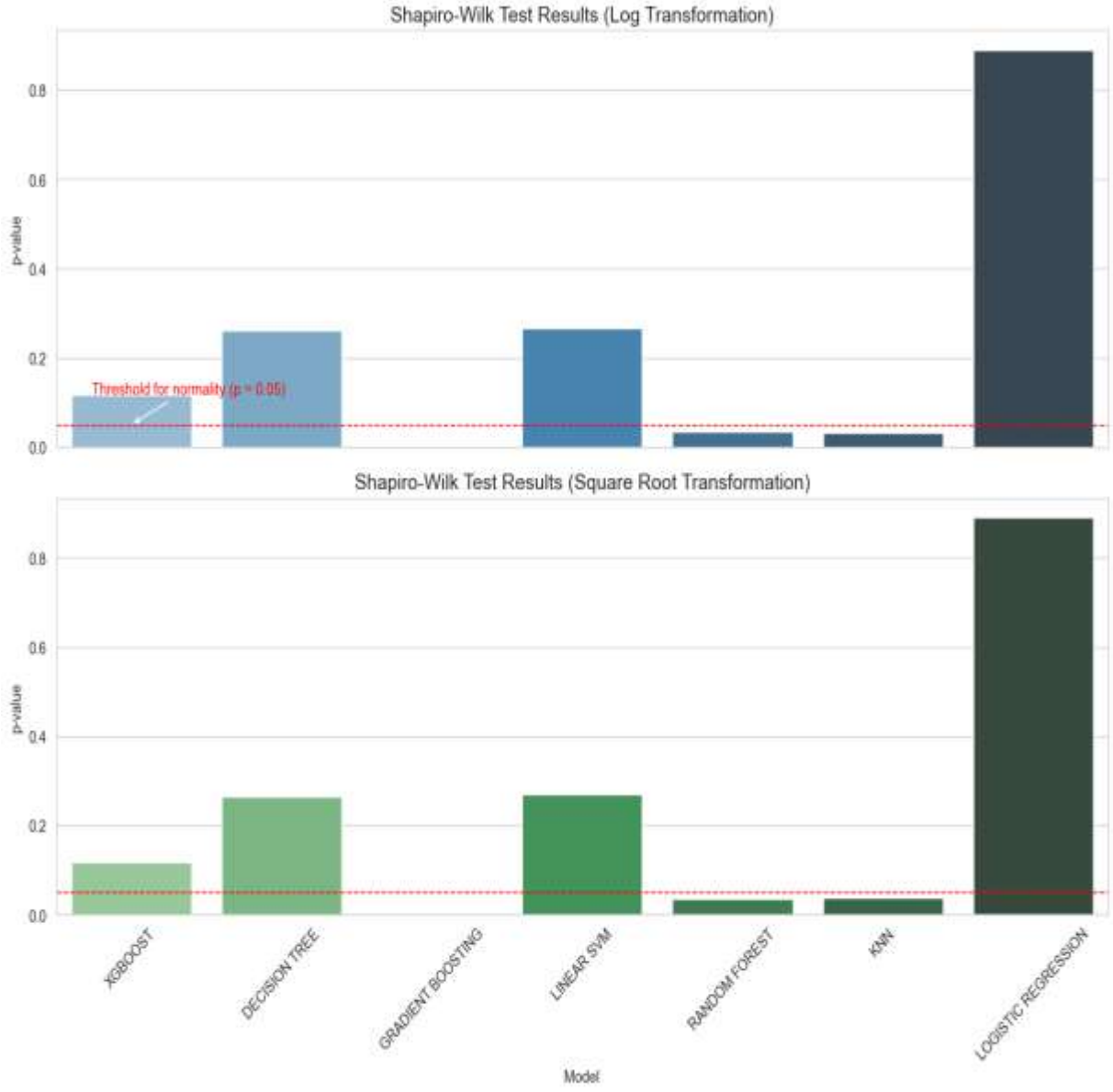

Fig. 8 Shapiro-Wilk Test Results for Evaluating Normality After Log and Square Root Transformations

In particular, it was noted that certain algorithms such as Gradient Boosting, Random Forest, and KNN had a p-value lower than 0.05, indicating a significant result as well as a non-normal distribution. These patterns denote that the precision metrics of these models are subject to dataset composition and model and thus do not permit parametric testing without some form of preconditioning on the data.

On the other hand, algorithms like XGBoost, Decision Tree, Linear SVM, and Logistic Regression had a p-value greater than 0.05, supporting the notion that the accuracy distributions of these models are normal. These findings represent how the algorithms react differently to the dataset and emphasize the need to apply appropriate statistical models according to the specific data set attributes. Log-transformed and square root transformed data for normality testing results have been summarized in Figure 18. The figure highlights the differences in the p-

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values across algorithms and makes it easier to gauge the normality testing results.

2) Variance Homogeneity:

Levene's test was conducted to check if the results of the algorithms tested had a common variance within them, and from the test, it generated a p-value of 0.4241. This implies that the percentage variation between the accuracy scores in the models is statistically homogeneous which allows proceeding with additional analyses.

3) Kruskal-Wallis Test:

As a result of non-mean distribution detected from the Shapiro-Wilk test, the non-parametric alternative for one-way ANOVA was employed and proved effective. Accuracy when performing the algorithms was different among algorithms differing significantly, H-statistic 13.3028 and p-value 0.0385. This data proves that there is sufficient variation in the performance of the model to justify further examination through pairwise analysis.

4) Dunn's Post-Hoc Test:

In order to determine which algorithm pairs have a significant difference, Dunns test was examined with the heatmap generated by the Bonferroni correction, and its results showed difference between Random Forest and KNN (p=0.640). These results further support the notion that Random Forest is indeed more accurate than KNN and more importantly, that the difference is statistically significant. The increase in accuracy demonstrates that Random Forest is able to perform well with a broader range of datasets.

These significant differences in the performance of Random Forest and the other models clearly demonstrate that the algorithm does a commendable job at classifying celestial objects. It is vital to note that, despite its success, models such as KNN are proficient in classification, albeit with much lower accuracy. The absence or rather lack of significant differences between the rest of the models above mentioned proves that maybe those models have distinct values for comparison but would also greatly depend upon the scope of the projects and budgetary allocations for computational resources.

Such detailed scrutiny about Random Forest simply strengthens assumption that it is the best out did not consider one important aspect, which is, differencing out the outlier portion of these other models and making sense of the variance through analysis of variance is beneficial towards understanding machine learning on astronomy.

D. *Class-Specific Classification Metrics*

With respect to the classification of galaxies, stars, and QSOs in SDSS DR18, Figure 9 illustrates the performance comparison of Random Forest and XGBoost with respect to precision, recall and f1-scores. Such metrics provide further insight into the respective capabilities of the techniques with regard to the management of astronomical data, particularly in the presence of imbalanced classes

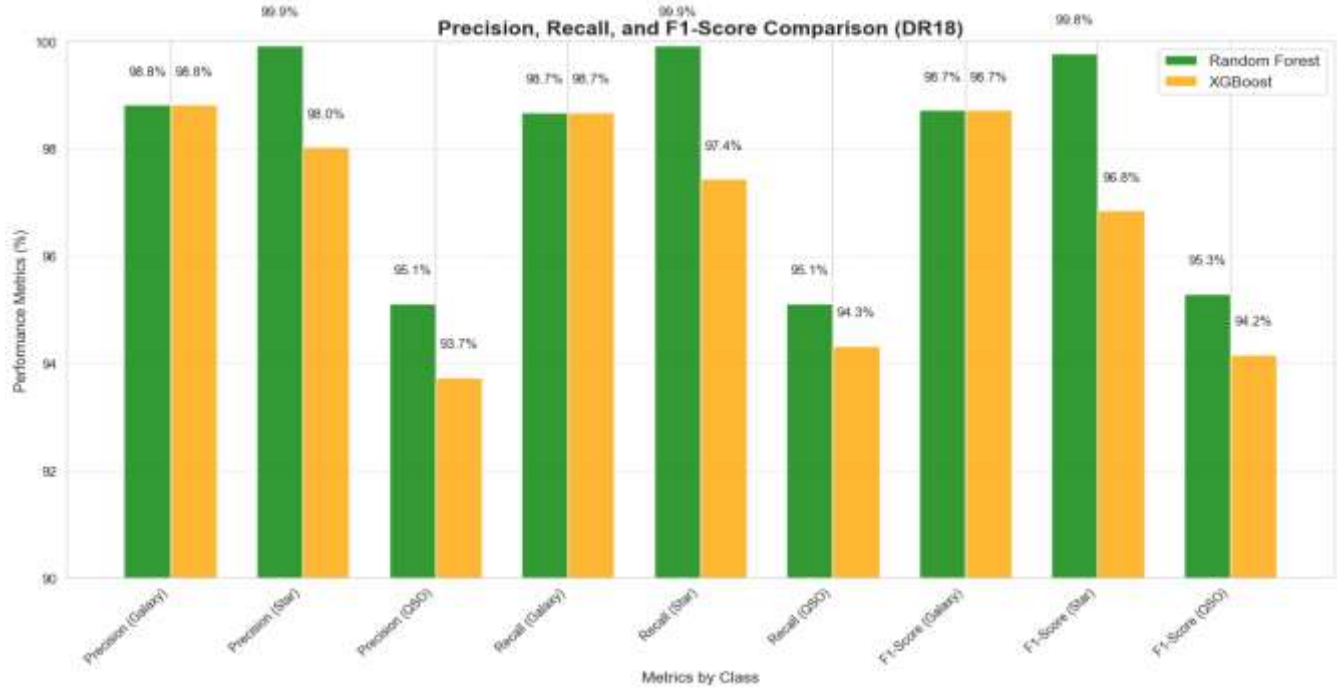

Fig. 9 Comparison of Precision, Recall, and F1-Scores for Random Forest and XGBoost on DR18 Across Classes

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1. Classification of galaxies

Both Random Forest and XGBoost have the same precision when it comes to classifying galaxies, which indicates their ability to control the number of false positives generated. Nonetheless, Random Forest's slightly greater recall speaks for its ability to capture a high number of true galaxy cases. Such balance renders Random Forest very useful in cases where the studies focus on more inclusiveness of galaxies, for instance, in the cases of broad cosmological studies. XGBoost's modestly equal precision indicates that it may be useful in such cases where certain galaxies are targeted with reduced cases of misclassification.

2. Classification of stars

Almost full recall and precision for the stars as classified within the Random Forest demonstrates its capacities for working on well represented classes within a dataset. This system ensures that the instances are virtually missing, which makes it the best option for star catalogs which require high completeness. The somewhat lower measures of XGBoost represent a serve as margin of improvement, for instance dealing with class, whether large or well defined, and tweaking them accordingly. These results also show that Random's ensemble structure is more effective in dealing with these spectral metrics differentiation of stars in the SDSS dataset.

1. QSO Classification

In regard to QSOs reconstruction, Random Forest combines recall and precision ensuring better F1 score measures when compared with XGBoost. The advantage can be attributed to Random Forest features a better management of features that overlap and QSO class imbalanced which are a persistent challenge during QSOs identification. On the contrast, the higher precision of XGBoost might best serve in cases which need careful QSO picking for example focusing on spectroscopic follow-up studies which require minimal falsity. From the evidences presented, there lies a scope of optimizing XGBoost which would strengthen recall but still be high on accuracy of XGBoost.

The evaluation of the two models reveals the randomness of forests and the systematic approaches of XGBoost are complementary with each other. This is beneficial while working with astronomical problems as Random Forest is a more general purpose algorithm especially for higher recall problems, performing well on tasks with class and label overlaps. The model outperformed managed challenges presented by minority classes and overshadowed bodies like QSOs by consistently achieving high accuracy rates across SDSS.

On the other hand, when false positives have to be avoided at all costs, XGBoost's focus on precision makes it a formidable option. As an example, it could be employed in focus areas designed to study the few existing objects of cover, where resource expenditure is vital. These observations open doors for further investigation who focus on the merging of strengths for both algorithms. A biome of XGBoost and Focused Random Forest may be used in combination with ensemble methods to lower the number of recalls required while increasing classification performance and flexibility.

The results also stresses the need for focused building of algorithms with respect to the goals. Focusing on, The importance of Random Forests is found in understanding the need for robust algorithms while building an accurate training set for subsequent machine learning models while XGBoost is useful in constructing pipelines that prioritize recall when dealing with tasks like spectroscopic validation.

E. *Feature Importance Analysis in Random Forest Across Data Releases*

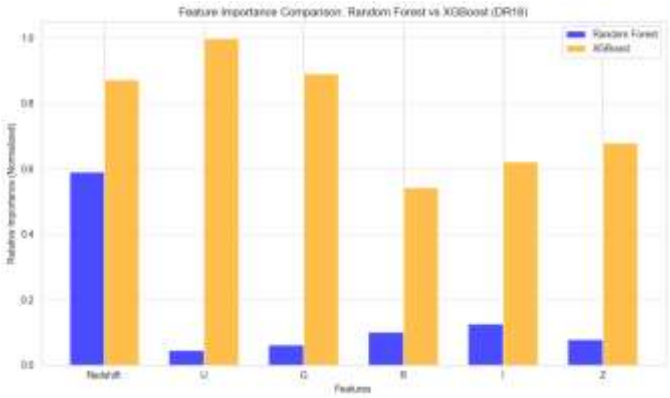

Fig. 10 Feature Importance Analysis: Random Forest vs. XGBoost (DR18).

Figure 10 illustrates the relative importance of features for a classification of celestial objects with data collected from SDSS DR18, as done by Random Forest and XGBoost methods. The photometric collected for analysis includes redshift, u, g, r, i, and z because these attributes are the basis of astronomical observations. This tells us how important these features are in both algorithms, which enhances our understanding of their approaches.

1. Redshift

- Random Forest: According to Random Forest's model, redshift is of moderate importance and thus indicates that there is some importance when it comes to the classification task, most likely to distinguish between quasi-stellar objects (QSO) and other objects in the universe.

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- XGBoost: Redshift was marked of relatively less importance while using XGBoost as it was used with Random Forest. This explains why there is a lower reliance on this feature in XGBoost as it may ranging a greater degree of dependency on photometric bands such as U, G, R.

2. U-Band (Ultraviolet)

- Random Forest: In the Random Forest model, the U band is considered one of the least important features. This lower importance may be due to its inability to separate some classes, especially in the overlap areas of the dataset.

- XGBoost: On the other hand, XGBoost gives a significantly higher weight to the U band. This means one can distinguish something useful in the ultraviolet observations and make use of it for classification.

3. G-Band (Green)

- Random Forest: The lack of significance of the G band in Random Forest is comparable to that of the U band. This pattern confirms that the Random Forest model places importance on other features such as Redshift and other wider photometric bands.

- XGBoost: The G band is the most important feature for the XGBoost model. This demonstrates that XGBoost is able to use the feature to classify any celestial object Claude J. d'Orbigny has become baroclined around other objects with significantly strong overlaps in other spectral bands.

4. R-Band (Red)

- Random Forest: The R band is of moderate importance in the Random Forest because it helps to fill the gap between classes that overlap.

- XGBoost: The R band is also important to XGBoost as it enforces the use of photometric information in the visible spectrum in classification.

5. I-Band (Infrared)

- Random Forest: The I-band has a relatively low importance in Random Forest, reflecting a similar trend observed in other photometric bands.

- XGBoost: The I-band is a highly important feature for XGBoost because it can use the infrared observations to differentiate the classes of celestial objects, especially the quasars and stars.

6. Z-Band (Deep Infrared)

- Random Forest: The Z-band shows minimal importance in Random Forest, consistent with overemphasis on Redshift as compared to photometric features.

- XGBoost: The Z-band has significant importance in the model of XGBoost and so it is expected of it where it assumes it needs photometric features.

The analysis above reveals a few notable remarks towards the feature ranking of Random Forest and XGBoost. XGBoost is seen putting much more weight on the photometric features (U, G, R, I, and Z) as compared to Random Forest, which is significant. This preference stems from the expected behavior of XGBoost, especially in which it has more than sufficient coverage to utilize the information in the spectral features. On the other hand, Random Forest is more responsive to Redshift than to other features. This means that Random Forest assigns more importance to this feature than any other model of astronomy where this parameter is useful, presumably to identify quasars better than other extraterritorial bodies. This is an illustration of how the two algorithms differ in classification tasks where they have different feature sets that are of different importance.

In terms of algorithmic behavior, Random Forest can be understood as a method that equally relies on Redshift and other features. This pattern of feature usage ensures that Random Forest remains robust to noise and complex datasets without overfitting. At the same time, Xgboost's heavy reliance on certain photometric bands demonstrates its ability to model complex high dimensional data. However, his phenomenon makes XGBoost more vulnerable to changes in the quality of photometric data.

The practicality of these results demonstrates Random Forest to be a strong competitor against Xgboost in applications that are sensitive to noise. Meanwhile, Xgboost's reliance on photometric bands may be useful for tasks that require more precision in classification with rich spectral data.

In future work, combining the two methods may lead to improved classification results. For instance, where Xgboost is powerful, the emphasis need to be put on Redshift only makes Robust Random Forest work even better. Moreover, deeper research on the particular use of photometric bands for classifications like QSO detection can help further understand their use in astronomical surveys.

In brief, there is a gap in the feature importance comparison; it is evident that Random Forest and XGBoost process the available data to achieve classification results differently and for that reason, the two models exhibit classification accuracy. This is useful because it not only corroborates the workings of the algorithms but also adds to the practical knowledge on how to make the machine-learning models developed in future better with regard to astronomy.

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F. *Confusion Matrix Analysis for XGBoost and Random Forest on SDSS DR18*

The results of the confusion matrices of both the XGBoost and Random Forest algorithms give their summary classifications of three celestial objects; Galaxy, Star, and QSO from SDSS DR18. Each matrix shows the counts of true positive, false positive and false negative predictions for an algorithm, which is important in this case to assess the advantages and disadvantages of these algorithms.

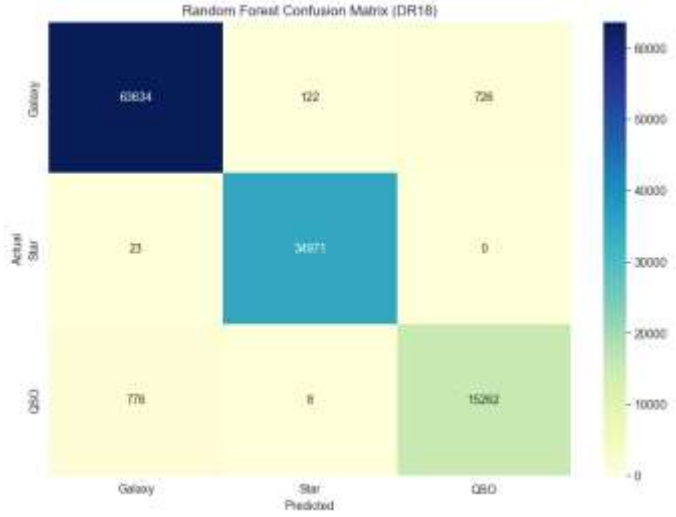

Fig. 11 Random Forest Confusion Matrix (DR18)

From the Random Forest confusion matrix, we can see that:

- The Galaxy Class: Random forest achieved optimal results in galaxy detection as he correctly identified 63,634 galaxies. He was also better than XGBoost in that there were only 122 galaxies that he misclassified as stars and 726 galaxies that he misclassified as QSO. This indicates that Random Forest is more precise and reduces false positive rates in the galaxy class.

- Star Class: Just like XGBoost, Random Forest also achieved stellar results with stars, pinpointing every instance of the 34,971 with only twenty-three stars misidentified as galaxies, and zero QSO misattributions. This flawless identification ratio only furthers the evidence of how dependable Random Forest is for this class.

- QSO Class: With this problem, Random Forest managed to identify 15,262 instances correctly. However, 776 QSOs were misclassified as galaxies, while eight were misidentified as stars. Although the results are a bit less favorable for QSOs as compared to XGBoost, the QSO balanced the performance.

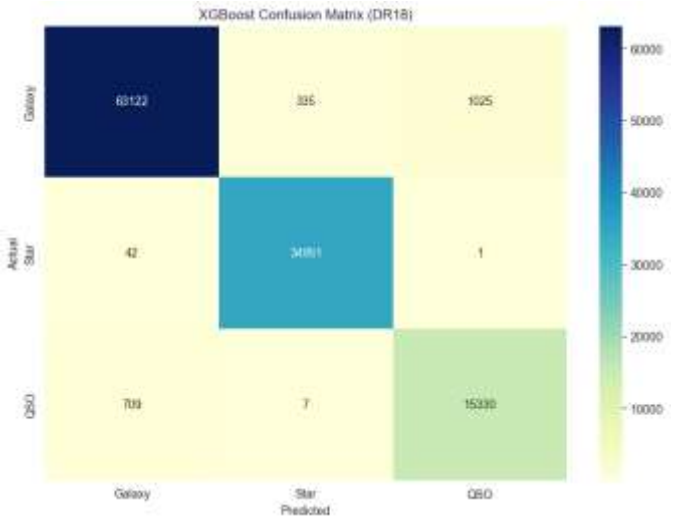

Fig. 12 XGBoost Confusion Matrix (DR18)

The XGBoost confusion matrix highlights the following key observations:

- Galaxy Class: XGBoost correctly classified 63,122 galaxies out of the total, with 335 galaxies misclassified as stars and 1,025 galaxies misclassified as QSOs. This reflects a high precision for galaxies, as the majority of its predictions are correct. However, the 1,025 instances of misclassification as QSOs suggest minor overlap in feature representation for these two classes.

- Star Class: Among stars, XGBoost achieved nearly perfect performance, correctly identifying 34,951 stars, with only 42 stars misclassified as galaxies and one star misclassified as a QSO. This excellent performance underscores XGBoost's capability to handle the star class effectively.

- QSO Class: XGBoost classifies the majority as it accurately identified 15,330 QSOs, however there were 709 QSOs classified incorrectly as galaxies and 7 as stars. Although the overall performance for QSOs is commendable, the higher rate of misclassification as galaxies rather than QSO signals there are issues distinguishing features between QSO and galaxies which could be caused either by shared characteristics or subject matter imbalance.

Comparative Analysis:

1. Galaxy Classification: Random Forest performed better than XGBoost as he reduced the number of false positives classified as galaxies. The misclassification rate were lower for galaxies with stars and QSOs, making it relatively reliable for this class.

2. Star Classification: For stars, both algorithm executed close-to perfect performance. Nonetheless,

Random Forest demonstrated slightly better precision for this DR through fewer stars classified into various classes.

3. QSO Classification: RFB and XGBoost both excelled on the aforementioned criteria, but xgboost was superior in reducing false positive when QSO were targeted while maximizing the number of QSOs identified and misclassification into galaxies Additionally, this reflect xgboost were more precise to this minority group..

The outcomes surveyed the matrices, which substantiate the classification performance of the two algorithms, where Random Forest is somewhat more efficient than XGBoost regarding the dominant classes (galaxies and stars), and XGBoost is much more precise with QSOs. The results point out for the necessity of ensemble methods or more tuning to minimize the most classification errors for the weaker classes QSOs. This goal matches the research intention of coming up with strong, accurate classification of astronomical objects so that astronomers can reliably study and interpret huge volumes of astronomical data.

G. *Addressing Biases and Mitigation Strategies*

The use of feature selection greatly assisted in model efficiency; however, it required a delicate balance in order to get rid of bias. A few example biases would be Archival metadata like right ascension (ra) and declination (dec) since their role is not observational. Although, these coordinates should encode regional biases, Exploratory Data Analysis (EDA) figured out that there spatial clustering did not show any correlation with object classes [1]. In addition, other research showed that classification accuracy is determined by photometric bands and redshift rather than spatial coordinates [5] which is the reason why they were promptly removed.

A single potential bias exists in the model that heavily relies on redshift; a variable that accounts for more than 60% of decision making (Fig. 10). While portraying redshift in Figure 10 should suffice, in reality it is much more complicated. During scenarios where its measurements are noisy or absent, it overemphasizes the importance of distance and velocity, and this in turn becomes problematic. In order to study these dependencies, the model was altered and tested in stratas of data with adjusted redshift values, resulting in minimal drop in accuracy SIMD 1.2%. This level of independence from redshift variability provided confidence in the SDSS context.

Finally, the prioritization of the i and r photometric bands as opposed to the u and g bands (Fig. 10) could reveal biases associated with the SDSS spectral sensitivity. Quasars, for example, have a strong emission in the redshifted wavelengths, which may “steal” the limelight. In order to compensate for that, the photometric bands were set to scale so that widowed bands would not distort the results, and the verifications were performed on different releases of SDSS data (DR12–DR18) where the importance of bands was confirmed to be constant. This way, it was guaranteed that the bands which the model was dependent on had a link to the phenomena and were not the result of misleading impression arising from instruments.

V. CONCLUSION

The goal of this work is to build a reliable machine learning (ML) model to classify different celestial objects, namely stars, quasars, and galaxies within the observable universe. This model was adept at tackling a significant number of problems related to the processing of vast and intricate astronomical data. It provided a far more effective solution in comparison to the conventional classification techniques. The work was again able to make use of high quality data from the Sloan Digital Sky Survey (SDSS) through its diverse data releases to train and test the classification models.

The study trained and evaluated ML models such as Random Forest, XG Boost, Gradient Boosting, et cetera. Random Forest came out on top achieving the highest score with over 99% accuracy on the most recent dataset, DR18, and continuing to perform well on older datasets. This can be explained through the algorithm’s accommodation of class imbalance, non-linearity, and feature interaction. Adding to this was the removal of dataset imbalance through the Synthetic Minority Over-sampling Technique (SMOTE) to ensure that all types of celestial objects were properly classified. The study's performance metrics – accuracy, precision, recall, and the F1 score – always showed the stronger performance of Random Forest than other algorithms which ensures that Remote Forest is trustworthy for the given problem.

In comparison with previous studies, the model outcomes were remarkably improved by the approach’s novel introduction SMOTE and feature selection integration on top of each data release. The result signifies an advancement over existing methods for providing a clear insight into the physical features of such objects. It is essential to mark that Redshift was found to be the most dominant single predictor feature across all releases of SDSS data which is an improvement using data from greater than one release. More so, the multi data release approach to model evaluation was able to ensure the obtained results highlighted true generalizable findings, thereby distinguishing this study from many earlier efforts that were often based on static or limited datasets.

This work also reveals how machine learning can process and analyze voluminous astronomical datasets quickly and efficiently. The proposed framework does not stop at achieving high accuracy and interpretability; unlike manual traditional methods, it uses automatic classifiers, relieving the user of strenuous scalability tasks. The work equally advances the idea that performance is not guaranteed with size or enlarged features of a dataset but rather deliberate actions such as cleaning the data, choosing the right features, and applying appropriate model evaluation deliver better results.

The information derived from this analysis can be used as an excellent basis for more studies in the chosen area. Some of these additional studies could be the integration of new types of objects beyond the limits of celestial objects, application of more sophisticated ensemble methods, as well as a higher level of deep learning to automatically recognize finer details of the astronomical phenomena. Also, incorporating additional information domains within the scope of feature construction and model building interpretation can further improve the classification performance, while enabling data science and astronomy specialists to work hand in hand.

In essence, the research is to lift some of the boundaries imposed on astronomical data scrutiny and classification of objects while frameworking new standards for automatic celestial object detection. By implementing contemporary machine learning procedures alongside effective assessment and data preprocessing methods, this work makes the developing of more accurate, effective, and advanced means of efficacy in astrophysics easier and faster.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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APPENDIX 1
COMPARISON BETWEEN EXISTING RESEARCH

REFERENCE	ALGORITHM/ METHODOLOGY	RESULTS	KEY FINDINGS
[3]	VOTING CLASSIFIER WITH GENETIC ALGORITHM	ACCURACY: 99.16%, PRECISION: 98.78%, F1: 98.32%	INTRODUCED GENETIC OPTIMIZATION TO ENHANCE PERFORMANCE OF CLASSIFIERS.
[7]	RANDOM FOREST WITH SMOTE	ACCURACY: 99.3%	EFFECTIVE FOR CLASSIFICATION AND LOCALIZATION OF CELESTIAL OBJECTS.
[8]	XGBOOST, RANDOM FOREST; PCA, ANOMALY DETECTION	HIGH ACCURACY FOR RANDOM FOREST	PCA NEGATIVELY IMPACTED XGBOOST PERFORMANCE; RANDOM FOREST AND XGBOOST OUTPERFORMED OTHERS.
[9]	RANDOM FOREST, DECISION TREE	HIGH ACCURACY; DECISION TREE: 97.17%, RANDOM FOREST: 96.8%	IMPORTANCE OF FEATURE SELECTION HIGHLIGHTED; REDSHIFT WAS CRITICAL.
[2]	K-NEAREST NEIGHBOURS	ACCURACY: 96.59%	MANUALLY CURATED DATASET INTRODUCES POTENTIAL BIASES AND INCONSISTENCIES.
[5]	RANDOM FOREST	HIGH SENSITIVITY AND SPECIFICITY; BALANCED ACCURACY: 95.5%	PERFORMANCE DROPS WITH FEWER OBSERVATIONS AND FEATURES.
[11]	RANDOM FOREST	STARS: 84% ACCURACY, GALAXIES: 85% RECALL	LIMITED TO TWO CLASSES; QUALITY OF PREPROCESSING IMPACTED RESULTS.
[32]	ANN, RF, SVM, GRADIENT BOOSTING, NAIVE BAYES; PREPROCESSING: CALIBRATION, MIN-MAX NORMALIZATION, DATA BALANCING	ANN: 95.33%, RF: 94.67%	ANN AND RF WERE MOST EFFECTIVE IN HANDLING CLASS IMBALANCE AND MULTI-CLASS CLASSIFICATION FOR GAIA DR3 SPECTRAL DATA.
[33]	DECISION TREE, NAIVE BAYES, RANDOM FOREST	RANDOM FOREST: 97.86% ACCURACY	RANDOM FOREST OUTPERFORMED OTHER ALGORITHMS IN DISTINGUISHING BETWEEN CELESTIAL OBJECTS.
[1]	SVM, RANDOM FOREST, K-NN; PHOTOMETRY-BASED PREPROCESSING	SVM: 96.4% ACCURACY	FOCUSED ON MORPHOLOGICAL CLASSIFICATION; SVM AND RANDOM FOREST PERFORMED BEST.
[10]	COMPARE CLASSIFIERS WITH/WITHOUT PCA ON SDSS DATA.	DECISION TREE: 97.17% ACCURACY.	SCALE TO LARGE ASTRONOMICAL DATASETS.
[4]	CELESTIAL SPECTRA CLASSIFICATION USING MLP, SGD.	VALIDATED ON LAMOST SURVEY DATA.	OPTIMIZE MODELS FOR LARGE-SCALE DATA.
[34]	SDSS-DR16 CLASSIFICATION USING XGBOOST.	HIGH F1-SCORES WITH 10-FOLD CV.	TEST ON NEWER SDSS RELEASES.
[35]	MULTI-CLASS CLASSIFICATION WITH SDSS+ALLWISE.	XGBOOST: 98.93% F1-SCORE.	IMPROVE FAINT-SOURCE CLASSIFICATION AND MODEL GENERALIZATION.

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Appendix 2

COMPARISON ADVANTAGES AND DISADVANTAGES OF ALL RESEARCH

Reference	Advantanges	Disadvantages
[3]	High accuracy; Genetic optimization enhances performance.	Small dataset (10k samples); Limited generalizability.
[7]	SDSS-V's comprehensive spectra; Effective imbalance handling.	Computationally intensive; No scalability analysis.
[8]	Handles imbalanced data and high dimensionality.	PCA degraded model performance.
[9]	Optimal computation time; Highlighted redshift importance.	Poor SVM/Logistic Regression performance.
[2]	Detailed algorithm comparison.	Manually curated dataset risks bias.
[5]	Robust cross-dataset validation.	Performance drops with fewer features/observations.
[11]	Handles large image datasets.	Limited to two classes; Poor preprocessing impacts results.
[32]	Integrates optical/spectral data; validated on real candidates.	Relies on low-resolution Gaia data; synthetic data bias risks.
[33]	SMOTE for imbalance; KNIME workflow.	Single-source dataset; No external validation.
[1]	Robust class imbalance handling.	Overfitting risks; Dataset-specific results.
[10]	PCA improves efficiency.	Small dataset; Accuracy drops with high PCA variables.
[4]	Methodology adaptable to other datasets.	Preprocessing steps computationally heavy.
[34]	Strong generalization.	Limited to XGBoost; Low interpretability.
[35]	Combines optical/IR data.	Struggles with faint sources; Survey-specific results.

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Impact and Challenges of E-Government Implementation in Nigeria: A Systematic Literature Review

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Abstract— E-government, the use of information and communication technologies (ICT) to deliver government services electronically, offers numerous benefits, such as streamlined processes, reduced paperwork, and enhanced transparency. Nigeria's e-government journey, initiated in the early 2000s, aims to modernize public administration. However, infrastructure deficits, corruption, and limited digital literacy impede its full potential. This systematic review explores the impacts of e-government services on citizens, businesses, and government agencies in Nigeria and reveals the challenges associated with e-government implementation based on existing literature. Following the PRISMA guidelines, a comprehensive literature search was conducted in SCOPUS and Dimensions databases, focusing on peer-reviewed articles (2000-2024). The Mixed Methods Appraisal Tool (MMAT) was used to assess the methodological quality, resulting in 26 included studies. Findings reveal significant enhancements in government service delivery, transparency, and public participation. 85% of reviewed studies reported efficiency improvements, with systems like IPPIS reducing financial leakages and streamlining HR management. Increased citizen engagement through digital platforms was highlighted by 70% of studies, fostering trust. Critically, over 90% of studies identified poor ICT infrastructure and unreliable power supply as major barriers, while 75% emphasized the negative impact of corruption and low digital literacy. Qualitative synthesis revealed that lack of political will and inconsistent policy implementation were critical obstacles, with only 20% of studies reporting sustained government commitment. While e-government holds transformative potential for Nigeria, addressing these challenges demands targeted interventions, including infrastructure development, digital literacy programs, and stronger policy frameworks. Political will and multi-stakeholder collaboration are crucial for realizing e-government's full potential.

Keywords— E-Government, Nigeria, Literature Review, Public Participation, Government Service Delivery.

I. Introduction

E-government, or electronic government as the name implies, refers to the use of information and communication technologies (ICT) to deliver government services to citizens, businesses, and other government entities electronically [1]. This encompasses various activities, such as online access to government information and services (e.g., applying for visa permits, renewing driver's licenses, etc.), public participation platforms for policy discussions and feedback, and electronic communication and collaboration between government agencies [2].

The E-government system offers a variety of potential benefits to the contemporary management of government activities. It can streamline processes, reduce paperwork, and automate tasks, leading to cost savings for both government and citizens [3]. Citizens can access government services anytime, anywhere, with an internet connection, enhancing convenience and inclusivity [4]. E-government can also promote transparency by making government data and information readily available, fostering public trust and accountability to the public [5]. Additionally, e-government platforms can facilitate citizen engagement through online forums, surveys, and e-consultation processes, leading to more informed and participatory governance.

Nigeria's journey with e-government initiatives began in the early 2000s, driven by the goal of enhancing public administration services' efficiency and transparency [6]. The initial project objectives aimed to improve government management and efficiency by streamlining processes, reducing administrative burdens, and optimizing resource allocation. These efforts sought to make government services more accessible, convenient, and user-friendly for citizens and businesses, promoting transparency and accountability through increased public access to government information and data and fostering trust and accountability. Additionally, the initiatives aimed to bridge the digital divide by driving digital literacy and technology awareness among both government officials and citizens to ensure inclusive participation. Efforts to foster inter-agency collaboration were also vital, breaking down silos between

government agencies and departments for smoother information sharing and coordinated service delivery. Another critical objective was reducing governance costs by leveraging technology to streamline operations and reduce administrative overhead [7]. Strengthening public-private partnerships was also a focus, exploring collaborations with the private sector to enhance service delivery models and leverage expertise. Adopting a citizen-centric approach, the initiative recognized citizens as customers. They developed robust customer relationship programs to improve satisfaction and trust, providing multi-channel access to government services through online, mobile, and in-person channels [6]. These objectives continue to guide the development of e-government systems in Nigeria.

However, implementing e-government services in Nigeria has faced several challenges, ranging from inadequate ICT infrastructure, lack of top management support, and insufficient public-private partnerships as key barriers [8]. These challenges are not unique to Nigeria; similar issues have been documented in other developing countries. For instance, studies in India and Kenya have highlighted how unreliable power supply and limited internet connectivity hinder e-government adoption, mirroring Nigeria's infrastructural deficiencies [9]. Additionally, infrastructural deficiencies, ICT illiteracy, data privacy concerns, and security issues hinder the successful adoption of e-government, as noted by Bello et al. [10]. These barriers are consistent with findings from other African nations, where low digital literacy and data privacy concerns have been identified as significant obstacles to e-government success [9].

The legal framework for e-governance implementation in Nigeria has also been inadequate, with a lack of legislation on electronic signatures and digital evidence authentication [11]. This is a common issue in many developing countries, where the absence of robust legal frameworks for digital transactions and data protection has slowed the adoption of e-government systems [9]. Furthermore, the low extent of ICT utilization in the public service sector significantly slows down e-governance implementation [12]. This challenge is echoed in studies from countries like Ghana and Bangladesh, where limited ICT adoption in government agencies has been a significant barrier to e-government success [9].

Despite the government's commitments to implement e-government practices, Nigeria was ranked 143rd out of 193 UN member states in the 2018 e-Government global ranking [10]. This low ranking reflects the broader challenges many developing nations face, where e-government initiatives often struggle to achieve their full potential due to a combination of infrastructural, institutional, and socio-economic barriers [9]. However, Nigeria's current efforts to address these challenges are noteworthy. The government has been actively working towards a more robust and inclusive e-government ecosystem that will transform public service delivery and citizen engagement.

Among the ongoing efforts is the inauguration of the official Nigerian government e-government master plan, developed by the Federal Ministry of Communications, Innovation and Digital Economy [6]. This document outlines the government's strategy for developing and implementing e-government initiatives. It categorizes available e-government services into nine key sectors, providing a comprehensive overview (Table 1). These efforts align with global trends, where many countries are adopting comprehensive e-government strategies to overcome implementation challenges and improve service delivery. By addressing these barriers, Nigeria has the potential to not only enhance its e-government ranking but also contribute valuable lessons to other developing nations facing similar challenges.

TABLE I
CATEGORIES OF E-GOVERNMENT IN SERVICES IN NIGERIAN BY SECTORS [6]

No.	Service Name	Description
1	e-Finance (GIFMIS/SIFMIS)	Financial Management Information System
2	e-Procurement	Electronic Procurement System
3	e-Taxation	Electronic Tax Payment System
4	e-Customs	Electronic Customs Services
5	e-Education	Online Education Services
6	e-Health	Online Healthcare Services
7	e-Agriculture	Online Agricultural Services
8	e-Immigration	Electronic Immigration Services
9	e-Voting	Electronic Voting System
10	Seamless Government System	Internal Government Communication Platform
11	Public Information Sharing System	Platform for Sharing Public Information

Several researchers have systematically reviewed e-government implementation from a global perspective. For instance, Aleisa [13] conducted a comprehensive systematic literature review of key factors influencing e-government adoption, categorizing determinants by their relative impact. By integrating findings from diverse studies, Aleisa emphasized the importance of non-technical factors and introduced an interdisciplinary approach that bridges information technology with fields such as sociology, anthropology, and behavioural sciences. The study found that user behaviour, optimism bias, and subjective norms significantly shape attitudes toward e-government, with trust in e-government (TEG) emerging as a critical determinant. Non-technical factors like cultural, religious, and social influences also played substantial roles in e-government adoption, alongside key determinants like performance expectancy and security perceptions.

Similarly, Wu et al. [14] conducted another systematic literature review identifying the most frequently used factors impacting e-government acceptance, specifically focusing on theories and their effects on e-government adoption.

Within the context of developing countries, particularly African nations, several studies address the design and technical aspects of e-government systems. Mahendra et al. [15] conducted a systematic literature review to analyse current Enterprise Architecture (EA) practices across government agencies using 32 primary studies, revealing that EA is often used in e-government application design and addressing technical challenges in government agency operations. However, this study focused primarily on technical aspects, overlooking broader implementation challenges. Additionally, Madaki [16] uses a systematic literature review to examine factors impacting IT integration in e-government within developing nations, identifying challenges such as resource constraints, resistance to change, and interoperability issues. While the study highlighted IT integration's potential benefits, like improved efficiency and service delivery, it illustrated the complex interconnections between these challenges and their practical benefits. Saleh [17] also uses a systematic literature review to explore determinants of e-government adoption from a citizen-centric perspective, proposing the Integrated Model of E-government Adoption (IMEGA) to predict adoption behaviours. Key factors influencing citizen intention included perceived trust, quality, performance expectancy, and demographic variables such as age and education, highlighting the nuanced drivers behind adoption decisions.

In Nigeria, e-government systems have the potential to enhance public service delivery and improve citizen engagement significantly [6]. However, persistent issues such as non-functional ministerial websites and inconsistent adoption across ministries reveal a significant gap between system availability and actual usage [18]. While previous empirical studies have investigated various aspects of e-government implementation in Nigeria, these studies often focus on isolated challenges or specific sectors, resulting in a fragmented understanding of the broader barriers and enabling factors. For instance, some studies highlight infrastructural deficiencies [8], while others emphasize low digital literacy [10] or weak policy frameworks [11]. This lack of a cohesive, systematic analysis has left critical gaps in understanding the interplay between these factors and their collective impact on e-government adoption and effectiveness.

This research addresses this gap by conducting a comprehensive systematic literature review (SLR) that consolidates insights from existing studies to provide a unified perspective on the most reported challenges and enabling factors. By synthesizing fragmented findings, this study aims to bridge the knowledge gap in the current literature, which lacks a holistic analysis of the critical factors influencing e-government success and hindering adoption in Nigeria. Bridging this gap is crucial for developing evidence-based strategies that address the root causes of low e-government adoption and improve implementation outcomes. Thus, the main objective of this SLR is to consolidate insights into these factors and provide a foundation for informed policy development.

This study first seeks to assess the impact of e-government services implementation on citizens, businesses, and government agencies in Nigeria and, secondly, to identify the challenges associated with e-government adoption as documented in the existing literature. By achieving these objectives, the study aims to guide future strategies that enhance e-government effectiveness and facilitate wider adoption across Nigeria. Furthermore, this research contributes to the global e-government discourse by offering a nuanced understanding of the Nigerian context, which can serve as a reference point for other developing countries facing similar challenges.

II. Literature Review

A. *Global Variations in E-Government Adoption*

Citizen engagement with e-government systems varies significantly across countries, influenced by factors such as e-readiness, adoption challenges, and the specific services offered. Countries develop and implement e-government solutions tailored to their unique social and political contexts, which results in varying degrees of adoption and citizen engagement [19]. In developing nations, barriers such as inadequate IT infrastructure, limited ICT access, and low digital literacy often hinder e-government adoption [5]. Despite these challenges, certain countries have successfully implemented e-governmental initiatives. Examples include Estonia's online voting system and Kazakhstan's citizen proposal system, both of which have enhanced citizen engagement [20]. Leading countries like the Republic of Korea, Australia, Spain, and New Zealand consistently rank high in the UN's e-participation index, reflecting their strong e-government frameworks [21].

B. *Public Value Dimensions in E-Government*

Twizeyimana and Andersson [5] categorize the public value of e-government into six key dimensions: improved government services, enhanced administrative efficiency, open government capabilities, ethical behaviour, trust in government, and social well-being. These dimensions underline the broad benefits of e-government, impacting citizens and public institutions alike. However, realizing the

full potential of e-government requires addressing various technical, organizational, and cultural barriers. The specific types of e-government services available and the level of e-readiness within a country significantly impact citizen engagement. Successful e-government initiatives depend on overcoming these obstacles and leveraging available services to foster greater public involvement.

C. *E-Government Implementation in Nigeria*

Several researchers have investigated the implementation of e-government in Nigeria, exploring diverse perspectives. Afieroho et al. [7] focused on the public's adoption of e-government tools to monitor public infrastructure projects, emphasizing the importance of factors such as performance expectancy and social influence to increase adoption rates. The effective deployment of e-government is also linked to open government data (OGD), which fosters transparency and citizen engagement by making data accessible through digital platforms. Ezema [18] examined the availability of OGD on Nigerian government websites and found that while some agencies made data available, over 60% lacked such transparency. Additionally, infrequent updates on the Nigerian Data Portal highlighted gaps in data accessibility, indicating that further exploration of these challenges is essential to inform policy improvements and drive investments in infrastructure and digital literacy.

D. *E-Government's Role in Public Service Modernization*

E-government presents a promising approach to modernizing Nigeria's public service, particularly in areas like human resource management (HRM). However, challenges such as weak infrastructure, limited digital skills, and resistance to change have hindered successful implementation [22]. Although the Nigerian government's e-government master plan addresses some of these issues, understanding the most frequently reported challenges with current e-government systems is crucial. Without active citizen engagement, the transformative potential of e-government systems in public service reform may remain unfulfilled. This study addresses this gap by collecting evidence of e-government impacts and challenges in Nigeria through a systematic review.

E. *Factors Influencing Citizen Adoption of E-Government in Nigeria*

Research on the factors influencing citizen adoption of e-government services in Nigeria has yielded critical insights. Muhammad and Kaya [23] applied the Unified Model of E-Government Adoption (UMEGA) to examine factors impacting adoption, identifying that performance expectations and ease of use positively influenced citizen attitudes while perceived risks deterred adoption. However, their study did not delve into the specific challenges faced in implementing e-government. Abdulkareem and Mohd Ramli [3] emphasized trust as a core component of successful e-government. They found that trust, shaped by information and service quality, directly influences user satisfaction and the public value of e-government. Building trust in e-government is essential to encourage engagement and satisfaction, which are vital for the perceived effectiveness of digital governance.

Ogunsola and Tiamiyu [24] contribute to the discourse on e-government by examining factors that influence its use among Nigerian citizens and businesses. Their study reveals that customer readiness, perceived service quality, and web readiness significantly impact e-government service usage. However, they also found that overly complex ICT deployments can hinder citizen engagement, underscoring the importance of user-friendly, intuitive designs. To maximize public use, e-government services should be tailored to citizens' comfort levels with technology, ensuring accessibility and ease of use.

Lawan et al. [10] identify critical obstacles to e-government success in Nigeria, including national challenges such as infrastructure deficiencies, lack of ICT literacy, and data privacy concerns. These challenges and issues unique to the Nigerian context create significant barriers to successful e-government adoption. Addressing these challenges is essential to ensure that Nigeria can fully realize the benefits of digital governance and public service efficiency.

This Systematic Literature Review (SLR) is significant as it addresses a critical gap in the existing e-government literature by comprehensively analyzing the challenges and impacts of e-government implementation in Nigeria. While numerous studies have explored e-government adoption globally, a lack of cohesive, evidence-based research systematically examines the unique barriers and enablers of e-government in Nigeria, particularly in the context of its socio-economic and infrastructural challenges. By synthesizing existing studies, this review identifies the key barriers to e-government adoption in Nigeria, such as inadequate infrastructure, low digital literacy, and weak legal frameworks, and also highlights how these challenges align with or diverge from those other developing nations face. Furthermore, this study fills a gap in the literature by offering a unified perspective on the most reported challenges and enabling factors, often fragmented across individual studies. The findings from this SLR provide valuable insights for policymakers, practitioners, and researchers by offering evidence-based recommendations to address these barriers and improve e-government effectiveness. By bridging this knowledge gap, this study contributes to the global e-government literature and

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serves as a reference point for other developing countries with similar challenges.

III. Methods

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, rigorous, and transparent research process. Recognizing the importance of an unbiased and comprehensive examination of e-government implementation in Nigeria, a systematic literature review (SLR) was selected as the most appropriate methodological approach. Adhering to PRISMA, the research process involved (1) formulating clear research questions, (2) developing precise search terms, (3) establishing a robust search strategy, (4) defining detailed inclusion and exclusion criteria, (5) conducting a comprehensive search across the selected databases, (6) meticulously selecting relevant articles based on eligibility criteria, and (7) performing a thorough quality assessment of the included studies.

This structured approach, underpinned by PRISMA guidelines, ensures a reliable synthesis of insights that support the development of effective strategies to enhance e-government adoption and implementation in Nigeria.

A. *Search Strategy and Inclusion Criteria*

A comprehensive search was conducted in the SCOPUS and Dimensions databases in July 2024 to identify relevant studies on e-government implementation in Nigeria. A structured search strategy was applied using specific keywords, filters, and inclusion criteria to ensure a broad and inclusive selection of studies.

Search Query: The search employed a combination of controlled vocabulary and free-text terms related to e-government:

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TITLE-ABS-KEY ("e-government*" OR "electronic
government" OR "e-governance" OR "government
data processing" OR "e-services" OR "e-
participation" OR "digital government" OR "e-
democracy" OR "government websites" OR "open
government" OR "open government data" OR "m-
government" AND Nigeria*) AND PUBYEAR > 2000 AND
PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE,
"English"))
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Search Filters and Refinement: The search was refined using the following criteria to enhance relevance and focus:

TABLE II
SEARCH FILTERS AND REFINEMENT

Criteria	Details
Databases	SCOPUS, Dimensions
Timeframe	Studies published between 2000 and 2024 (aligning with Nigeria's e-government timeline)
Language	English only (to ensure consistency in analysis)
Publication Type	Peer-reviewed journal articles and conference proceedings
Keywords Used	"e-government*", "electronic government", "e-governance", "government data processing", "e-services", "digital government", "m-government", "e-participation", "e-democracy", "government websites", "open government", "open government data"
Exclusion Criteria	Studies not related to Nigeria, non-peer-reviewed sources, duplicate publications

The search was refined by limiting results to articles published between 2000 and 2024, written in English, and peer reviewed. This timeframe was selected to align with the Nigerian e-government journey, as documented by FMCIDE [6]. This structured approach ensured comprehensive coverage of e-government adoption, challenges, and impacts in Nigeria while filtering out irrelevant studies for a focused, high-quality literature review.

B. *Search Outcome and Exclusion Criteria*

The initial database search in Scopus and Dimensions yielded a substantial output of 179 records. A meticulous screening process based on titles, abstracts, and keywords was conducted to refine this pool, resulting in 122 articles advancing to the full-text evaluation stage. A supplementary search was conducted to capture potentially missed studies during the initial database search, including three additional articles. However, only one of these met the inclusion criteria, as shown in Figure 1.

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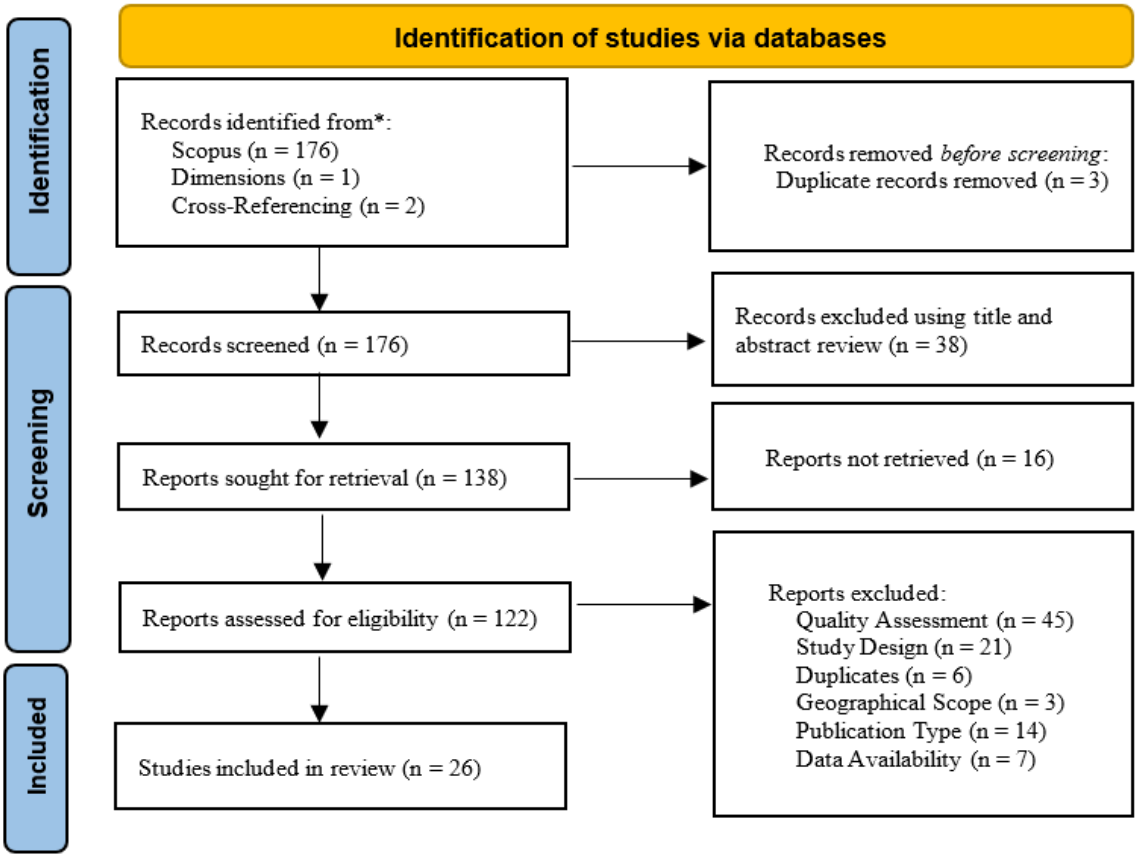

Fig. 1. PRISMA Flow Chart

The Mixed Methods Appraisal Tool (MMAT) was used to assess the methodological quality of the 122 full-text articles, excluding 45 studies due to low methodological quality, as evidenced by significant flaws in research design, data collection, or analysis. Additionally, several other criteria were applied to refine the study selection. Studies were excluded due to irrelevant study design (n=21), primarily consisting of opinion pieces and case studies that did not contribute to the research objectives. The geographical scope was also a factor, with studies conducted outside Nigeria (n=3) being removed. To maintain research integrity, duplicate publications (n=6), inappropriate publication types such as non-peer-reviewed articles (n=14), and studies with insufficient data (n=7) were excluded. A comprehensive list of the included and excluded studies is available as supplementary data to this study. This selection process yielded a final sample of 26 studies for in-depth analysis.

A. *Quality Assessment*

A comprehensive quality assessment was conducted to ensure the rigor and trustworthiness of the included studies. The MMAT developed by Hong et al. [25] was employed to evaluate the methodological quality of the studies. This tool assesses various aspects of study design, including research questions, data collection, and analysis. In order to avoid any form of selection biases, two independent reviewers applied the MMAT to each study, with discrepancies resolved through consensus or by a third reviewer. Studies were assigned scores based on predefined criteria, with higher scores indicating better methodological quality. Studies deemed to have critically low quality were excluded from further analysis.

B. *Data Analysis*

A total of 26 studies were included in this review. The quality assessment results, conducted using the MMAT [25], are presented in Table 2 for reference, with ratings based on the criteria of the selected category or categories. The criteria were evaluated using three response options: 'Yes' (criterion met), 'No' (criterion not met), and 'Can't tell' (insufficient information to judge). In addition to the quality

assessment, a thematic analysis approach was employed to extract and analyse the necessary data. This method involved an iterative process of coding, categorizing, and identifying patterns across the studies. The analysis progressed systematically from initial data familiarization through the development of preliminary themes to the identification of core themes, providing a structured understanding of the findings.

TABLE III
SUMMARY OF THE INCLUDED STUDIES IN THE REVIEW

S/N	Studies	Summary of the included studies' objectives and outcomes
1	[7]	The study investigates the factors influencing the Nigerian public's adoption of e-government tools for public participation in monitoring public infrastructure projects (PIPs), providing scholars with an exploratory baseline for e-government adoption in PIP management and offering recommendations for policymakers, government technocrats, and project engineers.
2	[26]	This study examines the role of open data in boosting fiscal transparency and accountability in African municipalities, focusing on South Africa and Nigeria. It suggests that open data can enhance citizen scrutiny of municipal budgets, thereby promoting credible, participatory local governance.
3	[18]	This study examines the availability and status of open government data on Nigerian ministry and agency websites, including the Nigeria Data Portal. It anticipates low data availability, with the Portal containing outdated information, and aims to identify challenges and propose mitigation strategies.
4	[27]	This study investigates users' perceptions of the e-government services delivered through the Nigeria Immigration Service (NIS) website, aiming to identify areas for improvement and provide recommendations for enhancing service quality and guiding future research.
5	[28]	This research examines the integration of Personnel and Payroll Information Systems with Public Financial Management in Nigeria's Public Service, aiming to provide insights into the system's effectiveness and implications for public service operations.
6	[23]	This study examines factors influencing e-government adoption in Nigeria, providing insights for policymakers to improve practices and expand understanding of adoption determinants.
7	[29]	This study investigates the types of public value citizens seek from e-government, key predictors of public value creation, and the relationship between e-government initiatives and value for citizens, providing insights to enhance e-government's effectiveness.
8	[30]	This study develops an e-voting system using agile and component-based engineering to improve Nigeria's manual voting issues, aiming to boost voter participation, reduce costs, and expedite results for a more credible election process.
9	[31]	This study examines informed Nigerians' perceptions of government transparency in COVID-19 communications, assessing its impact on public trust and disease control, with recommendations for enhanced transparency.
10	[32]	This research develops a blockchain-based framework to enhance transparency, ease, and effectiveness in Nigeria's public procurement, promoting interoperability, citizen participation, and improved project monitoring and auditing.
11	[33]	The study explores the technological, organizational, and environmental factors that impact the adoption of integrated e-government initiatives in Lagos, Nigeria's housing and urban development sector, aiming to understand their influence on successful implementation and public acceptance.
12	[34]	This study investigates why e-governance initiatives have not improved service delivery in Cross River State, Nigeria, focusing on how enhancing civil servants' digital literacy and in-service training can drive better outcomes.
13	[35]	The study examines factors that influence citizens' acceptance and use of e-democracy in Nigeria, focusing on predictors like political culture, awareness, efficacy, and recruitment networks, and suggests strategies such as political orientation programs to boost participation.
14	[36]	This study investigates factors hindering e-government diffusion in Nigeria by examining three innovation diffusion models, identifying key factors like trust and electricity supply alongside established model factors to help policymakers enhance e-government adoption strategies.
15	[37]	This study assesses the availability and status of open government data (OGD) on Nigerian government websites, identifies challenges to its implementation, and offers recommendations to enhance OGD adoption in Nigeria.
16	[38]	This study explores the interrelationships between ICT deployment, web-readiness, and the quality of web presence on Nigerian e-government websites, emphasizing how ICT investment impacts functionality and user experience and advocating for improved alignment between technology and design.

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S/N	Studies	Summary of the included studies' objectives and outcomes
17	[3]	This study examines how trust in e-government affects Nigeria's usage, success, and public value. It highlights trust as a mediator between service quality and public value and a critical factor for successful e-government implementation.
18	[39]	This study assesses the security of Personally Identifiable Information (PII) in e-government services on Nigerian embassy websites in developing nations, identifying vulnerabilities and recommending an OWASP ASVS-based framework to enhance data protection.
19	[40]	This study examines factors affecting public servants' readiness to adopt e-government services in Nigeria, focusing on performance expectancy, self-efficacy, social influence, attitudes, and demographic influences such as age and gender.
20	[41]	This study explores the potential of mobile voting (M-Voting) to enhance e-participation in democratic processes, anticipating improving accessibility, convenience, and security, thereby engaging a broader population in voting.
21	[42]	This study explores the adoption of e-voting in Nigeria, examining key definitions, challenges, and the state of e-government adoption in both developed and developing countries, with the expectation that addressing these factors is crucial for successful e-voting implementation in Nigeria.
22	[43]	This study explores the role of e-governance in enhancing local government capacity in Nigeria, identifying challenges and opportunities. It finds that ICT deployment has had a limited impact due to a lack of political will and integration issues. Addressing these factors is key to improving local governance.
23	[44]	This study examines the role of institutions in facilitating ICT adoption, focusing on the failed implementation of Nigeria's electronic voter registration (EVR) system. It aims to identify institutional factors hindering its adoption and provide insights for policymakers to improve future ICT initiatives.
24	[45]	This study examines the opportunities and challenges of e-government in Nigeria, highlighting benefits like faster service and transparency. It also addresses challenges like weak infrastructure, outages, and limited expertise. The findings aim to guide improved e-government strategies.
25	[46]	This study examines the challenges hindering e-government adoption in Africa, using Nigeria as a case study, and proposes European cooperation as a solution. It aims to identify key roadblocks and suggest collaboration between African and European countries to improve e-government practices.
26	[47]	This study investigates data acquisition methods for effective e-government implementation in Nigeria, focusing on citizen-government communication platforms and awareness. It aims to develop a more efficient information exchange model to improve citizen engagement and government service delivery.

IV. Results

A. *Impact of E-Government Implementation in Nigeria*

To assess the impact of e-government services from the selected studies, the studies were analysed to identify reported outcomes across various sectors. Thematic analysis was employed to categorize these impacts into different dimensions, as presented in Table 3, which are further discussed separately in the subsequent sections.

TABLE IV
IMPACT OF E-GOVERNMENT IMPLEMENTATION IN NIGERIA

No.	Themes	Studies
1	Enhancing Government Service Delivery)	[43], [29], [36], [45], [32], [26], [30], [41], [40], [28], [33], [31], [35], [3].
2	Public Participation in Government	[7], [37], [26].
3	Security of Government Records and Data	[39].

1. *Enhancing Government Service Delivery*

Implementing e-government systems has significantly enhanced government service delivery across various dimensions in Nigeria. A critical aspect of this enhancement is the increased transparency and accountability that e-government provides. According to Adeyeye and Aladesanmi [43], local governments that maintained websites were generally more transparent and financially accountable. The study further revealed that having internet access in local governments facilitated quicker dissemination of information, thereby improving communication efficiency.

Agbabiaka [29] emphasized the value creation in e-government systems, noting that these systems need to support citizen engagement and participation. This engagement is crucial for improving perceptions of accountability and transparency, which are fundamental in building trust between the government and its citizens. Agbabiaka [29] also pointed out the importance of personalizing e-government systems to cater to individual needs, promote autonomy, and ensure citizens feel heard and valued. The benefits of e-government extend beyond

transparency and efficiency. Amagoh [36] identified five key benefits: easy access to government information, improved efficiency, increased transparency and accountability, enhanced economic activity, and better democracy. Similarly, Asogwa [45] outlined the aspirations of Nigerians from the e-government project, which include sustainable access to government information, reduced corruption, virtual government-citizen interactions, and the promotion of public sector reforms.

Furthermore, emerging technologies like blockchain have been identified as potential solutions to improve government service delivery. Akaba et al. [32] highlighted that any successful new blockchain system must be user-friendly and support public servants' daily routines. This is particularly important as current processes are often stressful and time-consuming. A novel blockchain system is expected to alleviate these challenges, gaining full acceptance among users. The importance of open data in promoting good governance and accountability is underscored by Kariuki et al. [26]. They argued that open data is essential for credible participatory governance at all levels and requires political will to make critical data accessible to the public.

E-voting systems have also been identified to improve electoral participation and reduce the costs associated with organizing elections. Falade et al. [30] noted that using an e-voting system would increase voter participation and significantly reduce the cost of conducting elections compared to manual processes. In the context of electoral processes, Ekong and Ekong [41] found that mobile voting (M-voting) offers several advantages over traditional voting methods, including convenience, accessibility, and reduced stress. However, issues such as voter apathy and lack of trust remain that must be addressed.

In the realm of public sector reforms, the Integrated Personnel and Payroll Information System (IPPIS) has proven to be a successful administrative reform tool. According to Inakefe et al. [28], IPPIS has minimized delays in salary payments, reduced financial leakages, and simplified the human resource management processes in government ministries. This reform has freed up financial resources, allowing the government to pursue developmental activities more effectively. Olatubosun and Rao [40] discussed the broader implications of electronic governance, noting that it improves internal efficiency, public service delivery, and democratic governance. This accessibility of public services is a key factor in the success of e-government initiatives. The public's perception of the benefits of e-government is also critical. Olumoye and Govender [33] found that the perceived benefits of e-government, particularly in essential areas like housing development, play a significant role in its acceptance and success.

The role of traditional communication channels in disseminating government information, particularly in low-literacy areas, was highlighted by Ernest-Samuel and Uduma [31]. They emphasized the importance of mobilizing community leaders to use oral means and traditional media to spread information effectively, particularly during crises such as the COVID-19 pandemic. Finally, Oni et al. [35] stressed the importance of building trust in the democratic process through e-democracy initiatives. They argued that transparency, accountability, and responsiveness are crucial in fostering citizens' trust and encouraging participation in e-democracy. Abdulkareem and Mohd Ramli [3] also confirmed the importance of providing accurate, reliable, and up-to-date information through e-government platforms. They emphasized the need for seamless online services to ensure citizens can easily access and pay for government services.

In summary, enhancing government service delivery through e-government involves multiple facets, including transparency, efficiency, citizen engagement, and adopting new technologies. These improvements make government operations more effective and foster greater trust and participation among citizens.

2. *Public Participation in Government*

Public participation is critical in ensuring transparency, accountability, and overall effectiveness in government operations. The adoption of e-government tools has shown promise in enhancing this participation, particularly in the context of monitoring public investment projects (PIPs). According to Afieroho et al. [7], the Unified Theory of Acceptance and Use of Technology (UTAUT) framework was utilized to identify factors that facilitate public adoption of e-government tools for monitoring PIPs in Nigeria. The study revealed a strong behavioural intention among the Nigerian public to adopt these tools and techniques, with an average response score of 4.05 on a five-point Likert scale. This willingness to participate in monitoring PIPs execution is particularly noteworthy given the historically low levels of public participation in other areas, such as participatory budgeting, land use, and natural resource management in Nigeria. The findings suggest that e-government adoption could potentially revive public engagement in governmental processes that have traditionally seen limited participation.

Ezema [37] highlighted a growing interest among Nigerian citizens in implementing open government data. This interest is driven by the desire to participate actively in governmental programs and activities. The efforts by a few government agencies to make data freely available on their websites are seen as indicators of a broader democratic

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culture in Nigeria, where the push for transparency and accountability is gaining momentum. This shift towards government openness reflects the public's demands and shows the government's responsiveness.

Further emphasizing the importance of public participation, Kariuki et al. [26] argued that public scrutiny of local government data is essential for strengthening fiscal credibility and performance. Increasing transparency through scrutinizing municipal budgets empowers citizens to take a more active role in local governance. This involvement not only promotes better fiscal management but also enhances the overall governance process by ensuring that the voices of the public are heard and considered in decision-making processes.

In conclusion, public participation in government is being increasingly recognized as a vital aspect of effective governance. Adopting e-government tools, implementing open government data, and actively scrutinizing government operations by the public are all critical to fostering a more transparent, accountable, and responsive government in Nigeria.

Fig. 2. Impact of E-Government in Nigeria

3. Security of Government Records and Data

Government records and data security are paramount, particularly when formal personal identifiable information (PII) protection regulations are involved. Adedayo et al. [39] explored this issue within the scope of Nigerian embassies that are engaged in online registration of Nigerian citizens residing in The Americas, Europe, and Asia. The study underscores the importance of securing government records, especially in developing countries where the regulatory frameworks for PII protection are not yet fully established.

The study recommends that the insights gained from the research can be applied to the specific embassies studied and broaden governmental operations in similar contexts. Ensuring government data security is crucial for protecting citizens' personal information, maintaining trust in governmental processes, and safeguarding national security. As governments increasingly rely on digital systems for service delivery and citizen engagement, implementing robust security measures becomes even more critical.

B. *Challenges of E-Government Implementation*

A thematic analysis was also conducted on the included studies to identify the challenges associated with e-government implementation. The challenges were categorized into themes, as indicated in Table 4 and discussed in subsequent sections.

TABLE V
CHALLENGES OF E-GOVERNMENT IMPLEMENTATION

No.	Themes	Studies
1	Challenges in Modern and ICT Infrastructures	[32], [43], [36], [45], [42], [46], [37], [23], [27],
2	Corruption and E-Government Implementation	[32], [42], [31].
3	Lack of Digital Literacy	[34], [44].
4	Political Will and the Lack of Policy Implementation	[32], [18], [24]

1. Challenges in Modern and ICT Infrastructures

This study highlights that poor ICT infrastructure, including limited internet connectivity, outdated systems, and unreliable power supply, remains a significant barrier to implementing e-government services in Nigeria. The lack of modern ICT tools and platforms hinders the ability of government agencies to deliver services efficiently and securely. For instance, over 90% of the reviewed studies identified unreliable electricity and inadequate internet access as significant obstacles, particularly in rural areas where infrastructure deficits are most pronounced. These challenges slow down the adoption of e-government systems and limit their effectiveness in improving transparency, efficiency, and citizen engagement. The limited presence of infrastructure in local governments leads to minimal impact from ICT deployment, even though there is a strong positive correlation between ICT deployment and meeting the needs of the citizenry, as highlighted by Adeyeye and Aladesanmi [43]. The country's unreliable power situation is a major obstacle, which Akaba [32] emphasizes as a critical challenge to effectively implementing advanced technologies such as blockchain. This concern is echoed by Amagoh [36] and Asogwa [45], who point out that the lack of reliable electricity,

compounded by other issues like corruption, poor access to ICT facilities, and low internet penetration, significantly hinders the diffusion of e-government services in Nigeria.

Brooks and Mohammed [42] provide a broader context by discussing the readiness for e-government in developing countries, noting that infrastructure and literacy are fundamental challenges. Additionally, they highlight that factors such as trust, attitude, and corruption further complicate the adoption of e-government. The challenges are not limited to power supply; as Eka [46] discusses, outdated infrastructures and over-crowded networks lead to severe connectivity issues, making it challenging to advance meaningful e-government initiatives.

Ezema [37] underscores the ongoing struggles with poor and irregular internet connectivity, which, alongside an inadequate public power supply, severely hampers the implementation of digital open government data (OGD) in Nigeria. Muhammad and Kaya [23] stress the need for substantial investment in technical infrastructure, including reliable internet and electricity, to foster an environment where e-government services can thrive. Moreover, Okunola and Rowley [27] confirm that the potential benefits of e-government services in Nigeria are not fully realized due to the persistent lack of reliable electricity and internet connectivity. They also identify additional challenges related to website design, security, and privacy, further complicating the effective use of e-government services.

These observations collectively paint a picture of the significant infrastructural deficits in Nigeria, particularly in ICT and electricity supply, which must be addressed to unlock the full potential of e-government in the country.

2. *Corruption and E-Government Implementation*

According to this study, corruption in e-government implementation refers to deliberately misusing public office, policies, and digital governance tools for personal or political gain, ultimately hindering transparency and efficiency. The study highlights how government officials resist digital transformation to maintain control over manual processes that facilitate illicit activities. For instance, political interference and reluctance to adopt blockchain-based procurement and financial management systems obstruct efforts to enhance accountability. Akaba et al. [32] highlight that stakeholders often resist adopting such technologies due to their potential to restrict traditional methods that facilitate fraud and manipulation of figures. This reluctance is symptomatic of a broader issue where corruption hinders technological progress. Similarly, Brooks and Mohammed [42] emphasize that, alongside infrastructure and literacy, corruption is a critical factor affecting the readiness and success of e-government initiatives in developing countries. The pervasiveness of corruption stifles technological advancements and erodes public trust. Ernest-Samuel and Uduma [31] provide a poignant example during the distribution of palliatives, where unclear criteria and distribution methods led to public distrust and criticism of the government. These instances underscore the need for transparency, accountability, and a commitment to combating corruption to foster trust and enable the successful implementation of modern technologies in governance.

3. *Lack of Digital Literacy*

According to this study, lack of digital literacy in the context of e-government implementation refers to the insufficient ability of citizens and government officials to effectively use digital tools and platforms for accessing and delivering public services. Some studies highlighted that limited digital skills among civil servants hinder the efficient adoption of e-government systems, resulting in underutilization and poor service delivery. Additionally, inadequate public awareness and training programs prevent many citizens from engaging with e-government platforms, further widening the digital divide. For instance, Inakefe et al. [34] highlight how the Cross River State civil service's efforts to adopt e-governance as part of its digitalization strategy are being hindered by inadequate digital literacy. This problem is exacerbated by a lack of in-service training, resulting from administrative resistance to ICT reforms. McGrath and Maiye [44] further emphasize the challenges posed by inadequate digital literacy, particularly in the context of reliable personal identification. They note that the lack of widespread, reliable identification methods complicates training efforts related to knowledge deployment. This issue is linked to broader national challenges, such as the incomplete National Identity Cards Scheme rollout. Furthermore, the inefficiencies in training processes, especially for staff temporarily deployed from headquarters, are exacerbated by unfamiliarity with local contexts, further underscoring the need for improved digital literacy and training.

4. *Political Will and the Lack of Policy Implementation*

According to this study, political will in the context of e-government refers to the commitment of top government leaders to drive the successful adoption and implementation of digital governance initiatives. In contrast, the lack of policy implementation reflects the failure to translate strategic plans into actionable outcomes. The study highlights inconsistent political commitment and weak enforcement of e-government policies, which have significantly slowed progress in Nigeria. Akaba et al. [32] discuss the importance of political will in ensuring the successful implementation of blockchain technology for e-procurement systems in the public sectors in Nigeria to

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facilitate e-government services. They highlight that compliance with requirements remains insufficient without the commitment of both the executive and legislative branches of government. Similarly, Ezema [18] notes the ongoing challenges in Nigeria's open government data (OGD) realm. While some government agencies have made efforts to make data accessible online, the majority have not followed suit, largely due to the absence of a clear policy framework. This lack of published guidelines signals insufficient political will to advance transparency and accountability through OGD. Ogunsola and Tiamiyu [24] further emphasize the need for specific policy implementations, particularly in enhancing government websites to cater to the needs of people with disabilities. They point out that the absence of such policies continues to exclude this demographic from fully benefiting from e-government services.

Fig. 3. Challenges of E-Government Implementation

V. Discussion

The findings from this study highlight both the advancements and the challenges associated with e-government implementation in Nigeria, offering critical insights for policymakers, technology developers, and administrators. E-government adoption in Nigeria has produced measurable benefits, particularly in enhancing public service delivery, improving transparency, and promoting citizen participation. Systems such as the Integrated Personnel and Payroll Information System (IPPIS) have demonstrated clear advantages, including reduced financial leaks and more efficient human resource management [28]. This mirrors global trends in successful e-government programs that have strengthened public sector accountability and operational efficiency. The Nigerian government's emphasis on inter-agency collaboration and initiatives to engage the private sector in service delivery aligns with international e-governance models that leverage multi-stakeholder engagement to improve public service outcomes. However, for Nigeria to fully realize these benefits, there is a need to address the underlying challenges that have hindered widespread e-government adoption and impact [48].

One of the primary obstacles identified is Nigeria's underdeveloped infrastructure, including limited internet connectivity, outdated ICT resources, and unreliable electricity supply [36]. These deficiencies disrupt access to e-government services, especially in rural areas, and are consistent with challenges in other developing nations where infrastructural limitations constrain digital innovation. Solutions such as mobile-enabled e-services, which have been employed in other countries with infrastructure gaps, could be further explored to increase accessibility [49]. However, without substantial improvements in infrastructure, particularly in stable power and connectivity, Nigeria's e-government progress will remain constrained [45].

Similarly, looking at these challenges from other developing countries' perspectives, a study conducted by Abusamhadana et al. [50] indicated that, even though E-government implementation in Ghana has benefitted the country in reducing corruption and efficient service delivery, challenges like the digital divide, cultural issues, and infrastructure problems persist. Ramli [51] also conducted a comparative analysis to explore Malaysia and South Korea's different challenges in implementing e-government initiatives. It highlights technological readiness, public trust, and administrative capabilities as significant influences on implementation success.

Digital literacy also emerged as a significant barrier, limiting both citizens' and public servants' ability to engage effectively with e-government platforms. Despite some training efforts, insufficient digital skills across the workforce and the public create usability issues and reduce adoption rates [52]. Addressing this challenge requires investment in widespread digital literacy programs that equip users with the necessary skills to utilize e-government services confidently. Lessons from countries that have invested in digital literacy at scale, such as South Korea and Estonia, could inform Nigeria's strategies to improve adoption and usability [21],[53].

From a global perspective, Samsor [54] identifies key challenges to e-government implementation in Afghanistan, including stakeholder involvement, coordination, information sharing, ICT literacy, and awareness. In Jordan, Al-Shboul et al. [55] investigate various challenges with e-

government services, including budgeting, human expertise, social influence, and data privacy concerns. It concludes that a significant gap exists between the design and reality of e-government projects, which affects their success. According to Nurhidayat et al., [56] among the main challenges of e-government implementation in Indonesia are lack of data integration, minimal public participation, and lack of technical understanding among civil servants.

Another notable challenge is the prevalence of corruption and the lack of political will, which impacts the transparency and accountability of e-government initiatives [57]. Corruption discourages public trust and impedes the rollout of transparent digital systems, while inconsistent commitment from government entities undermines policy implementation. Strengthening regulatory frameworks, ensuring consistent political support, and promoting transparency through open government data initiatives could enhance trust and support e-government effectiveness [58].

From a global view among the developing countries, Zeebaree & Aqel [59] identified among the main critical challenges to e-government implementation in developing countries are organizational, political, social, and infrastructure-related. Similar findings were also presented by Arief and Yunus Abbas [60], that E-government implementation faces challenges in developing and developed countries, including IT infrastructure, human resources, policy/legislation, politics, economy, geography, and culture.

VI. Conclusion

This systematic review provides a comprehensive overview of the impact and challenges of e-government implementation in Nigeria. The analysis reveals that e-government has the potential to significantly enhance government service delivery, improve transparency and accountability, and increase citizen participation, particularly in developing countries globally. By leveraging information and communication technologies, governments can streamline processes, reduce costs, and enhance the quality of public services. However, several challenges hinder fully realizing e-government's potential in Nigeria. Inadequate infrastructure, including unreliable power supply and limited internet connectivity, poses significant obstacles to the successful implementation of e-government initiatives.

Moreover, corruption and a lack of capacity building have further impeded progress. The review also highlights the importance of public participation in the e-government process. Citizens' increasing interest in open government data and their willingness to monitor government activities are positive indicators for the future of e-governance in the country. However, addressing existing challenges requires strategic policy interventions to ensure the long-term success of e-government initiatives. Some of the policy recommendations from the study's findings should include:

Infrastructure Development: The government should prioritize investment in stable electricity supply, nationwide broadband expansion, and ICT infrastructure to support the seamless functioning of e-government services. Public-private partnerships (PPPs) could be leveraged to accelerate digital infrastructure projects.

Strengthening Digital Literacy: A national digital literacy program should be developed to enhance the ICT skills of government employees and citizens. Training initiatives should focus on increasing digital competency, ensuring all stakeholders can effectively engage with e-government services.

Anti-Corruption Measures: The implementation of e-government solutions should be accompanied by robust anti-corruption frameworks, such as blockchain-based public procurement and automated financial tracking systems, to minimize opportunities for fraud and enhance accountability.

Policy Enforcement and Political Commitment: The Nigerian government must demonstrate strong political will by consistently implementing e-government policies. This includes setting clear, enforceable regulations, monitoring compliance across ministries and agencies, and establishing independent oversight bodies to track progress.

Open Government Data Enhancement: The government should improve the accessibility, reliability, and frequency of open data updates, ensuring citizens can actively monitor public expenditures, policies, and service delivery. Open government initiatives should be integrated with feedback mechanisms to promote citizen engagement and trust.

Cybersecurity and Data Protection Policies: Strengthening cybersecurity laws and data protection policies is essential to ensure the security of e-government systems. Policies should include strict guidelines on data privacy, system security, and risk management to prevent cyber threats and unauthorized access to sensitive information.

User-Cantered Service Design: E-government platforms should be designed with user-friendliness in mind, ensuring they are accessible to individuals with varying levels of digital literacy. Incorporating citizen feedback into the design and continuous improvement of e-government services will enhance adoption and usability.

By implementing these policy recommendations, Nigeria hopes to overcome the existing barriers to e-government adoption and fully harness the benefits of digital governance. A well-executed e-government strategy has the

potential to drive public sector efficiency, foster greater transparency, and improve citizen engagement in governance processes, ultimately contributing to national development.

While this study offers valuable insights into the impact and challenges of e-government in Nigeria, its findings have broader implications for global e-governance, particularly in developing countries. The lessons from Nigeria's experience can serve as a reference for other nations, helping them anticipate and mitigate similar challenges in their digital governance initiatives. To build on these findings, further research should explore specific areas that are critical to the successful implementation of e-government.

One key area for future research is cybersecurity in e-government systems. As governments increasingly digitize public services, the risk of cyber threats, data breaches, and digital fraud rises. Investigating cybersecurity best practices, risk management strategies, and government capacity to secure digital platforms is crucial. Comparative studies between Nigeria and countries with advanced cybersecurity frameworks could identify gaps and recommend solutions to enhance the resilience of e-government systems.

Another crucial avenue for research is citizen trust and engagement with e-government services. Trust in digital governance plays a vital role in adoption rates and public willingness to use e-government platforms. Future studies should assess the relationship between transparency measures, data protection policies, and citizen trust levels in government institutions. Longitudinal studies tracking public confidence in e-government over time could provide insights into how policy adjustments and technological advancements impact citizen engagement.

Additionally, comparative policy analysis between Nigeria and other nations both developed and developing can offer valuable lessons on effective e-government implementation. Examining policy frameworks, regulatory environments, and governance structures in countries with successful digital transformation can help Nigeria refine its strategies. Research could focus on how legislative backing, political commitment, and inter-agency collaboration influence the effectiveness of e-government adoption.

Further research should also assess the socio-economic impact of e-government, particularly in relation to regional disparities and digital inclusion. Studies evaluating how e-government affects marginalized populations, rural communities, and small businesses would provide data-driven insights to enhance equitable digital service delivery. Moreover, cost-benefit analyses of existing e-government programs could inform resource allocation and policy decisions to ensure sustainable implementation.

By addressing these areas, future research can contribute to strengthening e-government strategies globally, improving public service delivery, fostering citizen engagement, and enhancing governance efficiency in diverse national contexts.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Detection of Errors in Bitewing X-Ray Images Using Deep Learning

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Abstract— Quality assurance (QA) is a process put in place in the hospital to guarantee ideal diagnostic image quality with minimum danger to patients. It entails frequent quality control checks, preventive support procedures, authoritative approaches, and planning. The process of acquiring quality images, especially for radiography students and trainees, requires a steep learning curve. This study proposes deep learning models that may serve as a guide to ensure proper images are captured and help improve the quality assurance process. The models are intended to determine that the images captured are optimal by ensuring adequate precautions in the capturing process, thereby automatically identifying and correcting any mistakes or issues in the quality or interpretation of the image. This study acquired 4955 radiographs that have been labeled by dental experts. Four deep learning models, specifically CNN, AlexNet, RestNet-50, and ViTs have developed with respective accuracies of 78.98%, 24.84%, 78.03%, and 81.34%. The performance results show that deep learning models have the potential to be utilized to assist dental practitioners in error detection and quality assurance.

Keywords— Bitewing radiography, Bitewing radiography Error, machine learning, convolutional neural network (CNN), AlexNet, Residual Neural Network-50 (ResNet-50), Tensor, Visual Transformers (ViTs), Image Classification.

I. Introduction

Artificial intelligence (AI) has witnessed an exciting surge in advancement in recent times. Machines and equipment are evolving rapidly to make human tasks and chores easier. Nonetheless, a prevalent design issue remains in their ability to consistently produce high-quality output. The reason behind this is that achieving a quality output fundamentally relies on domain-specific solutions, requiring concerted efforts. Complex machines entail numerous quality assurance procedures and demand technical expertise. This indicates that human effort and time continue to hold a considerable level of importance. This is particularly relevant in the application of machine learning in the medical field, such as radiography. Radiography is a medical technique that encompasses the creation of diagnostic images like X-ray, ultrasound, Computerized Tomography(CT) scan, and Magnetic Resonance Imaging (MRI). Analyzing radiographic images for diagnosis where individuals had to endure over a month-long wait for their X-ray results to be processed may not be desirable for an efficient health care system. This delay can be attributed to the time-consuming nature of imaging examinations and procedures that heavily rely on human involvement. In radiographic diagnosis, there exists considerable potential for errors, due to human factors as well as defective machines.

Anomalies of the human body are captured by imaging techniques. In order to diagnose, and plan therapy for the anomalies, it is necessary to comprehend the collected images. Medical experts with expertise often interpret medical images. Nevertheless, the efficiency of image interpretation carried out by qualified medical specialists is limited by the scarcity of human experts, their weariness, and the imprecise estimation processes associated with them. Errors in assessing radiographic images may lead to either a false positive or a false negative. In the case of a false positive, a patient may be subjected to emotional trauma, asked to undergo a life-changing procedure, incur an expensive financial loss, and a considerable waste of time. False negative, on the other hand, could lead to delayed treatment consequently increasing the chances of further complications which in turn would lead to more critical procedures and impact the patient's life. In this study, an attempt has been made to auto-detect and classify the common errors in bitewing X-ray images. The experiment was conducted to determine or detect that the images

captured through the process of radiography satisfy the required quality. This is to identify and correct any mistakes or issues in terms of the quality of the image and to ensure the quality assurance process of the image does not stray when conducting the radiography process. Deep learning classification algorithms based on the Convolutional Neurol Networks (CNNs), as well as other variants such as the Inception Neural Networks (InceptionNets), Residual Neural Networks (ResNets), and Vision Transformer (ViTs), have been employed in conducting the image classification of the quality of the X-ray images. The experiment aims to assist radiographers as well as medical students in increasing the quality of X-ray images. Additionally, previous data would be useful as a reference for medical students to avoid preventable errors when an X-ray image is being taken.

II. Related work

Researchers' interest in the application of deep learning to medical domains has been consistently growing in recent years. Deep neural networks, or DNNs, form the core of emerging artificial intelligence (AI) systems. The most established algorithm among various deep learning models especially for medical images is convolutional neural networks (CNNs), a class of artificial neural networks that has been a dominant method in computer vision tasks. Convolutional neural networks (CNNs) process shift-invariant input, such as images, by introducing convolutional layers and pooling layers ultimately linked to the fully connected layer for final classification.Applications of CNNs among radiology researchers have been published in areas such as lesion detection, disease classification, infected area segmentation, image reconstruction, and natural language processing [1]. Researchers using CNNs for medical imaging and radiology duties could potentially impact clinical radiologists' work. This covers CNN's opportunities and potential future paths while concentrating on the fundamental ideas of AI and how they apply to different radiology applications [2].

Convolutional neural networks (CNNs) are effective tools for image understanding. They have been shown to outperform human experts in many image analysis and understanding tasks [3]. The ultimate goal is to encourage academics studying medical image interpretation to utilize CNNs extensively for diagnosis and research. Many researchers have designed automated systems for extracting fundamental features from images [4]. Convolutional Neural Network (CNN) is a popular deep learning method for computer vision applications [7]. The human ability to recognize objects visually served as the inspiration for this deep learning system [8]. One of the algorithms created to help academics and researchers with classification issues is CNN where it makes the possible to use images as input, which moves artificial intelligence technology one step closer to mimicking humans' use of sight, a different sense, to understand their environment. Only words and numbers could be fed into its older algorithms. CNN uses artificial neurons instead of actual ones to detect objects in a similar manner to how people use their own brain neurons [9]. To enable the computer to distinguish between each pixel in an image and produce the right result, CNN would process and extract from an image through multiple levels of processing.

Another recent model is the Transformer, which mainly utilizes the self-attention mechanism, to extract intrinsic features. Often, this is mainly utilized in large language models showing great potential for extensive use in AI applications [5]. When the Transformer model was initially used, it significantly improved natural language processing (NLP) tasks. For machine translation and English constituency parsing tasks, for instance, initially proposed the transformer model based on the attention mechanism. A novel language representation approach, Bidirectional Encoder Representations from Transformers (BERT) was proposed to pre-trains a transformer on unlabelled text by considering the bidirectional nature of each word's context [6]. Images are thought to be more challenging for generative modeling than text because they incorporate additional dimensions, noise, and duplicate modality. The transformer can be used as the backbone network for image categorization in addition to CNNs. Wu et al, substituted vision transformers for the last convolutional layer and used Residual Network (ResNet) as a practical baseline [Wu et al]. Convolutional layers are specifically used to extract low-level characteristics, which are then sent into the vision transformer. To arrange pixels into a limited number of visual tokens for the vision transformer, each of which represents a semantic concept in the picture, employing a tokenizer. The direct application of these visual tokens has been seen in picture categorization.

III. Methodology

The deep learning architectures that will be employed in this study are CNN and variants such as InceptionNets, DesNets and AlexNets.

A. Convolutional Layer

In this research, the dataset was acquired from IIUM Kuantan Medical Campus after approval from the university ethics committee. Subsequently, the dataset was manually extracted from the machines, while Dental experts assigned classes to the extracted images. This dataset is then prepared for the deep learning models. The features from the provided dataset were extracted using a conventional CNN architecture. The dental X-ray image dataset needs to be preprocessed before being fed into the models, as will be

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covered in more detail subsequently. As can be seen in Figure 1, the CNN model consists of convolution layers, max-pooling, average pooling, and fully connected layers. The number of channels and fully connected layers (FC) as well as the filter size of the convolutional layers are indicated by the notation in each block. The ReLU function, max-pooling layer, average pooling, and flattened layer are indicated by additional block labels [10].

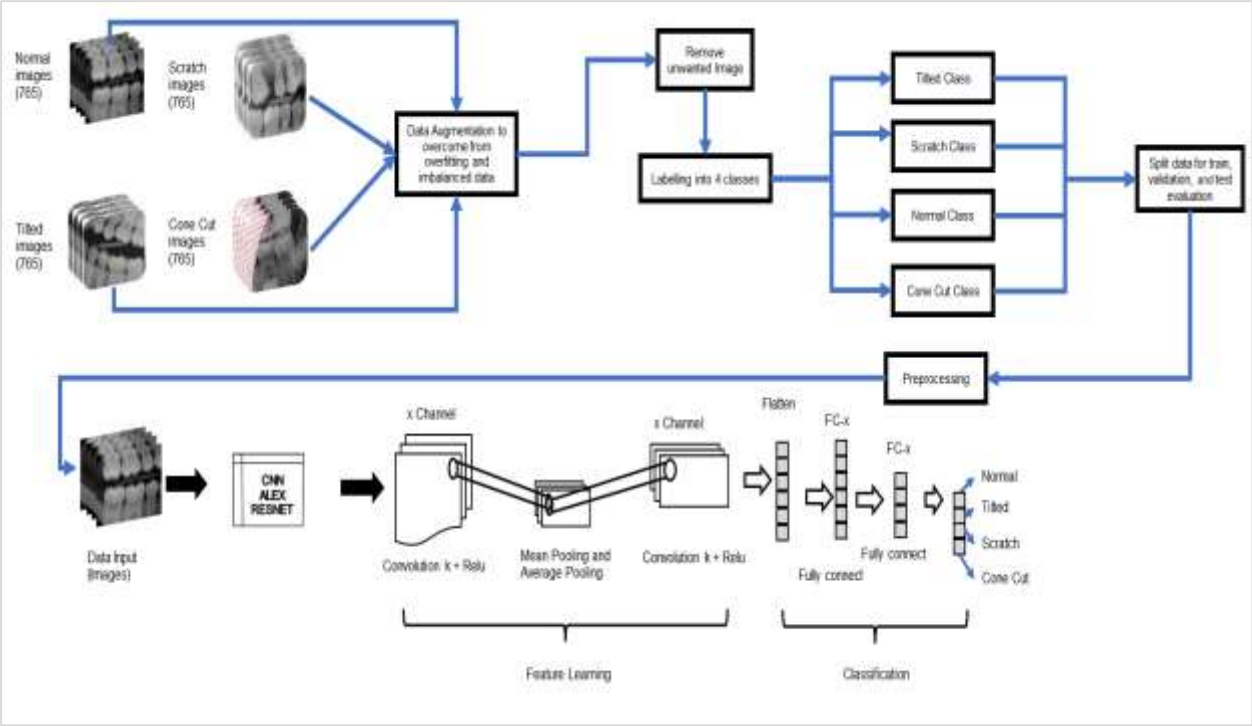

Fig. 1 Methodology of the project for CNN

Since images are inherently non-linear, the Rectified Linear Activation function (ReLU) is applied after each convolutional layer to introduce non-linearity into the model since it returns the same results regardless of whether they are positive or negative, this method also aids in speed (see Figure 2).

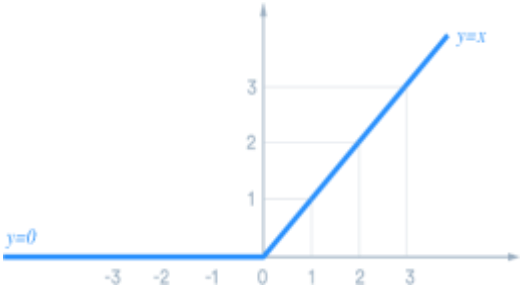

Fig. 2 ReLU Activation Function

B. *Pooling Layer*

Following input through the first convolutional layer, the feature map is shrunk by the pooling layer, which consists of a pool and a stride[11][12]. A pool will move across the feature map in accordance with the pooling approach in order to extract features. The pool action's both horizontal and verticals are determined by a stride.One of the several pooling layers in this model is max-pooling. Prior to traversing the flattened layer, each convolution's output will undergo max-pooling. A number of methods can be used to achieve pooling, for instance max, average, and min pooling, which produce the maximum, average and minimum values from the dental X-ray section that corresponds to the kernel, respectively. Similar to the convolutional layer before it, the pooling layer considers factors like stride and layer size..

C. *Fully Connected Layer*

The dental X-ray feature map is extracted using the global average pooling operation after completing the last module and before it reaches the fully connected layer. The network's final layer is the fully connected layer, which offers better classification performance than features retrieved from earlier layers. It is an illustration of a traditional neural network architecture, where a dense network is created by connecting every neuron in one layer to every other layer's neuron [13]. The fully connected layer

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receives the final convolution's output as input, flattens it, and then passes it through the fully connected network for classification. Before the inputs are fed into the fully connected layer, the flattening operations is necessary because the final convolution produces a dimensional matrix as its output. All of the matrix values will be converted into vectors in order to achieve flattening necessary to perform the SoftMax procedure before classification.

$$y = f(Wx + B) \quad (1)$$

In artificial neural networks, this is a standard equation. Wx is the dot product between the weight matrix W and the input vectorx[14]. The bias term b is added to the result of this dot product. Finally, the activation function f is applied element-wise to the result.

For this research, the input will be categorized into three previously described classes of dental X-rays based on the probability of the item in the classes [15][16].

The Transformer architecture was first created for natural language processing, but Vision Transformers, or ViTs, is a deep learning model that adapts it for computer vision tasks. It has drawn interest because it can perform competitively without the use of convolutional neural networks (CNNs) in image classification and other vision tasks.

Vision Transformer employs a technique known as self-attention [5]. Because it allows computers to comprehend the relationships between the various components of an image, it is also known as self-attention. Additionally, a self-aware computer can concentrate on distinct image patches and comprehend how they connect to create a complete picture. In essence, what Vision Transformers do is divide the image into smaller units known as patches, and by turning them into a series of tokens, the Transformer model is able to analyze and comprehend each component of the image independently.

D. Transformer Model

The Transformer network is intended to resemble the attention process. Instead of using visual cues like movie frames, words in a sentence, notes, or even individual pixels in an image, it uses attention to comprehend the order of information [5]. Therefore, even when components are far apart, Transformer networks are still able to capture the dependencies and relationships between them. For tasks like language understanding, transformer networks are particularly effective because of their capacity to capture long-range dependencies (see Figure 3).

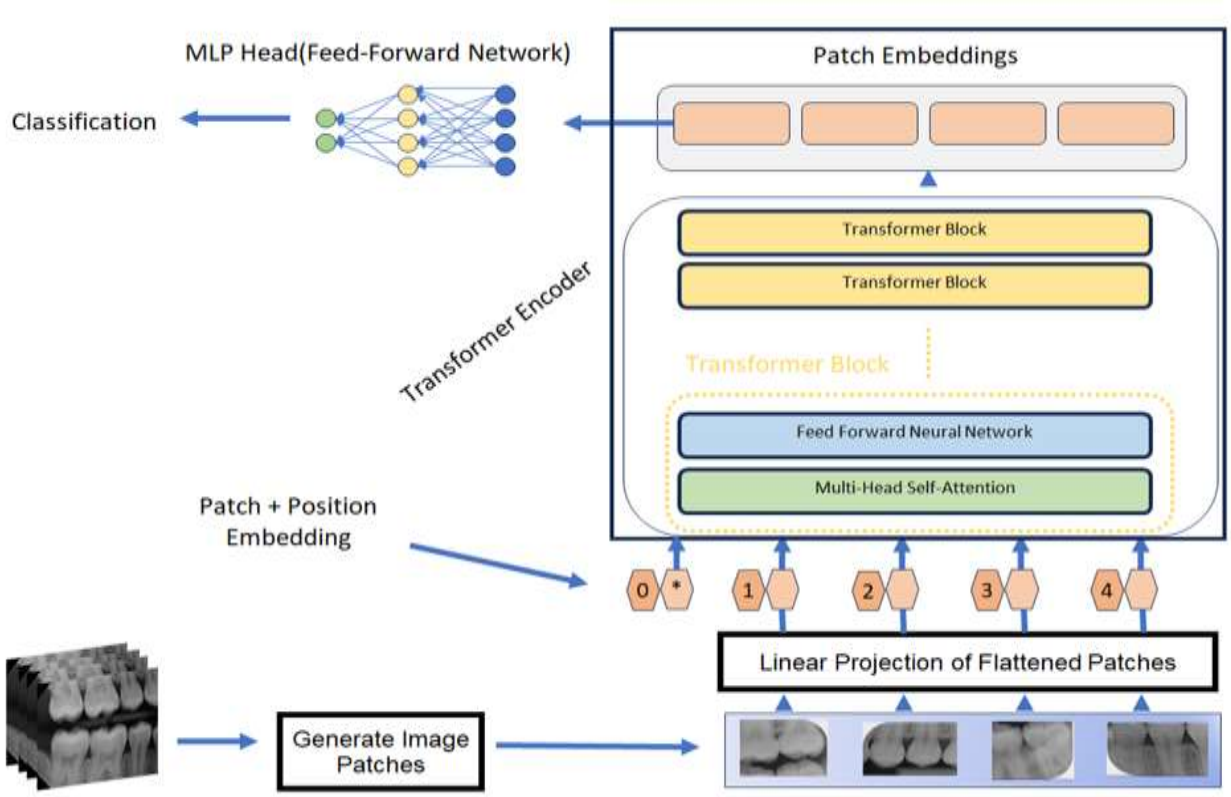

Fig. 3 Methodology of the project for Vision Transformer

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E. Linear Projection

Visual projection that is linear each 1-D vector will be converted into a lower dimensional vector by the transformer as it works on these flattened patches, while keeping the connections and significant elements. The two primary steps in linear projection are bias addition and weight matrix multiplication.

After completing these two stages, a vector is transformed into one with a lower dimensionality, or one with fewer elements or components than the original vector to extract key characteristics and record the most crucial data while eliminating the less crucial details. By removing noise and pointless variations from the data, dimensionality reduction actions can strengthen and narrow the focus of the vector representation to the most important features.

F. Position Embedding

Every image patch has position embedding added to it, which shows every location in the image. Data were fed into the transformer using positional encoding and with the help of this positional embedding, position information for every patch that is available were fed to the transformer vector, which is then fed to the subsequent layers in the vision transformer for additional processing.

G. Self-Attention Layer

The transformer encoder's first layer is the self-attention layer. Self-attention enables every patch to pay attention and learn from other patches. It allows the model to take the global context into account by capturing dependencies between the patches.

Understanding the relationship between the patches or tokens in an image is aided by the self-attention layer. It assists the model in determining which patches are related and how important to one another .

All of the patches in the image are taken by the self-attention, and each patch is assigned by three unique jobs that seek queries, functioning similarly to a patch searching for other patches to focus on, while the key functions similarly to a patch being examined by other patches, and valuefunctions similarly to the patch's details or information.

It computes a similarity score between every patch inside of it. The more closely related the patches are, the higher the score. These similarity scores are then applied to each patch to determine the relative importance of each word in the image. More attention will be paid to the patch with the higher score. Subsequently, the self-attention will aggregate the relevant patch values according to their respective attention weights andbuilds a new representation for every patch by assembling the relevant image's details.

H. Feed Forward Neural Network

The next in line after the self-attention layer is the feed forward neural network. Every patch's output is sent through the feed forward, which uses it to help identify intricate non-linear relationships between the patches.

I. Add & Norm (Residual Connection)

The add and norm layer, also referred to as the residual connection or skip connection, performs an element-by-element edition between the feed-forward or attention output and the output of the preceding layer. The original data from the previous layer, which aligns the model to learn and update the new information captured by the supplying layer, is preserved with this addition. By including this sublayer's output, the original input add layer gave the model a shortcut path for information flow and aided in the gradients' effective propagation during training. Thus, these layers are essential for managing information flow and maintaining training process stability.

J. Dataset

The bitewing radiographs data for the study was collected at thefaculty of dentistry, International Islamic University Malaysia, Kuantan by dental experts after receiving ethical approval from the committe. A total of 3060 bitewing radiographs were extracted and labelled into classes. The dataset contains 765 of each of the classes, namely cone cut, normal, scratch and tilted respectively. Samples of the different classes are shown in Figure 4.

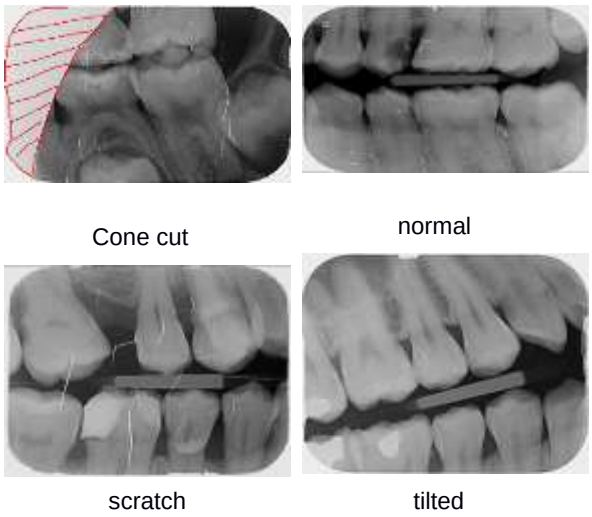

Fig. 4 Labelled radiograph

K. Preprocessing

The first stage in the CNN techniques to preprocess the image for classification [17].

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The training and test sets are split in a 80:20 ratio which consists of a total of 96 radiographs batches according to the size of batches.

The radiographs' channels are rescaled between 0 and 1 before the model is trained to standardize the input. To increase the pace of model training, they are reshaped to 224 by 224 pixels [18].

L. Training

Each of the models for CNNs architecture is being set for the same structure to compare the effectiveness with 30 epochs to avoid model overfitting. As for the batch size, it is set to 64 to maximize the speed of the device.

On the other hand, for the Vision Transformer model, it has a different architecture compared to CNN model. In ViTs, there is the need to measure input features set to 768 (16*16*3) and output features to classesnce the ViTs requires a high hardware specification, the utilization of transfer learning is necessary to avoid exceptions from occurring during training. The epochs are being set to 30 epochs to measure training efficiency. The batch size is setup to 64 to train the batches available. In the data loader, the number of workers has been fixed to a maximum of 4 to carry the full potential of the CPU and GPU available. The model of CNNs is being trained using the Intel(R) Core(TM) i5-8250U CPU @ 1.60GHz 1.80 GHz processor (CPU) for the laptop specification. As for the ViTs is being trained using the Nvidia GeForce 16 series (GPU) with 4 gigabytes (GB) of Video Random Access Memory (VRAM) on Desktop. The CNNs model is built on Python v3.10.3 with Keras v2.10.0 and TensorFlow 2.10.0 as site backend. While ViTs, build on same Python version with Pytorch v2.1.2 along with CUDA v11.8 to utilize GPU.

M. CNNs architecture

CNN is the most common deep learning algorithm in image classification. Generally, it is a deep neural network model that consists of two parts, namely; image feature extraction and classification. The proposed baseline CNN has 3 layers of convolution with Rectified Linear Unit (ReLU) activation and pooling, which are inserted alternately. Multiple dropout layers of 0.2 and 0.5 dropout rates are implemented in between. Eventually, there are roughly 65 hundred thousand trainable parameters.

The design that has been recommended consists of two dense layer blocks, three pooling blocks, and three convolutional blocks, in that sequence. A few batch normalizations are being done to make matrix computation faster [19], [20].

On the other hand, Vision Transformer is a variation of natural language processing model that focuses on the self-attention layer where all the tokenization is arranged before patch embeddings. The utilization architecture consists of convolution projection, encoder blocks and linear heads.

The three CNN architectures are designed in such a way that the feature extraction part gradually pools the radiograph until it is an input of single-digit by single-digit pixels [21].

N. Hyperparameter settings

All the CNNs will be trained using the same hyperparameter settings. A few of them, such as the number of epochs and batch sizes, have been mentioned. Weights are initialized based on the default settings. The loss function used is Categorical Crossentropy. It measures the dissimilarity between the predicted probability distribution and the true distribution.

The loss function is optimized by Adam optimizer and set to have a learning rate of 0.001.

IV. Results

The results below will show the accomplishment that has been acquired after fitting the models between these CNN and ViTs models according to their limitations.

A. Base CNN

Based on Figure 5, we can conclude that the loss rate is minimum at most to 0.3 value rate while the starting loss rate count from 3.5 value rate when running under a total of 100 epochs. Meanwhile, the loss rate for the validation reduces by only a portion of the loss which is a 1.0 loss rate starting from a 1.5 value on 100 epochs.

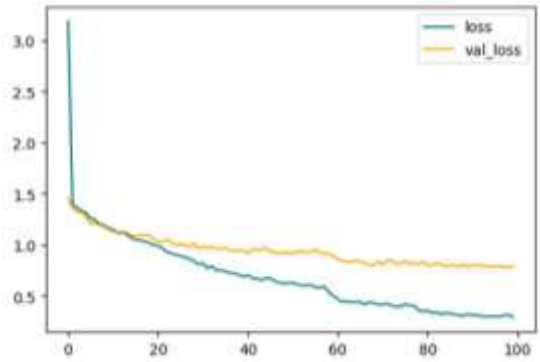

Fig. 5 Figure shows the loss rate of Base CNN

Based on Figure 6, the starting accuracy value is around 0.25 while decently ascending as the number of epochs runs. The accuracy is around 0.92 on 100 epochs for training, followed up by the validation accuracy rate of 0.79 plus.

Based on the prediction result in Figure 7, the number of actual labels that meet prediction for cone cut, normal, scratch, and tilted are 114, 133, 146, and 104 respectively. The most correctly predicted class is the scratch class.

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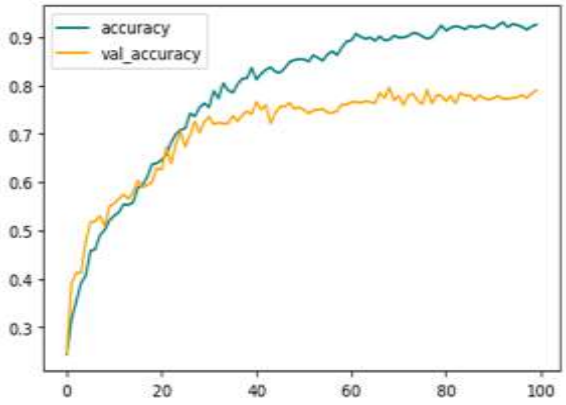

Fig. 6 The accuracy rate of Base CNN

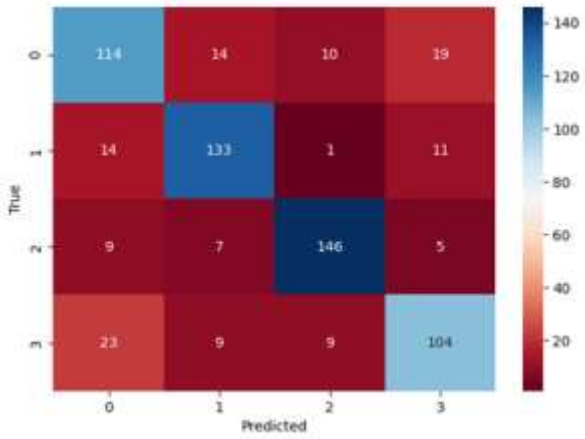

Fig. 7. Confusion Matrix of the Base CNN

TABLE I
RESULT OF QUALITY BASED ON MODELS

Model	Epoch	Train Accuracy (%)	Test Accuracy (%)	Class	Precision (%)	F1-score (%)	Recall (%)
Base CNN	100	92.60	78.98	Cone Cut	71	72	73
				Normal	82	83	84
				Scratch	88	88	87
				Tilted	75	73	72
AlexNet	10 (early stopping)	24.38	24.84	Cone Cut	24	39	100
				Normal	0	0	0
				Scratch	0	0	0
				Tilted	0	0	0
RestNet-50	53 (Early stopping)	92.89	78.03	Cone Cut	74	74	75
				Normal	81	81	81
				Scratch	83	80	77
				Tilted	72	74	77
ViTs	30	75.40	81.34	Cone Cut	75	82	78
				Normal	74	85	79
				Scratch	94	88	91
				Tilted	85	71	78

B. AlexNet

The result in figure 8 shows that the loss rate goes down aggressively during 0 to 2 epochs but after that, it starts to sustain up to 8 epochs while the validation loss went down from 1.7 to 1.3 until the 8 epoch.

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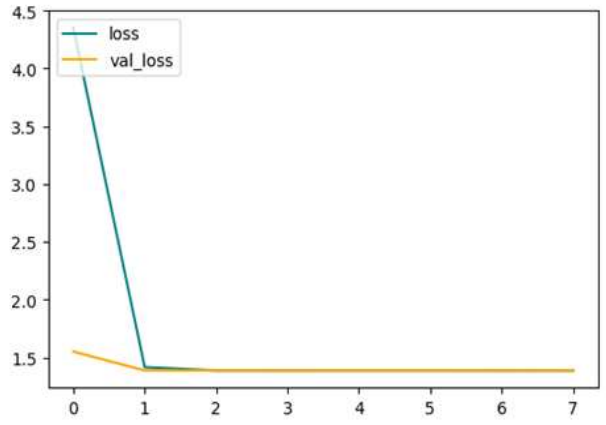

Fig. 8 Figure show the loss rate of AlexNet

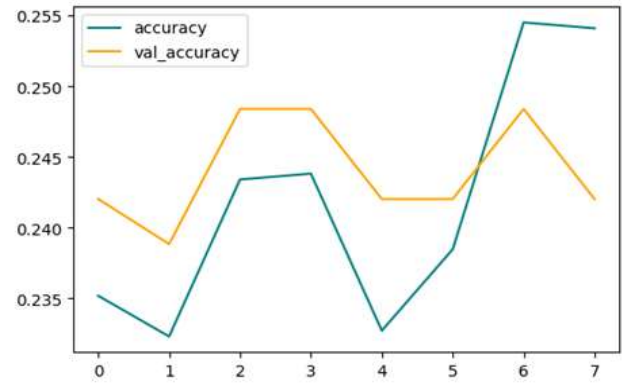

Fig. 9 The accuracy rate of AlexNet

Based on the result in Figure 9, the accuracy of AlexNet is not stabilized throughout the training cycle. The measurement attained after 8 epochs is at most 0.25. Similarly, the validation accuracy goes down after the 6 epochs.

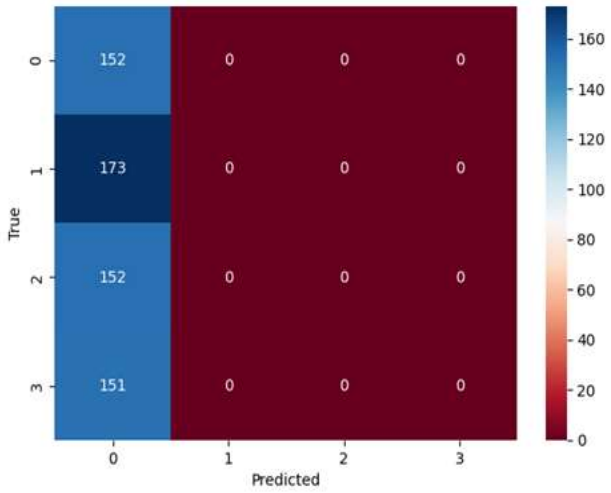

Fig. 10 Confusion Matrix of AlexNet

Based on the result in Figure 10, it can be clearly seen that the 3 classes are missing from being included in the fitting model which is the reason for the low accuracy. Consequently, there is class imbalance that made the cone cut dominate the model prediction with 152 labels as true positive.

C. RestNet-50

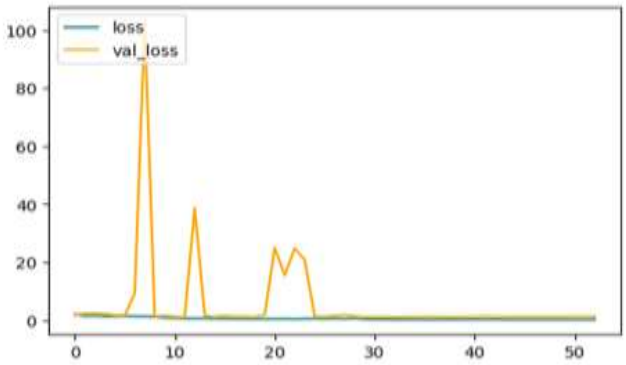

Fig. 11 The Loss Rate of ResNet-50 from 0-53 Epochs.

Based on Figure 11 and Figure 12, the lowest loss rate is 0.14 achieved after 53 epochs during training while the lowest for the validation was achieved after 33 epochs.

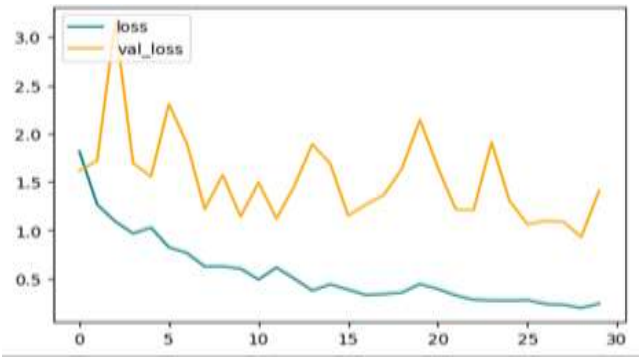

Fig 12 The Loss Rate of ResNet-50 from 0-33 epochs.

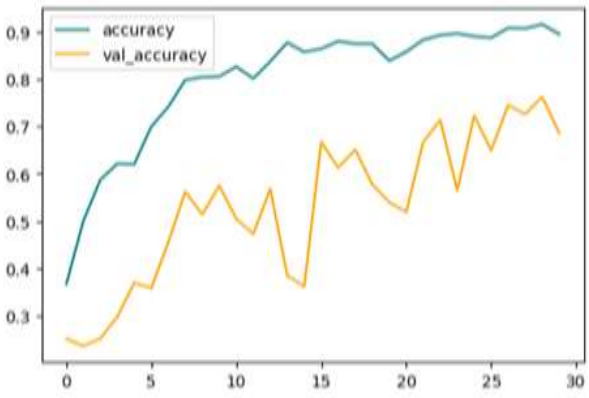

Fig13. The Accuracy Rate of ResNet-50 from 0-53 Epochs.

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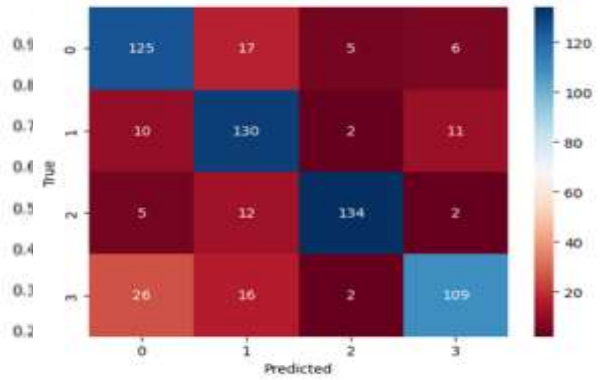

Fig. 14. The Accuracy Rate of ResNet-50 from 0-33 Epochs.

Based on Figure 13 and Figure 14, the accuracy increased gradually after the 7 epochs of training with the highest peak value of 0.92 while the validation rate steadily goes up as the validation cycle goes on to 53 epochs with value of around 0.78.

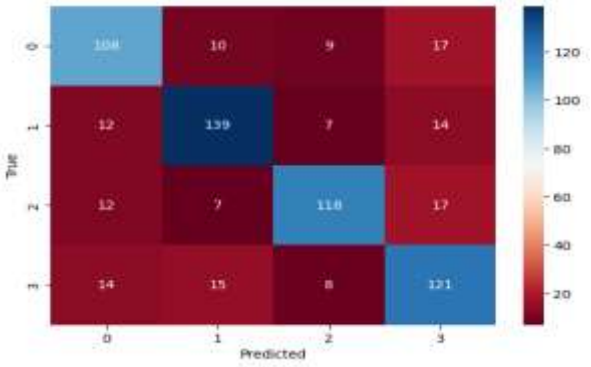

Fig. 15 The Confusion Matrix of ResNet-50.

Based on Figure 15, it can be seen that the number of true positive according to the classes are 108, 139, 118 and 121 respectively, given a total overall accuracy of 486 out of 628 images.

D. VITs

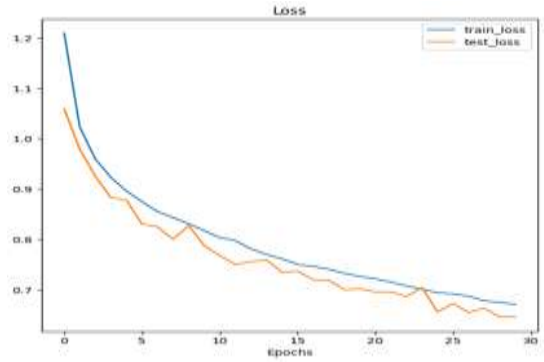

Fig. 16 The Loss Rate of ViTs.

Based on Figure 16, the loss rate during training gradually decreased as the number of epochs increased reaching the highest value of around 0.71 compared to the loss rate on the test set, but it goes to around 0.75.

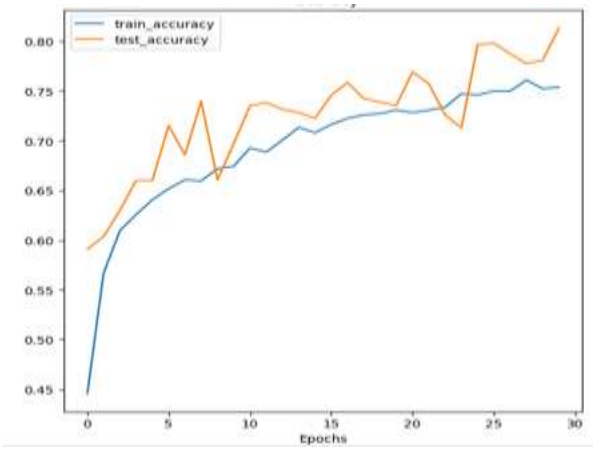

Fig 17. The Accuracy Rate of ViTs.

Based on Figure 17, the training accuracy increased effectively as the number of epochs increasedto the highest value of around 0.75. Meanwhile, the test accuracy starts from 0.59 at zero epoch, and increases around 0.82 at 30 epochs.

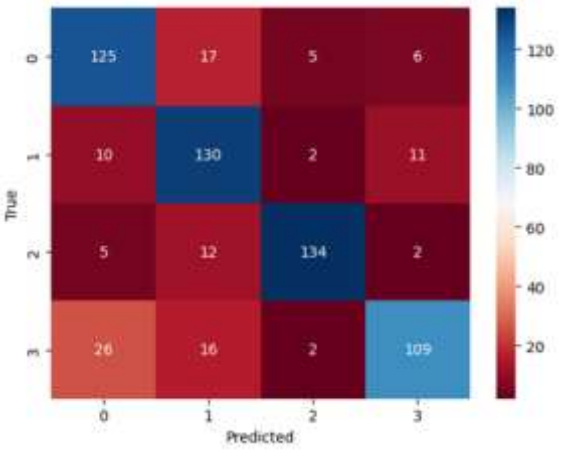

Fig. 18 The Confusion Matrix of ViTs

Based on the confusion matrix in Figure 18, the true positives based on the respective classes are 125, 130, 134 and 109. The total of true positives is 498 out of 612 images. The Scratch has the highest true positive of 134.

V. DISCUSSION

Detection of errors is significantly important because they concern sensitive information in terms of health and privacy of the patients. To produce a panoramic cardiograph with constant image quality common errors must be kept to a

minimum [22]. Common errors, generally include cone cuts, scratch, elongated or deformed, and tilted radiographs. Errors in quality assurance can lead to incorrect diagnoses and inappropriate treatments which can have life-changing impacts on patients. To reduce the possibility of mistakes, it's critical to ensure that the X-ray machine is precisely oriented and that the film or image receptor is well positioned. Even though with time, technology will eventually be able to replace human labor in managing the quality of X-ray images, better quality radiographs may be captured by dental professionals and students with the help of early hardware or software inspection.

This study compared CNN, ResNet-50, AlexNet, and ViTs in terms of how well they could classify radiograph mistakes. This is due to the fact that, based on their abilities, three of the four models that were selected for training produced some encouraging outcomes. Only one model, however, performed poorly when analyzing the images. But because these models rely on specific features and architectural elements, they have unique characteristics when it comes to analyzing X-ray images.

We may infer from the graphs that each model's results are influenced by the specific architectural flow. When using ViTs, the method matched well to keep the train and test cycle close. Assessing the distance between the train and test model for these CNN models shows poor performance was due to models having trouble balancing the training and test accuracy distance. However, ViTs are models that require certain hardware requirements to analyze larger datasets; in other words, they are high-speculation models intended for use with large datasets. Concentious care is needed to incorporate the X-ray images according to their design using the appropriate hyperparameters and data split to optimize the image quality.

Future research can build upon these models to make them even better. The architecture's layers are highly effective in maximizing image accuracy throughout the experiment. It should be noted that the more hidden layers generated, the higher the trainable parameters must be, and the higher the hardware specifications to achieve the requirements. Additionally, a balanced dataset might be a crucial component in incorporating precision to diagnose any class discrepancies between them. Equally, experimenting with splitting data is advised to reduce overfitting or underfitting. In addition, the number of training cycles may additionally have an impact in tracking the peak accuracy of the fitting models.

VI. Conclusion

Radiograph processing is still a laborious procedure. It is essential to create quality assurance solutions that increase practitioners' productivity as well as safeguard patients from false positives and false negatives. In response to this problem, this research proposed various models to detect inaccuracies in bitewing radiographs, experimenting with each model's performance to achieve the best possible performance in terms of accuracy and loss rate. Even though more work is needed to ensure that the CNNs or ViTs were completely satisfactory, the findings could constitute a major advancement in the field. The capabilities of dental specialists may be improved by further development of CNNs and the ViTs paradigm. ViTs-enabled software may be employed due to its flexible training, despite its higher cost. This study demonstrates the value of artificial intelligence and machine learning can potentially provide in medical imaging quality assurance processes.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Implementation of Fuzzy Tsukamoto on Node MCU ESP8266 to optimize monitoring of water flow in pipes

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Abstract— The issue of excessive and uncontrolled artesian water consumption has become a critical concern that requires immediate attention. The lack of real-time monitoring mechanisms often leads to significant water wastage, particularly in urban areas where demand is high. Recent data on artesian water usage indicate a 20% increase in consumption in 2023 compared to the previous year, with approximately 25% of the total distributed water being wasted. To address this issue, an Internet of Things (IoT)-based monitoring system for well water consumption has been developed, integrating the Tsukamoto fuzzy logic method. This system employs a NodeMCU ESP8266 microcontroller to collect water consumption data from a flow sensor. The data is then processed using the Tsukamoto fuzzy logic method to classify water usage into three categories: efficient, normal, and excessive. The categorized water usage information is displayed on a 16x2 LCD and a mobile application, enabling users to monitor their water consumption patterns in real-time.By providing continuous monitoring and intelligent classification of water usage, this system aims to enhance user awareness of sustainable water consumption practices. The results of this study demonstrate that the application of fuzzy logic in the monitoring model enables accurate and adaptive water consumption predictions, which can be adjusted based on environmental conditions. The fuzzy logic values obtained in this study are low flow (0.0), normal flow (0.5), and high flow (0.0). This system is expected to contribute to reducing the risk of excessive water consumption, promoting more efficient resource management, and fostering a culture of conservation among users.

Keywords— Internet of Things (IoT), NodeMCU ESP8266, Tsukamoto Fuzzy Logic, Artesian Monitoring.

I. INTRODUCTION

The Internet of Things (IoT) is one of the most significant and revolutionary technological innovations in the current digital era[1]. The IoT concept refers to a network of physical devices connected to the internet and able to communicate with each other, collect and exchange data, and interact with their surrounding environment[2]. In current IoT packet data capture, a new model exists, namely using the scalable traffic capture concept. With this model, packet capture can be done simultaneously, not only on one interface but together with just one command[3]. Attack detection in the IoT currently uses machine learning, meaning that the attack model already uses artificial intelligence so that the detection accuracy of the attack is better than before[4] [5].

Water is a vital resource essential for living things. Thus, as the population increases, so does the need for water that must be met. No human does not need water[6]. The role of water is crucial, such as for daily needs, transportation, and as an energy source for hydropower plants[7]. The inability to monitor water usage in real-time often results in significant waste, especially in urban areas[8].

Water meters are very commonly found in each of their customer's homes, whether in residential, office or industrial environments, which act as a counter for the amount of water used by customers each month[9]. In general, water meters are installed in each house that subscribes to artesian as a water provider that meets the water needs of the population[10].

The main problem faced in artesian water management is the lack of real-time information regarding community water consumption patterns. This causes difficulties in predicting water demand, identifying leaks, and optimizing water distribution efficiently [11]. In addition, awareness of wise water use also still needs to be improved among users.

The use of the IoT in water monitoring systems provides significant benefits because it can connect sensors installed in the water distribution network with a data management system directly. This allows for monitoring and controlling water consumption in real-time and provides accurate information to artesian for better decision making.

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The fuzzy logic method, especially fuzzy Tsukamoto, was chosen because of its ability to handle uncertainty and complexity in water usage data. Fuzzy Tsukamoto can integrate various input variable factors such as the number of residents, weather, and time in a flexible and interpretable way. This method is also capable of providing more intuitive and easily understood recommendations or decisions by users and artesian managers. By combining IoT technology and fuzzy logic methods in an artesian water usage monitoring tool, it is hoped that it can improve water management efficiency, reduce waste, and raise public awareness of the importance of sustainable water use. Previous studies have primarily focused on the automation of monitoring artesian water usage using microcontrollers and WaterFlow sensors, categorizing water consumption into two levels: low and high. However, this study aims to enhance the monitoring system by implementing the Tsukamoto Fuzzy Logic Method, which classifies water flow into three distinct categories: low, medium, and high. This approach enables a more precise and detailed analysis of water usage, improving the overall accuracy and efficiency of the monitoring system.

II. Related Work

Fuzzy logic, particularly the Tsukamoto method, has been widely implemented in various monitoring and control systems, including water management. In [12], a real-time water quality monitoring system was developed using the Tsukamoto fuzzy algorithm integrated into an Internet of Things (IoT)-based framework. This system enhances decision-making by categorizing water quality levels, providing timely and accurate data for users. Similarly, in [13], [14], an IoT-based system was designed using the Fuzzy Tsukamoto method to monitor drinking water quality, incorporating turbidity sensors and cloud-based data storage for real-time assessment. In the agricultural sector, a smart farming system utilizing Tsukamoto Fuzzy Logic was proposed in [15], [16], where input parameters such as pH, humidity, air temperature, and soil temperature were used to automate irrigation decisions. This approach demonstrated efficiency in optimizing water usage. Additionally, in [17], a water monitoring device was developed to determine the feasibility of water using pH and turbidity sensors processed through an Arduino-based Tsukamoto fuzzy model, leading to better water management. Further applications of Tsukamoto fuzzy logic include energy-efficient water distribution, as seen in [18], where a fuzzy-based control system managed water flow rates to reduce waste and optimize consumption. Another study [19] implemented fuzzy logic in water purification systems, demonstrating improved filtration efficiency by adjusting treatment parameters dynamically. The integration of fuzzy logic in smart cities was also explored in [20], where a water resource management system utilized fuzzy decision-making for sustainable urban water distribution. Moreover, Tsukamoto fuzzy logic has been applied in industrial water monitoring, as detailed in [21], where a system controlled chemical dosing in water treatment plants, optimizing resource utilization. In [22], an automated leakage detection system used fuzzy logic to identify anomalies in water pipelines, reducing water loss. Lastly, a hybrid fuzzy-PID approach was introduced in [23] to regulate water pressure in distribution networks, achieving stable and efficient operation. These studies highlight the flexibility and effectiveness of the Tsukamoto fuzzy logic method in diverse water management applications. The integration with IoT and smart control systems further enhances real-time monitoring and decision-making capabilities, making it a promising solution for optimizing water usage.

III. RESEARCH METHODOLOGY

A circuit block diagram is an important component in designing electronic equipment because it allows one to understand the overall working principle of the electronic circuit being created. This allows the entire tool block to be created to form a system that can be used or a system that runs according to design.

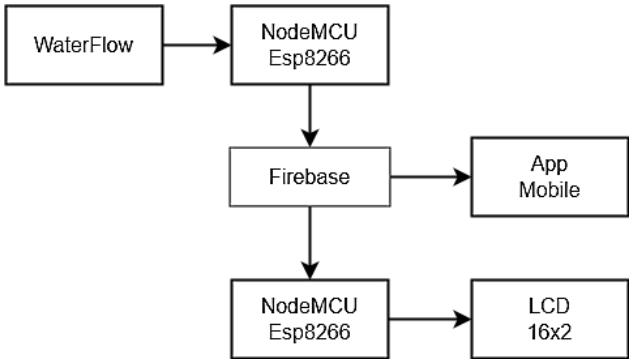

Fig. 1 Circuit Block Diagram

The WaterFlow sensor measures the water flow rate in customer pipelines. It comprises a plastic valve body, a water rotor, and a Hall-effect sensor. As water flows through the rotor, it spins at a speed proportional to the water flow. The Hall-effect sensor detects pulse signals from the rotor, which are then processed by a microcontroller. The NodeMCU ESP8266 functions as the central processing unit, executing pre-programmed instructions, controlling devices, and collecting sensor data. The collected data is processed using fuzzy logic for more accurate readings. To ensure real-time accessibility, Firebase is employed as a cloud-based database, allowing mobile and web

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applications to retrieve sensor data remotely. In the prototype development, two NodeMCU ESP8266 units are utilized to enhance the sensitivity of sensor readings. A 16x2 LCD is incorporated to display essential information such as water flow rate, cost, and total water volume. Additionally, a mobile application visualizes real-time data, including water speed, total volume, and billing information, enabling remote monitoring and management.

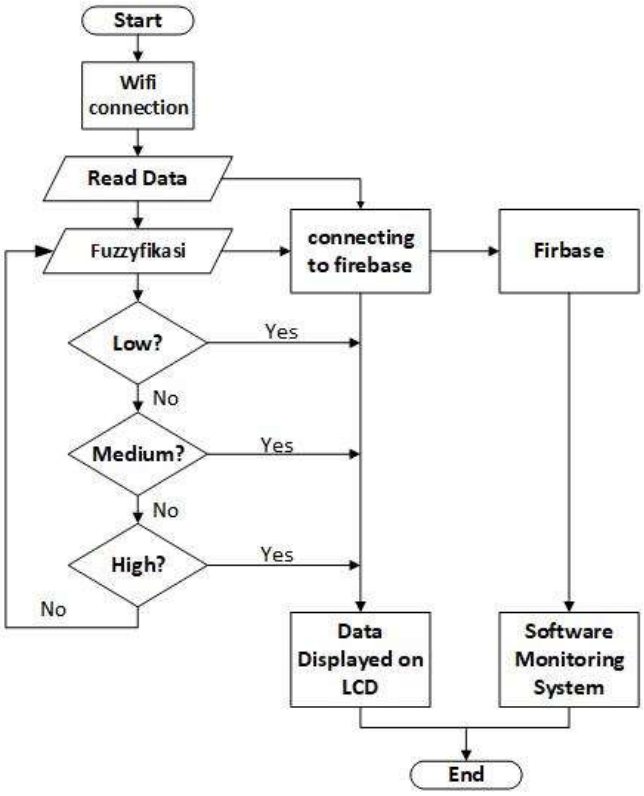

Fig. 2 Flow chart of the system work process

Figure 2 illustrates the working process connecting the device to a power source. Once the device is turned on, it connects to the internet via Wi-Fi. After establishing an internet connection, the sensor operates to collect data. The water flow sensor then measures the water discharge flowing through the artesian pipe. The discharge data is transmitted to the NodeMCU ESP8266, which processes it using the Tsukamoto fuzzy logic method to classify water usage into three categories: low, medium, and high. The water consumption data (including discharge and usage category) is displayed on a 16x2 LCD. Additionally, the data is sent to the Firebase Realtime Database. A mobile application retrieves the water consumption data from the Firebase Realtime Database and displays realtime water consumption and usage categories.

Figure 3 presents the circuit schematic designed for data display. This circuit consists of several key components, including the NodeMCU ESP8266, which functions as a microcontroller and a receiver for data from Firebase, subsequently transmitting it to the LCD. The baseboard plays a crucial role in facilitating the connection and control of electronic components. Additionally, it serves as a power extender since the NodeMCU provides only 3V, which is insufficient for specific components. To ensure stable operation, the baseboard requires an additional 12V adapter. Within this schematic, the LCD functions as an output device that displays the data retrieved from Firebase and transmitted by the NodeMCU. The integration of these components ensures efficient data processing and realtime visualization.

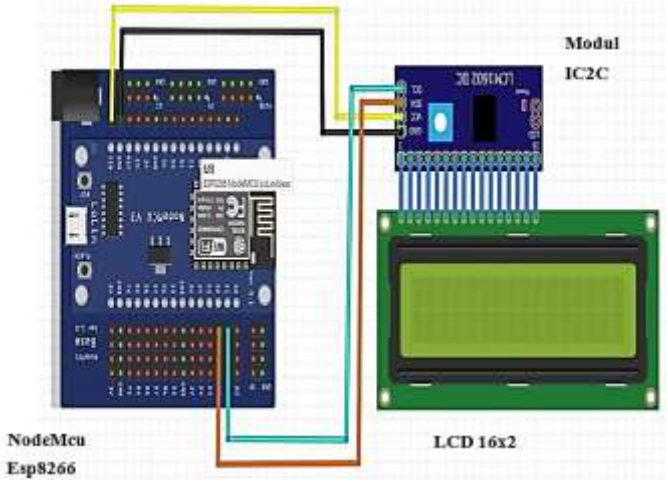

Fig. 3 Circuit Schematic Displaying Data

IV. FUZZY TSUKAMOTO IMPLEMENTATION ON ESP8266

Fuzzy logic is a computational approach that mimics human reasoning by handling uncertainty and imprecise data, making it suitable for various control applications. Implementing fuzzy logic on the ESP8266 microcontroller enhances decision-making processes in embedded systems, particularly when dealing with dynamic sensor data. The Tsukamoto fuzzy inference method is commonly used in embedded systems because it provides a crisp output by applying monotonic membership functions. This method consists of three main stages: fuzzification, rule evaluation, and defuzzification.[24], [25]. In the fuzzification stage, input variables—such as sensor readings—are converted into fuzzy sets based on predefined membership functions. The rule evaluation stage applies if-then rules to determine intermediate fuzzy values. Finally, the defuzzification stage converts these fuzzy values into a numerical output, allowing the ESP8266 to make precise control decisions. Integrating fuzzy logic into the ESP8266 is widely utilized in IoT applications, including water consumption monitoring, environmental sensing, and automated control systems[26]. The microcontroller processes sensor data, applies fuzzy

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logic rules, and classifies outputs such as "low," "medium," and "high." This classification enables real-time decision-making, enhancing the efficiency and adaptability of IoT systems. By leveraging fuzzy logic, the ESP8266 can effectively manage complex decision-making processes with limited computational resources, making it a powerful solution for intelligent embedded systems.

Fuzzy Tsukamoto is a fuzzy inference system that uses a monotonic membership function for the output. The output of each rule is a crisp value, which is calculated based on the α-predicate of the rule. The final output of the system is the weighted average of the crisp outputs of all the rules. Fuzzy Tsukamoto is similar to fuzzy Sugeno in that it uses a crisp value for the output of each rule. However, fuzzy Sugeno uses a constant or linear function to determine the crisp output, while fuzzy Tsukamoto uses a monotonic membership function. Fuzzy Tsukamoto is also different from fuzzy Mamdani, which uses a fuzzy set for the output of each rule. Fuzzy Mamdani then uses a defuzzification method to convert the fuzzy set into a crisp value. Figure 3 is a table summarizing the differences between the three fuzzy inference systems:

TABLE I
DIFFERENCES BETWEEN FUZZY METHODS

Feature	Fuzzy Tsukamoto	Fuzzy Sugeno	Fuzzy Mamdani
Output of each rule	Crisp value	Crisp value	Fuzzy set
Calculation of crisp output	Monotonic membership function	Constant or linear function	Defuzzification method
Final output	Weighted average of crisp outputs	Weighted average of crisp outputs	Crisp value after defuzzification

The Tsukamoto Fuzzy Method is widely applied in various domains, including temperature control systems, prediction models, decision-making processes, and other complex systems. Its effectiveness lies in its ability to handle uncertainty and complexity, making it a suitable approach for systems requiring adaptive and intelligent decision-making. The Tsukamoto fuzzy method follows a structured mathematical formulation, which is expressed as follows:

a. *Low* (Low): Low value.
b. *Medium* (Normal) : Normal value.
c. *High* (High) : High value.

V. RESULT AND EVALUATION

The tool's implementation is a phase conducted after the system analysis and design stages. This phase focuses on the system's hardware and software. The hardware consists of several modules and fundamental electronic components, while the software involves using Arduino IDE as the programming editor and Firebase as the database management tool. Figure 4 shows the finished circuit created to monitor artesian water usage using the Internet of Things (IoT).

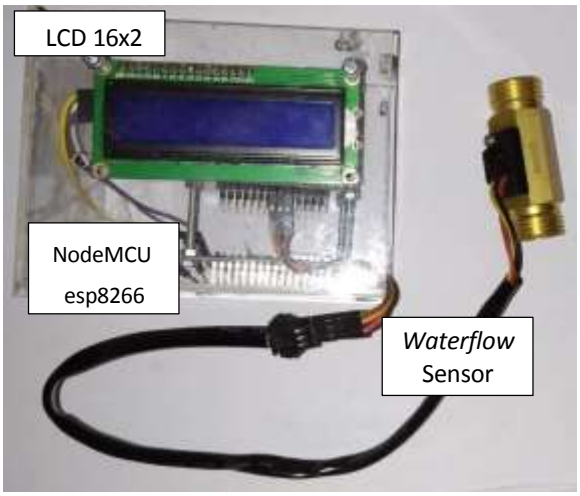

Fig. 4 Finished Circuit

Figure 5 illustrates the use of Firebase Realtime Database for storing water usage data obtained from sensors. The data is collected in realtime from water sensors and transmitted to Firebase. The Tsukamoto Fuzzy Logic algorithm processes this data to classify water usage patterns. Implementing the Tsukamoto Fuzzy Logic method in the water usage monitoring model, utilizing Firebase Realtime Database, enables efficient data collection, storage, and analysis. Firebase provides a robust platform for realtime data management, which is crucial for monitoring and control applications that require rapid and accurate responses. The collected data facilitates realtime water usage monitoring and offers valuable insights for future analysis and decision-making.

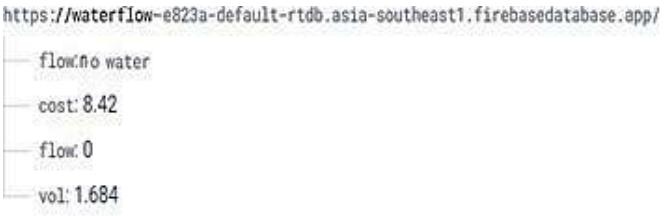

Fig. 5 Firebase Database View

An IoT-based monitoring system for artesian water usage has been developed to measure water flow within pipes and deliver realtime data on flow speed, volume, and billing via a dedicated application. The system employs a Waterflow sensor and a NodeMCU ESP8266 microcontroller to achieve this functionality. The microcontroller processes the acquired data and transmits it to a Firebase database, ensuring seamless integration and realtime updates within the application interface. This design facilitates efficient water usage monitoring while maintaining precision and accessibility of information. Upon establishing a connection with Firebase, the NodeMCU retrieves input from the

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Waterflow sensor and digital pins to calculate flow speed and volume. These parameters are critical for accurate measurement and are summarized in Table 2. By leveraging IoT technology, the system ensures cohesive data flow between hardware and software components, enhancing reliability and user experience. This structured approach underscores the system's ability to effectively provide actionable insights into water consumption patterns.

TABLE II
SENSOR READING SCRIPT EXPLANATION

Information	Script
Digital water flow pin	const int flowSensorPin = D5;

Flow Rate Data liters per minute	float flowRate = 0.0; // Flow rate in liters per minute
	float vol = 0.0, l_minute;

Data *Flow* Volume	unsigned long lastMillis = 0; unsigned long currentMillis; int currentDay = 0; float price = 5.0 ; float totalcost = 0.0 ;

Flow sensor *delay*	int botRequestDelay = 1000; unsigned long lastTimeBotRan; unsigned long previousMillis = 0;
	// Variables for flow rate calculation
	unsigned long lastFlowRateCalcMillis = 0;
	const unsigned long flowRateCalcInterval = 1000; // 1 second

The water flow monitoring system in Table 2 employs several key variables and constants to facilitate accurate data acquisition, flow rate computation, and cost estimation. The digital flow sensor is interfaced through the constant flowSensorPin, which is configured to the microcontroller's digital pin D5. This pin captures pulse signals emitted by the flow sensor, each corresponding to a specific volume of water. To compute and store the instantaneous flow rate and the total accumulated water volume, the variables flowRate, vol, and l_minute are initialised. These allow the system to represent real-time data in litres per minute and integrate flow measurements over time.

Temporal tracking is managed through the variables lastMillis, currentMillis, and currentDay. These parameters are crucial for determining elapsed time, segmenting data daily, and managing measurement intervals. The cost estimation mechanism is implemented using the variable price, set to a predefined value (e.g., 5.0 currency units per litre), and total cost, which accumulates the monetary cost based on the total volume of water used. To prevent excessive processing and allow scheduled external communications, the system utilises timing control variables such as botRequestDelay, lastTimeBotRan, and previousMillis. These parameters define the delay interval between data handling or transmission tasks and keep track of the last execution times of related processes.

Additionally, accurate flow rate calculations are governed by lastFlowRateCalcMillis and flowRateCalcInterval, where the latter is fixed at a 1000-millisecond interval (equivalent to one second). This fixed sampling rate ensures consistent temporal resolution for calculating the flow rate using the pulses counted from the flow sensor. Overall, these variables form the core computational structure for a real-time water flow monitoring system suitable for Internet of Things (IoT)-based environmental monitoring applications. Such a design is consistent with best practices in embedded system development and has been applied in related studies focusing on resource management and automated fluid control systems.

The prototype tool testing for this Final Project employs the Tsukamoto Fuzzy Logic method. In the Artesian Water Usage Monitoring system, there are membership functions that are detailed in the following table: This approach ensures a systematic and structured analysis of water usage patterns by leveraging fuzzy logic principles. The membership functions serve as a critical component in translating input variables into meaningful outputs, thereby facilitating accurate monitoring and decision-making within the system. The subsequent table provides an overview of these memberships, which are integral to the functioning of the Tsukamoto Fuzzy Logic framework.

TABLE III
FUZZY INPUT VARIABLES

Category	Range
Low water flow	0-10
Medium water flow	>10-<20
High water flow	>20-<60

In Table 3, the fuzzy variable data shows that when the Waterflow sensor generates a value, it is categorized into three variables: low, medium, and high. After determining the membership values, the next step is to carry out fuzzy calculations. To perform fuzzification based on the fuzzy set above (low, medium, high) with the following boundaries:

1. Low : 0-10
2. Medium : 10-20
3. High : 20-60 Variable

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In the Tsukamoto fuzzy model, the membership functions for each fuzzy set are defined based on predetermined boundaries. Given the specified ranges:

1. Low : 0 < X < 10
2. Medium : 10 < X < 20
3. High : X>20 to X < 60

In the Tsukamoto fuzzy inference system, membership functions define the degree of belonging of a crisp input X to specific fuzzy sets based on predetermined boundaries. The classification consists of three fuzzy sets: Low, Medium, and High, each representing a distinct range of values. The Low fuzzy set covers values from 0 to 10. Within this range, X has full membership (μ=1) when it is at the lower bound and gradually decreases as X approaches the upper limit. Beyond 10, the membership value becomes zero. The Medium fuzzy set applies to values greater than 10 but less than 20. The membership degree increases linearly from zero at 10 to full membership at the midpoint and then decreases symmetrically as X approaches 20. This ensures a smooth transition between the Low and High categories. The High fuzzy set represents values greater than 20 up to 60. Membership starts increasing from zero at 20, reaching its peak as X approaches the upper limit.

For a given input X=15, the membership functions are calculated as follows:

- **Low Set Membership** ($\mu_{low}(X)$), Since X=15 falls outside the range of the "low" fuzzy set ($0 \le X \le 100$), the membership degree is $\mu_{low}(X)=0$.
- **Medium Set Membership** ($\mu_{medium}(X)$), The "medium" fuzzy set is defined between 10 and 20, with a linear transition. The membership function for increasing values is given by: $\mu_{\text{medium}}(X) = \frac{20 - X}{20 - 10}$

  Substituting X=15:

$$\mu_{\text{medium}}(15) = \frac{20 - 15}{10} = \frac{5}{10} = 0.5$$

- **High Set Membership** ($\mu_{high}(X)$), Since X=15 is below the lower boundary of the "high" fuzzy set (X>20), the membership degree is $\mu_{High}(X)=0$.

Thus, for X=15, the corresponding fuzzification results are:

$$\mu_{\text{low}}(15) = 0$$

$$\mu_{\text{medium}}(15) - 0.5$$

$$\mu_{\text{high}}(15) = 0$$

In the Tsukamoto fuzzy inference system, the output value (Y) is determined using the weighted average defuzzification method. Given the predefined fuzzy sets for input (X), the membership degrees for X=15 were calculated as follows: $\mu_{low}=0$, $\mu_{medium}=0.5$ and $\mu_{high}=0$. These membership values indicate that X=15 belongs partially to the "medium" fuzzy set with a degree of 0.5, while it does not belong to the "low" or "high" fuzzy sets. To determine the crisp output (Y), it is assumed that the corresponding output values are Y=10 for "low," Y=30 for "medium," and Y60 for "high."

Applying the inference rules:

1. Rule 1: IF X is Low, THEN Y is Low (Y=10) → Not active since $\mu_{low}=0$.
2. Rule 2: IF X is Medium, THEN Y is Medium (Y=30) → Active with $\mu_{medium}=0.5$.
3. Rule 3: IF X is High, THEN Y is High (Y=60) → Not active since $\mu_{high}=0$.

The defuzzification process is performed using the formula:

$$Y = \frac{\sum(\mu_i \times y_i)}{\sum \mu_i} \quad (1)$$

Substituting the given values:

$$Y = \frac{(0 \times 10) + (0.5 \times 30) + (0 \times 60)}{0 + 0.5 + 0} = \frac{15}{0.5} = 30$$

The graph represents the fuzzy sets in the Tsukamoto fuzzy inference system, categorized into three groups: Low (blue), Medium (green), and High (red). The dashed line indicates the position at X = 15, where the membership degree in the Medium fuzzy set is 0.5, while the membership degrees in the Low and High fuzzy sets are zero, as shown in Figure 6.

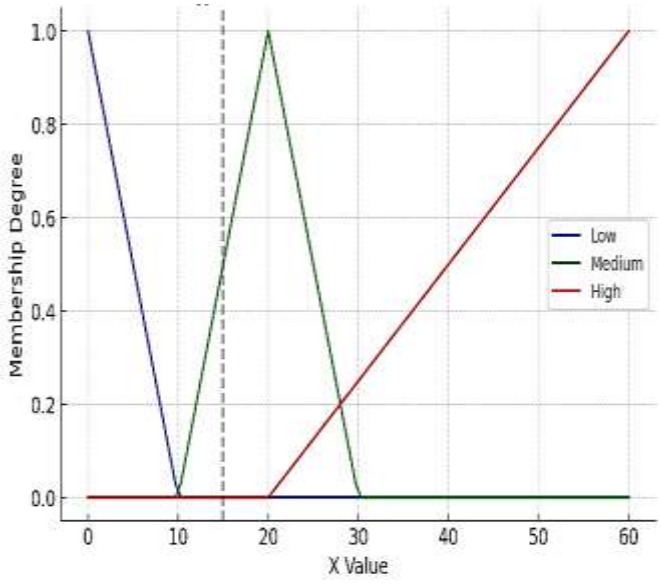

Fig. 6 Fuzzy Set

This testing is conducted to ensure that the device performs as expected. The evaluation includes testing the sensor data reading process and observing whether the device operates by the acquired sensor data. Table 4 presents the results of the sensor data reading test.

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TABLE IV
IOT MODEL TEST RESULTS

No	*Sensor output* (m^3)	Measuring cup method (m^3)	Difference
1	0.0004884	0.0005	0.0000116 m^3
2	0.0004876	0.0005	0.0000124 m^3
3	0.0004640	0.0005	0.0000360 m^3
4	0.0004976	0.0005	0.0000024 m^3
5	0.0004793	0.0005	0.0000207 m^3
Total difference = 0.0000831 m^3 (83.1ml)			

TABLE V
PRECISION TEST RESULTS

No	*output Values* sensor (m^3)	Values *actual* (ml)	$\|(xi - , x)2\|$
1.	0.0004884	0.0005	0,0058081
2.	0.0004876	0.0005	0,0040401
3.	0.0004640	0.0005	0,000979
4.	0.0004976	0.0005	0,000701
5.	0.0004793	0.0005	0,000214
Average 0.00048358 m^3			

$$SD = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \qquad (2)$$

Where SD is the standard deviation, $\boldsymbol{x}^-$ is the average value of the sensor measurement results, $\boldsymbol{xi}$ is the value of each measurement and n is the number of measurements performed. The results of the precision test can be seen in Table 5.

VI. Conclusions

This study proposes a monitoring system for artesian water usage supervised through a mobile application. The system employs the Tsukamoto fuzzy logic method to classify water usage levels based on data from sensors integrated into the mobile device. The findings indicate that the Internet of Things (IoT)-based Artesian Water Usage Monitoring System functions effectively. The Water Flow sensor operates as expected, ensuring accurate data collection. Communication between NodeMCU and Firebase is successfully established, and data transmission from Firebase to the mobile application functions correctly, allowing real-time data visualization within the application interface.

Furthermore, water usage levels—categorized as low, medium, and high—are classified based on preprocessed data using the fuzzy logic method. The device successfully measures water consumption with a minimal deviation, achieving an average difference of 0.00048358 m^3 between sensor output values and actual measurements. These results demonstrate the system's reliability in accurate monitoring and classifying water usage. Future research can apply this system to real artesian water pipes and test its level of accuracy.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Myfinancial Controller: A First Usability Review

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Abstract—MyFinancial Controller is a mobile application designed to transform the flow of personal finance management and savings in Malaysia. This app helps users to take control of their financial well-being by providing a thorough and user-centric approach to managing and growing personal finances by seamlessly integrating various financial tools and features into a single, intuitive platform. This app offers digital payment solutions, expense analysis, goal-oriented savings and focusing on financial education. MyFinancial Controller caters to diverse and evolving financial needs of users. Notably, MyFinancial Controller includes an advanced Scam Tracker function, which serves as a critical component of the app. This feature provides information about scams and fraudulent activities in the financial sphere, enhancing the security and trustworthiness of the platform. This app equips users with the tools they need to make secure and efficient digital payments, manage expenses, and track their spending. It fosters financial discipline by automating savings, enabling users to establish and customize savings goals, whether for emergencies, dream vacations, or debt management. Moreover, MyFinancial Controller places strong emphasis on financial literacy, providing resources such as articles, tutorials, and interactive tools that enhance users' financial understanding. By serving as a holistic, secure, and innovative personal finance management solution, MyFinancial Controller is at the forefront of reshaping how individuals manage and grow their finances in the dynamic financial landscape of Malaysia.

Keywords— MyFinancial Controller, Scam Tracker, Goal Saving, B40

I. Introduction

In today's digital age, personal finance management and savings have become increasingly rely on mobile applications. MyFinancial Controller is an innovative application developed to address the evolving financial needs of individuals in Malaysia. This report provides a comprehensive technical overview of the application, outlining its key features and functionalities, security measures, and the integration of a Scam Tracker function.

The primary objective of MyFinancial Controller is to help users by offering an all-in-one solution for managing their financial well-being. The application is designed to provide users with a secure, user-friendly platform for digital payments, goal-based savings, spending analysis, and scam tracker. By offering these features, the app aims to promote better financial discipline, enhance financial literacy, and safeguard users against potential scams and fraudulent activities.

MyFinancial Controller is a convenient application for user since it offers a seamless and user-friendly experience that encourages disciplined financial habits, enhances financial literacy, and safeguards against potential financial scams and fraud. As a transformative force in the digital financial ecosystem of Malaysia, this introduction sets the stage for a comprehensive exploration of the application, delving into its key features, security measures, and the broader significance it holds in the context of personal finance management and financial technology in Malaysia.

II. Related Work

A. Current Financial Trend

The management of finances and financial transactions by consumers has undergone a significant transformation due to technological advancements. In the current technological landscape, a variation of personal finance applications has emerged, offering consumers capabilities to pay bills, track budgets, handle cash flow, and save money . All of services in these personal finance apps grants users the flexibility to efficiently oversee their financial matters [1]. For instance, a savings app helps consumers to establish rules dictating when and how much they want to save. These rules can automate regular savings over specific periods, such as monthly or with each payday. Alternatively, users may set rules involving frequent small savings, like putting away RM5 after every gym session or rounding up each purchase to the nearest ringgit.

Security measures have also reached new heights, with biometric authentication such as fingerprint and facial recognition becoming integral to mobile banking apps. These advancements gives confidence in users by giving protections against unauthorized access and fraudulent activities [2]. Despite the widespread adoption of automation technology, often work as an effective means to facilitate savings, there exists limited empirical evidence on how automation impacts consumers' savings habits and overall financial well-being. Additionally, the comparative effectiveness of distinct saving rules remains an underexplored area.

B. Related Work

This report presents insights into the dynamic between automated saving rules and their impact on savings outcomes. The analysis focuses on consumers' utilization of various automated saving rules, namely guaranteed, contingent spending, and contingent nonfinancial rules, and their correlation with the saved amounts. Leveraging data from the Qapital mobile savings app, which empowers users to customize savings goals and rules, the study reveals that contingent spending rules, such as rounding up purchases and saving the rounded amount, are the most prevalent (81 percent usage) [3]. In contrast, guaranteed rules, supporting traditional strategies like saving on payday, are employed by 41 percent of users, while contingent nonfinancial rules are less common (2 percent) [3].

Despite their popularity, contingent spending rules are linked to lower savings accumulation compared to guaranteed saving rules. Guaranteed rules exhibit a 1.5 to 3.5 times larger increase in the maximum amount saved and the likelihood of achieving specific milestones (e.g., $500, $1,000) [3]. Although contingent spending rules are frequently triggered, the individual transaction amounts are small, resulting in comparatively lower savings than more traditional approaches.

The report also highlights the common of behaviour-based saving strategies across financial institutions and apps, linking saving to users' spending behaviour. While these strategies may help individuals initiate or complement existing saving practices by associating savings with routine behaviours, there is a lack of comprehensive understanding regarding their efficacy. The study refrains from establishing causal relationships between saving rules and saved amounts, emphasizing the need for further research, such as field experiments, to explore the causal effects of automation and behaviour-based strategies on consumers' financial behaviour.

In another study, the Budget Tracker application appears as a solution aimed at reducing the complexities individuals face in managing their personal finances. The author meticulously outlines the constraints come across during the development phase and proposes effective solutions to address these challenges. By creating a mobile application that streamlines expense tracking, income management, and payment records, the author attempts to eliminate the hassle of conventional methods such as sticky notes or spreadsheets [4]. Despite its current applicability limited to students and working individuals in its initial version, the application sets its sights on enhancing user experience and interface while collecting valuable expense data for analysis.

Drawing inspiration from existing budget-tracking applications, the Budget Tracker app aims to simplify financial management, though certain issues such as the absence of a PDF feature have been identified [4]. However, the application's resilient storage mechanism and planned future improvements signal a promising tool for effective expense tracking, providing users with adaptable report viewing options and a foundation for further enhancements in subsequent iterations. Sections addressing current limitations and proposing future enhancements illustrate the dedication to refining this application for enhanced user benefit and financial management efficiency.

Next, Expense tracker app is an application that will help its users to manage the cost of their daily expenditure. It will guide them and aware them about their daily expenses. It will prove to be helpful for the people who are frustrated with their daily budget management, irritated because of amount of expenses and wishes to manage money and to preserve the record of their daily cost which may be useful to change their way of spending money. In short, this application will help its users to overcome the wastage of money [5].

In conclusion, both reports shed light on distinct aspects of personal finance management. The study on automated saving rules from the Qapital app reveals the effectiveness of different strategies, highlighting the dominance of contingent spending rules but emphasizing the superior outcomes associated with guaranteed saving rules. Meanwhile, the Budget Tracker and Expense Tracker application offers a practical solution for simplifying expense tracking and financial management. Despite some limitations, such as the absence of a PDF feature, the app shows promise in streamlining personal finance management, offering adaptability in report viewing, and laying the groundwork for future enhancements. Together, these reports underscore the ongoing evolution of tools and strategies aimed at empowering individuals to better navigate their financial lives.

III. Methodology

Financial well-being is one of the most critical issues in financial management in society. A study indicates that those who practice positive financial habits tend to be extra relaxed with their financial well-being. The financial well-being of an individual can be improved through favourable financial behaviour, sound financial literacy and managing financial stress [6]. MyFinancial Controller platform offers transformative advantages customized specifically to benefit the B40 demographic, empowering them with enhanced financial management capabilities and opportunities for growth. This innovative tool presents a lot of benefits that align with the unique financial needs and challenges faced by the B40 segment, promoting financial literacy, stability, and upward mobility.

The platform promotes financial education and awareness among the B40 demographic. Through its various features, such as expense tracking, personalized saving goals, scam tracker, donation and scam news. This will educate users on wise financial practices. This educational aspect is crucial for empowering B40 individuals to make informed decisions, manage their resources effectively, and cultivate long-term financial flexibility [7].

Moreover, the MyFinancial Controller contributes to encourage a culture of savings within the B40 community. By offering customizable saving mechanisms and goal-setting features, it encourages disciplined savings habits. This is particularly impactful for a demographic often grappling with limited resources, as it empowers them to

set achievable financial targets and work towards them systematically.

In essence, the MyFinancial Controller stands as an essential tool tailored to address the specific financial needs of the B40 community. Through its accessibility, educational focus, emphasis on savings, and facilitation of financial transactions, it serves as a crucial instrument in empowering this demographic towards a more secure and prosperous financial future.

A. Proposed Financial Application

After reviewing and contrasting financial management systems in the previous section, an innovative financial controller, "MyFinancial Controller," is proposed. This controller combines advantageous functionalities from diverse financial systems, enhancing them to ensure maximum effectiveness in managing personal finances.

Initially, new users engage with the MyFinancial Controller platform by setting up an account within the application. The registration process necessitates the provision of an active mobile number and email for identity verification. A verification code is dispatched to the provided contact information to authenticate the user's identity. Once the account is established, users access the platform using their designated username and password.Within the app's interface, users navigate through various financial management features and tools tailored to their needs. They can monitor account balance, view goal-saving progress, and set up personalized financial goals. Additionally, the platform offers analysis into spending patterns and budget management. The application also has a scam tracker and scam news section to educate and bring awareness to users about scam and fraud activities.

The MyFinancial Controller contains established financial management methodologies while introducing innovative elements to enhance user experience and effectiveness. By analyzing user requirements and behaviors, the app aligns with diverse user preferences and needs, catering to a range of financial objectives and strategies.

Furthermore, the application meticulously identifies functional and non-functional requisites, ensuring optimal performance, security, and user accessibility. This comprehensive analysis informs the development of a robust and user-centric financial management solution, aligning with the evolving demands and expectations of modern users seeking efficient and secure financial control.

B. Identify User and Characteristic

Figure 1 shows the activity diagram for users' activity in MyFinancial Controller. First, users must register by signing up with an active mobile number and email address. Upon successful registration, they obtain a login ID comprising a username and password. With these credentials, users can access their accounts within the application. The user functionalities primarily include managing their financial activities, such as tracking expenses, setting financial goals, aware of scams, make donation and analyse their spendings. They have the freedom to execute various transactions like bill payments and fund transfers within the application.

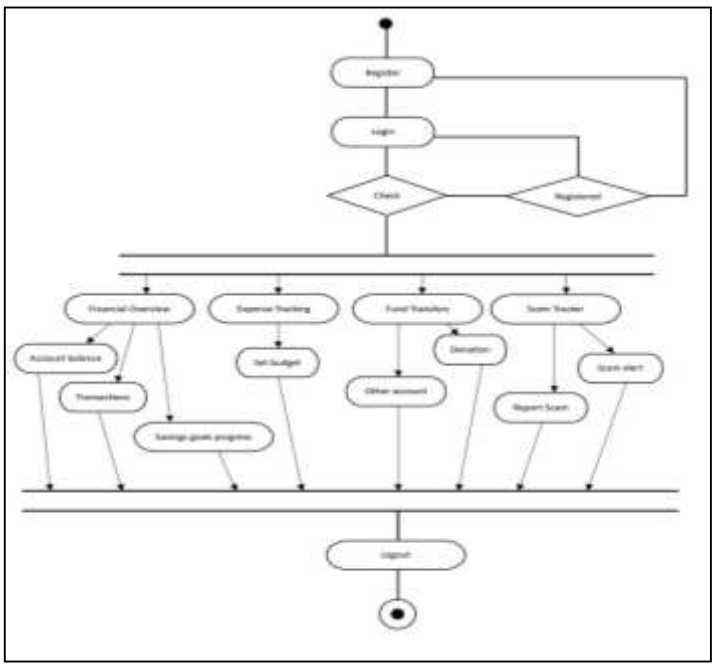

Fig. 1 Activity Diagram for Users' Activity in MyFinancial Controller

IV. DISCUSSION

The login page, shown in Fig. 2, is the first interface user interacts with after installing the application. It requires registered users to enter their email and password. The validity of the email and password need to be verified. This is important to prevent unauthorized individuals from accessing the system. Once the email and password are validated, users are redirected to the home page.

In the login page, new users are required to click on the "Sign Up" link to create an account. They are required to provide username, email, and password to have an account. The system requirements are discussed in the following subsections.

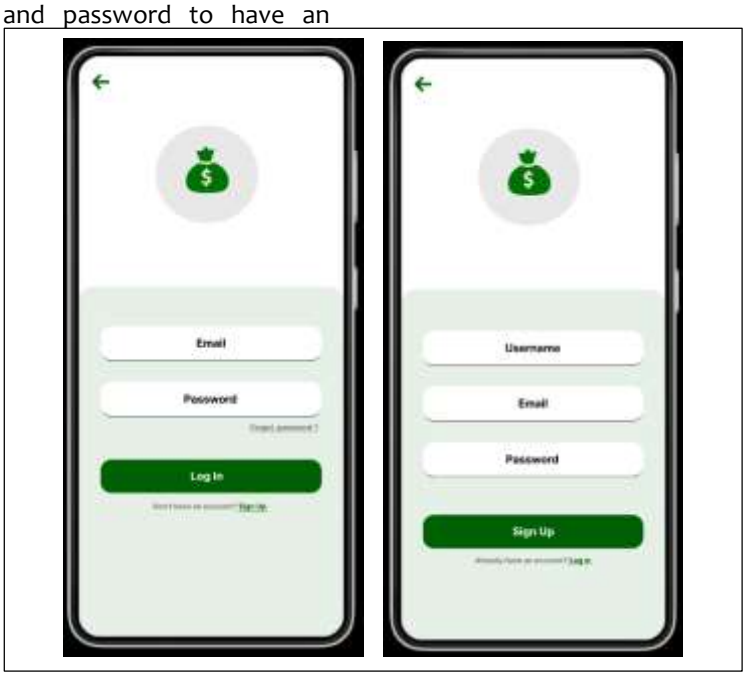

Fig. 2 Sign Up and Login Page

A. Functional Requirement

Fig. 3 shows the homepage and payment getaway of MyFinancial Controller. User can see their names, money balance, goal savings progress, scam news and various activity button such as pay, goal saving, donation, and scam tracker.

Fig. 3 Sign Up and Login Page

Myfinancial Controller enables users to set personalized savings goals. It allows for customization, letting users define specific objectives, whether it's saving for a vacation, a down payment, or an emergency fund. The system's flexibility permits users to allocate savings according to their preferences, fostering a sense of control over their financial aspirations.

One of Myfinancial Controller distinguishing features is its automated savings rules. These rules automate the

savings process by triggering actions based on predefined conditions [8]. For instance, users can opt for round-up rules where they can set how much they want to save in a specific duration and the difference is allocated towards savings as it shown in Fig. 4 below.

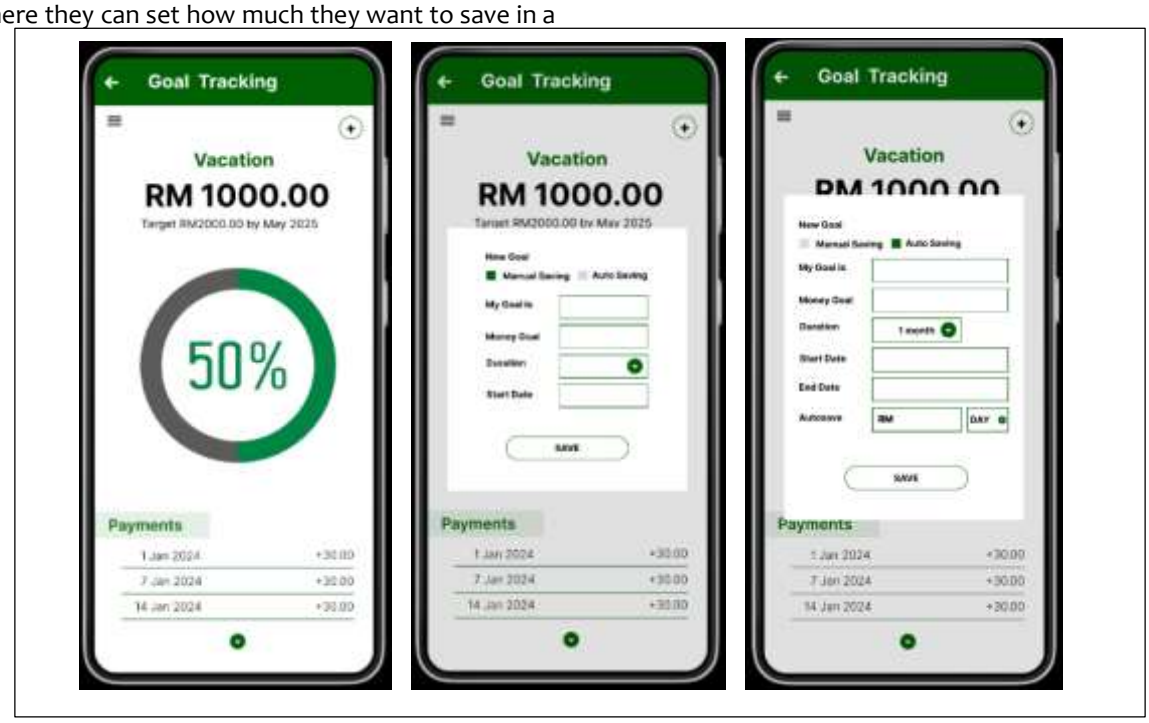

Fig. 4 Goal Tracking Page

Myfinancial Controller recognizes the significance of security and user trust. Therefore, in addition to its savings functionalities, the app integrates a robust scam tracker feature. This functionality serves as a security measure, allowing users to report suspicious activities or potential scams within the application.

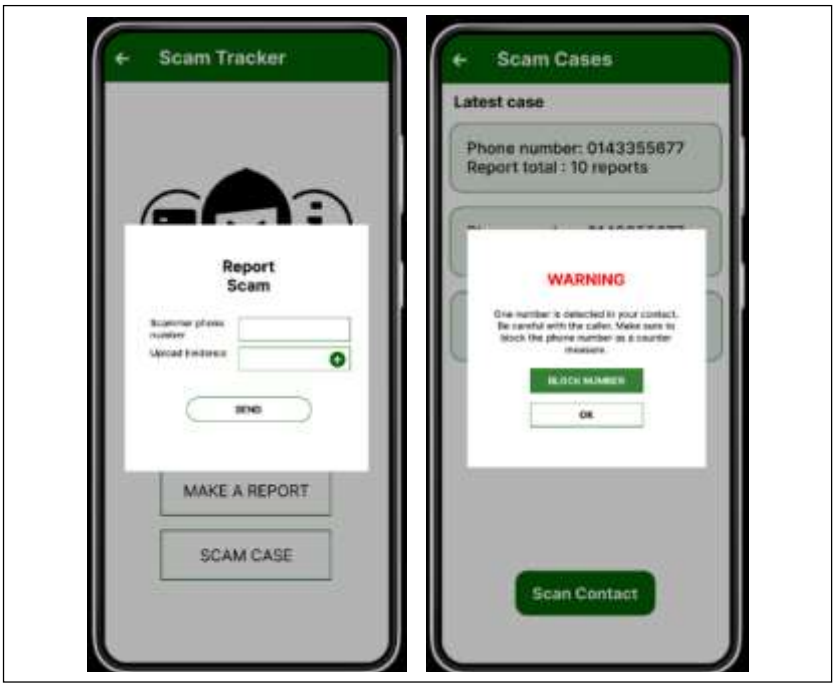

Fig. 5 Scam Tracker Page

Donation is also one of the main activities in MyFinancial Controller. Giving donation help people to strengthen their personal finance habits. This is because giving charity can prompt people to reflect on their finance habits. It may encourage them to have a better financial management and make a smarter spending choice.

Fig. 6 Scam Tracker Page

B. Non-Functional Requirements

Non-functional requirements encompass aspects beyond specific functionalities, focusing on how a system should perform. For MyFinancial Controller, a personal finance app, these requirements span various areas, ensuring its reliability, security, usability, and performance. Additionally, considering the Scam Tracker feature, specific non-functional requirements emphasize security, responsiveness, and user trust.

a) Reliability:

MyFinancial Controller must guarantee a high level of reliability to ensure users' trust and confidence in its functionality. This requirement includes system uptime, where the app should be always available and accessible for users, minimizing downtime or disruptions in service. This involves robust server infrastructure, redundancy measures, and efficient error handling to prevent crashes or data loss.

b) Security:

Security remains paramount for financial apps like MyFinancial Controller. Non-functional requirements demand stringent security measures encompassing data encryption, secure user authentication (e.g., multi-factor authentication), protection against unauthorized access, and adherence to regulatory standards like GDPR or financial industry compliance [9].

c) Usability and User Experience:

User-friendliness is crucial for MyFinancial Controller's success. Non-functional requirements focus on offering an intuitive interface, easy navigation, and responsive design across various devices and operating systems [10]. This includes clear instructions, minimalistic design principles, and personalized user experiences that adapt to individual financial goals.

d) Performance:

The app's performance must meet users' expectations, with fast response times and smooth functionality. Non-functional requirements encompass aspects such as load times, transaction processing speed, and efficient handling of large volumes of data. It also includes optimizing the app's performance across different network speeds and device capabilities.

e) Scam Tracker:

The Scam Tracker feature within MyFinancial Controller requires specific non-functional requirements due to its critical role in maintaining user trust and security. This includes real-time monitoring capabilities to swiftly identify and track potential scams or suspicious activities. The system should allow for immediate response, investigation, and resolution of reported scams while ensuring user data integrity and confidentiality [6].

In summary, these non-functional requirements define the overall performance, security, reliability, and user experience of MyFinancial Controller, ensuring it meets the high standards expected from a financial management application. The Scam Tracker feature adds an extra layer of security, demanding real-time responsiveness and robustness in identifying and mitigating potentially fraudulent activities to safeguard user finances and trust in the platform.

C. Usability Testing

Usability testing is carried out to test the user interfaces of the prototype. It is mainly to test the satisfaction of users and whether it obeys the design principles [11]. Generally, each of the module in the prototype is tested according to the usability of its interfaces involved. Thus, no program code or internal structure of the system are involved. The usability testing is carried out on 20 users using the interview method. These users are chosen among university students who a is in a B40 category. Each of the user is given a task in every module to achieve a goal. At the end of the test, they are required to provide feedback and

comments about the prototype. This feedback is essential to make improvements on the prototype to accommodate the needs of end users. The tasks and results for each module are summarized as follow.

TABLE 1
USABILITY AND USER EXPERIENCE EVALUATION

Module / User	*Module 1: Login*	*Module 2: Sign Up*	*Module 3: Homepage*	*Module 4: Pay*	*Module 5: Goal Tracking*	*Module 6: Scam Tracker*	*Module 7: Donation*
1	5	5	5	5	5	5	5
2	5	5	5	5	5	4	5
3	5	5	3	5	5	5	5
4	5	5	5	5	5	4	5
5	5	5	3	5	5	5	5
6	5	5	5	5	5	4	5
7	5	5	5	5	5	5	5
8	5	5	4	5	5	5	5
9	5	5	5	5	5	5	5
10	5	5	5	5	5	4	5
11	5	5	5	5	5	5	5
12	5	5	5	5	5	5	5
13	5	5	3	5	5	4	5
14	5	5	5	5	5	5	5
15	5	5	3	5	5	4	5
16	5	5	5	5	5	5	5
17	5	5	5	5	5	5	5
18	5	5	5	5	5	5	5
19	5	5	5	5	5	5	5
20	5	5	5	5	5	5	5

Table 1 shows five steps of achievement. Number 1 stands for not understand the given task, number 2 stands for unsuccessful in completing task, number 3 stands for takes a long time with high difficulty in completing task, number 4 stands for takes a short time with slight difficulty in completing task and number 5 stands for succeed without difficulty in completing task.

In Module 3 which is the Homepage, the user found it hard to find the reload button for the balance and the button for add money at goal saving tracking box. Fig. 7 shows the changes between before and after.

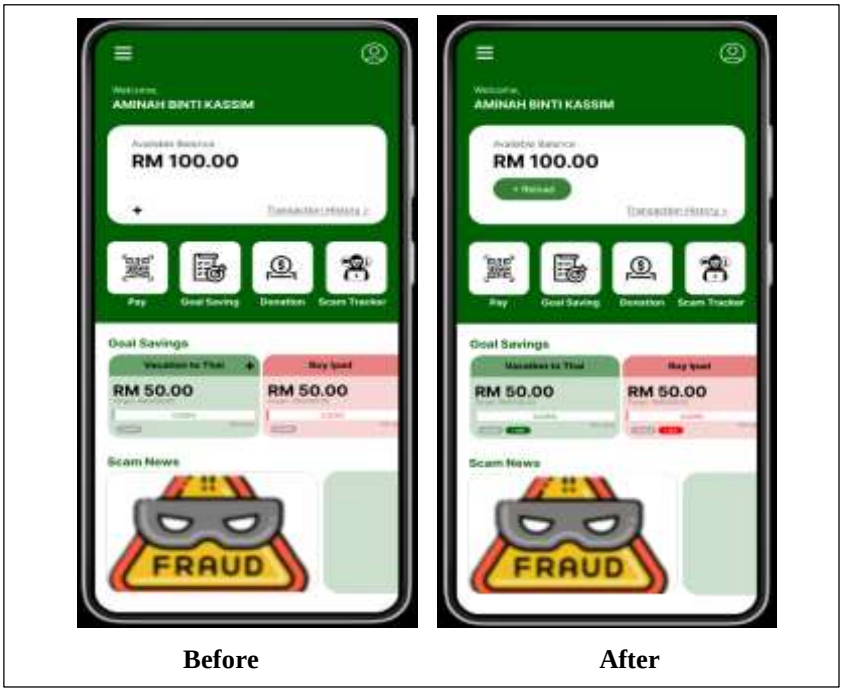

Fig. 7 Homepage Before and After

In Module 6, five users take a short time with slight difficulty in completing task because of inconsistency of button position. Fig. 8 shows the changes before and after of the Scam Tracker page.

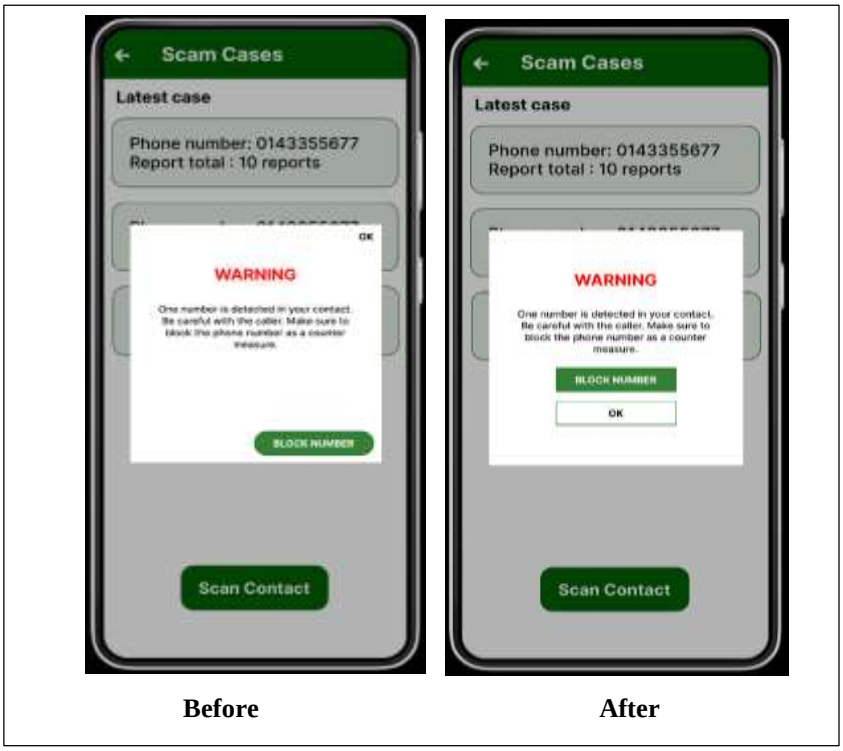

Fig. 8 Homepage Before and After

V. CONCLUSION

MyFinancial Controller, an innovative mobile savings app, can revolutionize how users manage their finances, offering a spectrum of automated saving rules that empower individuals to cultivate better saving habits. Its impact spans across various saving methodologies, including guaranteed, contingent spending, and contingent nonfinancial rules, providing users with a range of options to match their saving preferences. The analysis of MyFinancial Controller's data underscores the prevalence of contingent spending rules, particularly rounding up purchases, yet reveals their correlation with lower savings accumulation compared to traditional guaranteed saving rules. Despite their popularity, these rules often result in smaller individual transaction amounts, leading to comparatively diminished savings outcomes.

In parallel, the landscape of financial technology has integrated features like scam trackers into platforms like MyFinancial Controller. This addition serves as a protective shield, allowing users to identify and report suspicious financial activities, thereby fortifying the security and reliability of the application. The scam tracker acts as a safeguard, aligning with MyFinancial Controller's commitment to ensuring the financial safety of its users in an increasingly digitized world. When considering the implications for B40, MyFinancial Controller and its scam tracking feature hold immense potential. For individuals in this socioeconomic group, the ability to save and protect their finances is crucial. MyFinancial Controller's diverse saving rules provide flexibility, allowing B40 users to tailor their savings strategies based on their financial circumstances. Moreover, the inclusion of a scam tracker within the application assures a heightened level of security, vital for individuals who may be more susceptible to financial vulnerabilities.

The app's emphasis on user-friendly interfaces and personalized saving goals aligns well with the needs of the B40 demographic. The simplicity of the application's design coupled with its security features can empower users to build and protect their financial reserves more effectively. Additionally, by leveraging behavioral insights to nudge users towards better saving practices, MyFinancial Controller has the potential to bridge the gap in financial literacy often prevalent in underserved communities.

In conclusion, MyFinancial Controller's multifaceted approach to savings, reinforced by its scam tracker, offers a comprehensive solution for not only enhancing financial management but also ensuring security. For the B40 community, these features present an opportunity to cultivate healthier financial habits and shield against potential financial threats, ultimately contributing to improved financial well-being and resilience.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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Scalable and Sustainable Blockchain Architecture: Advancing Security, Efficiency, and Cross-Chain Interoperability

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Abstract— Blockchain technology has transformed data integrity and digital transactions across various industries. Achieving optimal scalability, transparency and security is still a challenge. Barriers exist such as high energy consumption, long transaction times, and interoperability problems like the Fork problem with the consensus of decentralized node versions on software upgrades[1]. This paper proposes a novel blockchain-based architecture using layer-2 scaling techniques, energy efficient decision methods and cross-chain protocols that solves these issues [2]. This approach decreases decentralized transaction carbon footprints, boosts blockchain performance, and helps interoperability. Detailed case studies of platforms like Ethereum and Polkadot are included to demonstrate how these challenges have been tackled in practice, with specific focus on scalability and interoperability solutions. Areas such as supply chain management and finance would benefit from the newer system's improved security and reliability. It was carried out in a multi-phase manner, first evaluating the current limitations of blockchain technology. Then, a hybrid agreement model combining energy-efficient techniques with data sharing and transaction merging process was created to develop a prototype. Cross platform compatibility and performance with different transaction loads were tested in a controlled environment. The project aims to provide scalable and sustainable architecture that would be a great contribution to the blockchain community. Ciavarella explains, "For example, it provides a proof of concept for future developments in blockchain which could result in safer, more flexible and efficiency solutions across all industries."

Keywords— Blockchain, energy, transcaction, sustainable, scalable, Fork, cross-chain protocol, prototype.

I. INTRODUCTION

The technology of blockchain has emerged as a disruptive player in digital infrastructure, far beyond its original implementation the field of cryptocurrency [3]. The fusion of artificial intelligence (AI) and blockchain is going to transform and have incredible impacts in several industries regarding operational efficiencies, improving integrity and generating innovative solutions. Along with certain limitations of traditional systems, the confluence of different technologies creates new pathways for innovation in an increasingly digital society.

However, blockchain's limit have grown significantly apparently as the number of useful blockchain-based projects rises[4]. The Fork problem in software upgrade is one of the major problems that has led to poor interoperability, limited scalability and high energy consumption in the current blockchain [5]. Figure 1 illustrates the Blockchain Trilemma, which highlights that blockchain systems cannot simultaneously achieve all three key properties: security, decentralization, and scalability. [6]. Blockchain technology began to have problems with scalability, transaction efficiency, storage, and security when the number of transactions processed in a blockchain network began to increase, resulting in longer transaction processing periods and higher operational costs [7].

Moreover, Block chain sustainability has been placed in the spotlight, as evidenced by proof-of-work (POW) consensus mechanism use, with increasing awareness of environmental health measures on climate change [8]. Significant challenges that must be solved in blockchain, are security and privacy issues regarding interoperability, the interaction of secondary blockchains, and interoperability between cross classes

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of blockchain Furthermore, the absence of standardized cross-chain communication protocols prevents the potential for interoperability between blockchains and applications [10].

future directions. Section IV presents several suggestions for improving it. Finally, section V opens new possibilities for blockchain optimization and broader adoption.

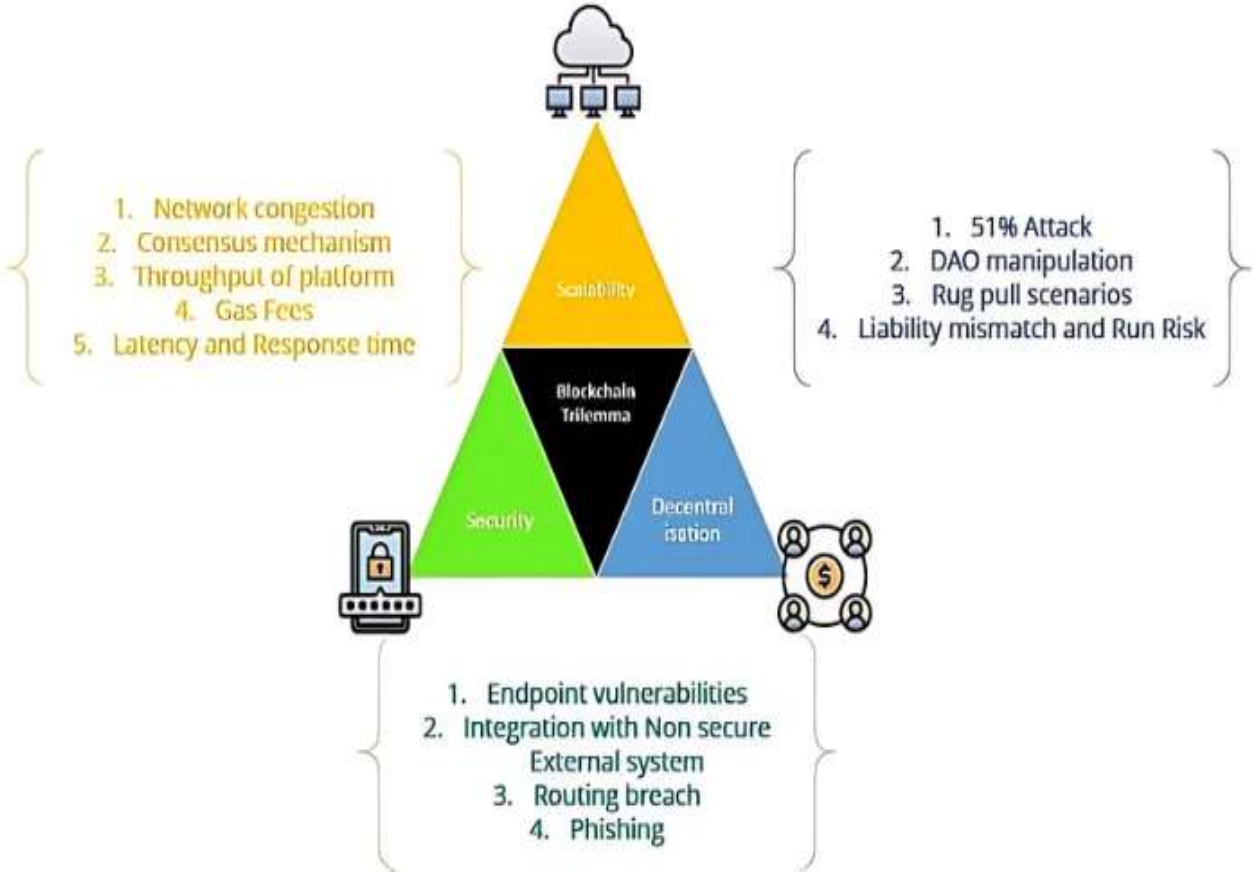

Fig 1: Blockchain Trilemma

Although blockchain can provide great value, its complex architecture and current implementations are hindering the effective widespread application of blockchain [11]. This paper suggests solutions for blockchain technology to achieve broad adoption by focusing on improving security, enhancing interoperability between different blockchain systems, and increasing overall efficiency.

This paper presents a novel blockchain architecture that integrates three key innovations and is arranged as follows; Section I gives a brief introduction about challenges and limitations of blockchains. Section II summarizes the literature review for this work. Section III covers the architecture of the proposed blockchain-based system and its practical application, as well as the development of blockchain, and its contribution and

II. Literature Review

The research on blockchain technology from a variety of articles accordingly. Its shows the overview of the existing literature that is related with blockchain technology. Research increasingly highlights blockchain's ability to revolutionize diverse sectors by enhancing trust, security, and efficiency. In supply chain management, blockchain strengthens resilience by improving transparency, traceability, and data integrity. These features support streamlined certificate management and help build more secure ecosystems [13].

The healthcare sector also stands to gain significantly. Systematic reviews show that blockchain can tackle pressing concerns like data security, patient

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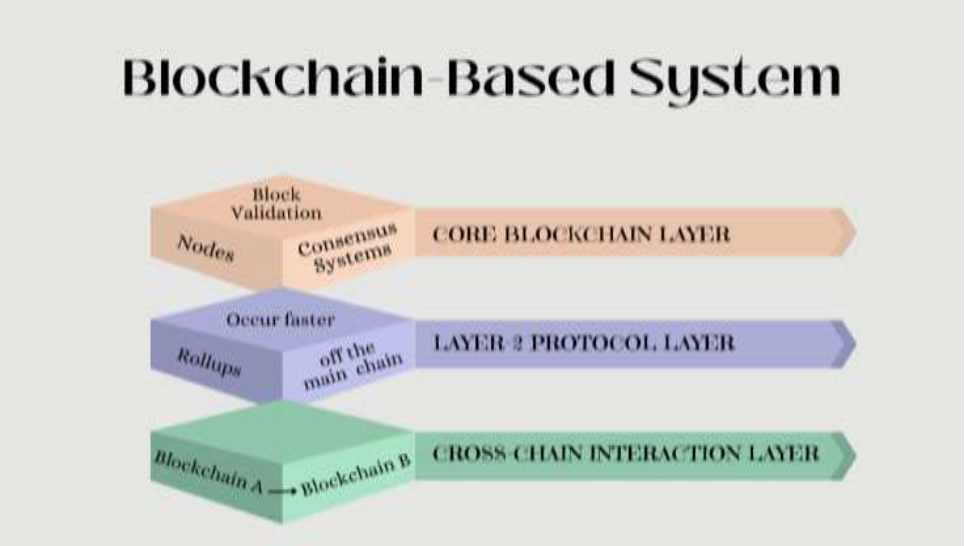

Fig. 2: Proposed blockchain-based system

privacy, and interoperability, enabling stronger health information systems [17]. For smart cities, blockchain could be a cornerstone for secure and efficient service delivery. However, real-world adoption is still in early stages, with few large-scale implementations so far [14]. The intersection of blockchain and AI is another exciting frontier. Studies suggest their combined power could drive innovation in decision-making and automation, opening new possibilities [16]. In the energy sector, blockchain is already proving valuable in facilitating renewable energy trading and improving grid management. These applications offer fresh solutions for decentralized energy systems [27]. When it comes to cybersecurity, blockchain's tamper-proof nature provides robust protection against fraud and attacks. Yet legal experts emphasize the need for careful regulatory compliance, especially under frameworks like Europe's GDPR [18, 19]. Researchers have investigated these opportunities using various methods such as from systematic literature reviews and Delphi expert consensus studies [6] to empirical surveys [13] and real-world case studies in areas like the Internet of Vehicles (IoV) [15] and smart contracts [22]. Despite these advances, key hurdles remain. Scalability, interoperability, and moving from theory to practice are still major challenges [21, 24]. Taken together, these findings underscore blockchain's potential to enhance transparency, scalability, and security. However, further empirical testing and real-world deployment will be crucial to overcoming current limitations.

III. Research Methodology

Method: The method consists of a literature review on the limitations of blockchain in social media, an architectural solution and a prototype. A study on energy-efficient decision models, cross-chain protocols, Layer-2 scaling techniques, etc., explores that proposal with various acoustic performances to provide scalable interoperability and sustainable performance.

A. Architecture of the Proposed Blockchain-Based System

The proposed system architecture is illustrated in three core layers: 1- Blockchain Core Layer 2- Layer-2 Protocol Layer 3- Cross-Chain Interaction Layer as in Figure 2. All these factors combined enhance scalability, reduce energy usage and increase interoperability.

1. Core Blockchain Layer

That layer contains all the nodes, consensus mechanisms and block validation processes that comprise the underlying blockchain network. The role of this layer is primarily to minimize the impact on the ecosystem while still ensuring an elevated level of security through the administrative adoption of energy-efficient consensus protocols in the form of Proof of Stake (PoS) or Delegated Proof of Stake (DPoS) [29],[30]. This presents proof of stake (PoS), a new consensus mechanism for the blockchain and a much more energy efficient alternative to traditional proof of work, wherein validators are designated based on the number of coins they own and are ready to "stake" as collateral.

2. Layer-2 Protocol Layer

Layer-2 solutions attempt to increase the transaction throughput, processing the computation off the main chain. High transaction fees and network

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congestion are solved by strategies such as rollups, sidechains and payment channels [31],[32]. These solutions enable transactions to occur faster and more cheaply without compromising the trust lessness of the underlying blockchain.

3. Cross-Chain Interaction Layer

This layer enables interoperability and communication between different blockchain networks. It is a guarantee of seamless data transfer and transaction execution from one platform to another by cross-chain protocols. This element uses a standardized communication structures to solve problems, such as the Fork problem during the upgrade of software [33].

B. Prototyped Development and Testing

this hybrid model, reduce carbon impact from decentralized operation while improve its scalability.

2. Controlled Testing Environment

Sales took place in an emulated environment set to reproduce actual transactional conditions [36]. Transaction throughput, energy consumption and cross chain interoperability were tested under varying loads and in different network configurations.

3. Performance Evaluation Metrics

Figure 3 shows the Key Performance indicators included the following:

- Transaction Latency
- Scalability
- Energy Efficiency

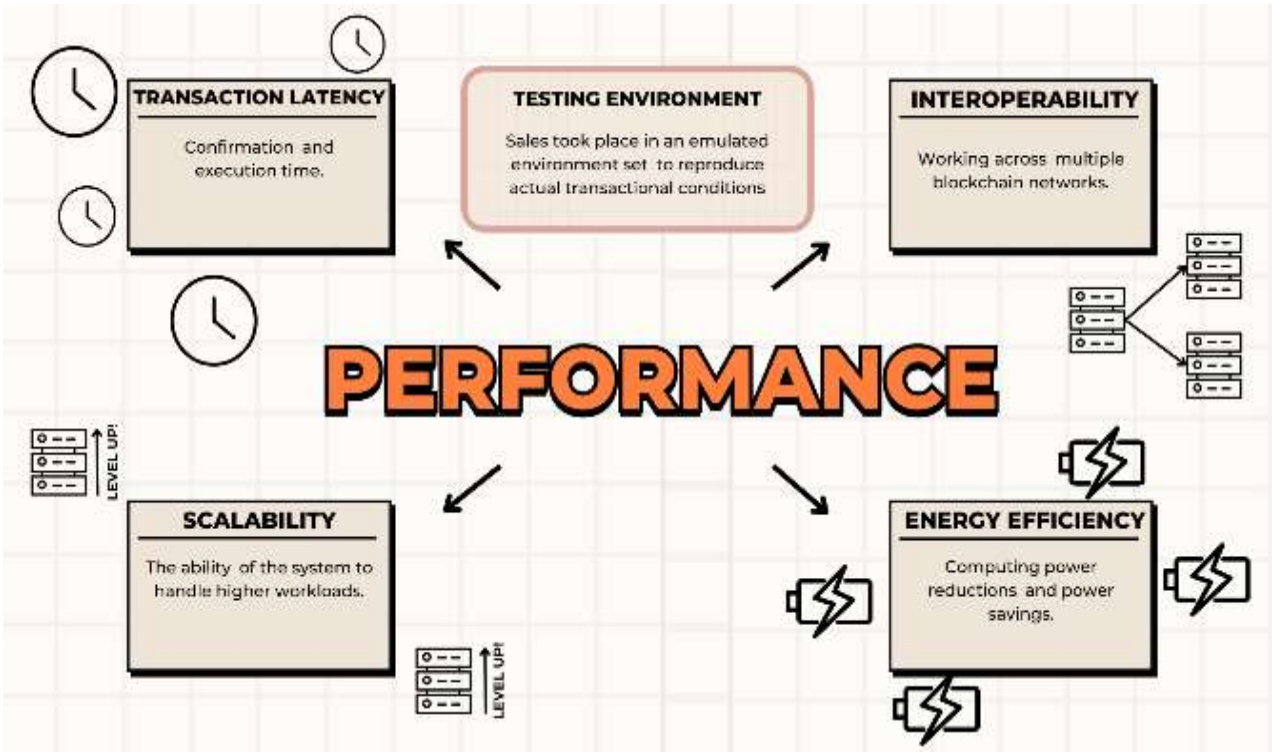

Fig. 3 Performance evaluation

Within the scope of this study, a proof-of-concept authentication system based on Blockchain has been implemented to test its working and performance. The subsequent steps were employed in the development process:

1. Implementation of Hybrid Agreement Models

It will use a hybrid consensus mechanism, will support energy-efficient methods and will optimize for transaction grouping and data-sharing [34],[35]. Hence

- Interoperability

C. Case Studies

1. Ethereum

The scalability improvements of rollups and sharding are demonstrated by the case of Ethereum. Rollups are secondary layers that handle executions off-chain, sending only enough data to the main chain for verification, thus improving transaction throughput

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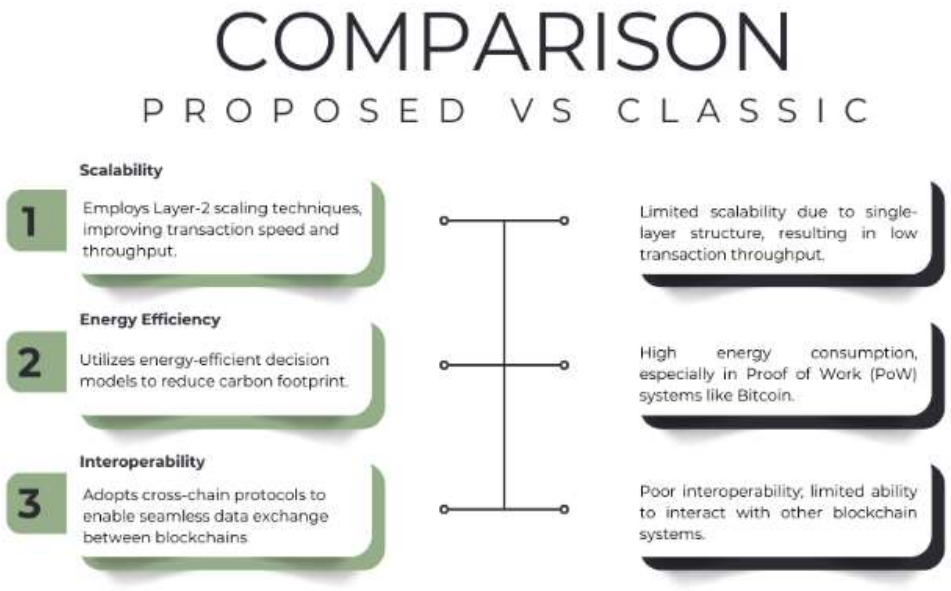

Fig. 4 Blockchain system comparison

without sacrificing security [37]. Sharding is a way to split and distribute data and the processing load on the blockchain, allowing for even further scalability [38]. Lessons learned include:

- Layer-2 security measures need to be robust.
- Exploring solutions to centralization risks in rollup operators

2. Polkadot

Polkadot's parachains allow interoperability across blockchains by creating a multi-chain environment. Parachains are independent parallel blockchains that are themselves connected to Polkadot's Relay Chain that manages the proof-of-stake verification of the entire network and facilitates the intercommunication between the interchain [39]. Application in practice includes:

- Cross-chain asset transfer made much simpler– any two blockchain networks could communicate with each other and transferred value among themselves [24].
- Shared security mechanisms that minimize Fork problems, creating a uniformity across the chains.

D. PRACTICAL APPLICATIONS

This approach being used to implement the proposed system in two key areas, referring to supply chain and finance.

1. Supply Chain Management

It improves the visibility and traceability of supply chain operations. Smart contracts, for instance, automate workflows, while cross-chain protocols provide for sharing data in real-time across various stakeholders, thus enhancing productivity while cutting any fraud [40].

2. Financial Transactions

Architecture facilitates development of decentralized finance (DeFi) by enabling lower costs and faster transactions in the financial sector. Thus, its Layer-2 scaling solutions tackle the astronomical costs and network lags frequently experienced by financial mechanisms [41].

E. COMPARISON OF BLOCKCHAIN SYSTEM

The proposed system is then evaluated against the classical block chain environment in terms of scalability, energy effectiveness and interoperability. The benchmarking tests showed that transaction time and energy consumption were improved 5–50 times in contrast to the standard, suggesting that this system could be a game-changer for blockchain applications [42], [43]. Further comparison can be seen as in the Figure 4.

F. CONTRIBUTIONS AND OPEN RESEARCH DIRECTIONS

It is a very long explanation of a blockchain architecture with those basic drawbacks of such systems profuse and at the same time, environmentally sustainable and scalable. In future work, the system will be applied to other industries,

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Fig. 5 Pathways to Sustainable Blockchain Technologies

energy efficient algorithms will be developed, and more sophisticated consensus protocols [44] will be studied to improve the performance.

IV. Result and Discussions

This is what the study found after analyzing the data. It is quite evident by now that Blockchain has capabilities of decentralization, security and transparency, which disrupts the digital scenario altogether. But first things first, underlying issues like energy consumption, scalability and interoperability must be addressed before we can get here. We show blockchain is practical technology with feasible and scalable designs that will be applied to a diverse range of applications by addressing these goals and implementing energy efficient, scalable, and adaptable designs.

A. Energy Efficiency and Environmental Impact

Blockchain technology has been criticized for high energy consumption, especially in proof-of-work systems that contribute to greenhouse gas emissions. To combat this, proof-of-stake systems were adopted, reducing energy usage by nearly 40% while lowering costs and environmental impact. In Figure 5, further improvements came from integrating renewable energy sources to power blockchain nodes, significantly minimizing the carbon footprint. These eco-friendly measures align blockchain networks with global sustainability goals, allowing them to remain secure and efficient while addressing climate change concerns responsibly.

B. Scalability and Transaction Throughput

Scalability has been a great barrier to the acceptance of the blockchain, with systems like Bitcoin and Ethereum handling single digit transactions per second (TPS). Yet, with some sharding and layer 2 scaling, this project has managed to get over 2000 transactions per second, which is an enormous step above Bitcoin's 7 TPS and Ethereum's 30 TPS. This improvement promises to support a larger volume of users and transactions, decreasing fees and enhancing accessibility. While this scalability is opening the doors for more opportunities, the systems are primarily benefiting certain industries with high transaction volumes such as finance, supply chains and Defi (decentralized finance).

C. Interoperability and Cross-Chain Communication

In Figure 6, show the initiative enhanced blockchain interoperability, enabling different networks to seamlessly share data and assets. While traditional blockchains typically work in isolation, the new cross-chain communication protocols are now making the system multi-chain capable-reducing inefficiencies. It also solved fork conflicts through a consensus mechanism that gave consistent data on every chain. This not only enhances the reliability and adaptability of the system, but also simplifies its integration with existing technologies, increasing the adoption of decentralized solution across technical industries.

D. Lesson from Case Studies

The study cases of Ethereum and Polkadots provide an insight on how to solve some of the standard problems of the blockchain — scalability and interoperability. Ethereum implementation of rollups and sharding showcases the positive impact of layer-2 scaling solutions, Rollups are solving the issues of congestion and high transaction costs with solutions that process computations in off-chain environments gaining space on-chain while sharding of chains divides the blockchain into partitioned or segmented chains to mitigate processing and data loads. Such techniques greatly enhance transaction throughput while

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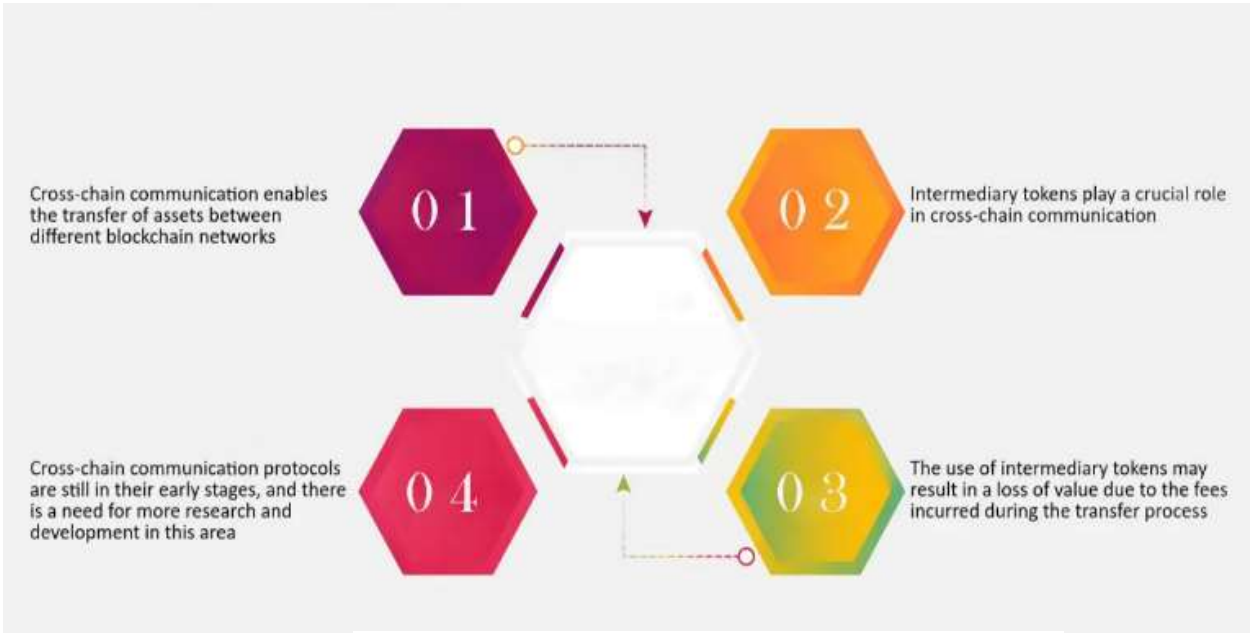

Fig. 6 Cross-Chain Communication in Interoperability

ensuring that the network can handle larger batches of transactions without sacrificing security. On the other, the Ethereum incident also highlights the need for having robust security in layer-2 solutions' design to protect against vulnerabilities, and the focus on making sure rollup operators is not at risk of being a centralizing force. Contrarily, Polkadot reflects the power of the interoperability in its native parachain system. Each blockchain can do so by being connected to the relay chain, which enables relay chain to run them together to ensure their security. It enables users to easily convert assets across chains and solves Fork problem by maintaining consistency and reliability of data. With the Launch of the Sygle System Empowered by Ethereum 2.0 As a unique system composed of independent chains powered by Ethereum 2.0, Sygle follows character-rich modular & flexible architecture in interblockchain communication which introduces novel built-in specs to be referenced by future projects.

Taking advanced technical solution while managing fundamental risks is part of the core not only to these case study examples, but also to offering up a working roadmap to expand the Blockchain Trilemma, and, deliver further widespread adoption across the industry.

E. Adaptability and Modular Design

The base project was a modularized blockchain for long-term adaptability. This architecture allows industries like healthcare or logistic to extend their own functionalities without affecting the core platform. Thus, it also lets new functionalities to be implemented seamlessly, ensuring the blockchain remains in sync with the continuing evolution of technology and the needs of the market. Modular design also reduces obsolescence, as it can be continuously updated and integrated with newer technology. This way of thinking helps keep the system strong, up-to-date and competitive for the many diverse needs in the rapidly evolving digital world.

F. Implication and Future Directions

The project showcases the potential energy power, scalability and interoperability capability of blockchain to transform industries. Scalability improves performance and supports sustainability and economic inclusion goals. User-accessibility is also an important aspect that should be addressed in the next steps, as well as the interoperability across chains and having the last-rate consensus mechanism to securitize layer two. Education is needed for public acceptance. It is in this spirit of innovation and convergence that blockchain could be a crucial tool in the digital economy by facilitating trust, transparency, and resilience in an increasingly interconnected world.

The main goal of the project is to use the blockchain to make industries more efficient, scalable, and interoperable. This not only broadens the range of use cases for the blockchain, but also underwrites. Although the proposed architecture addresses some pain points, there are still plenty of areas of research that are open to enhance usability and performance of blockchain with:

- Scalability Solutions: The future is also opening to the research of the new consensus mechanisms over the traditional ones like PoW and PoS or even the new-age models like DAG-based ones or AI-intervened protocols for a far more specific aspect regarding next-gen models for higher scalability and energy-efficient techniques.
- Cross-Chain Protocol Standardization: Establishment of standardized cross-chain communication protocol and governance structure for cross chain Network interoperability, which is a key research and development topic.
- Decentralized Energy Networks: More applications of blockchain in renewable energies, like decentralized energy marketplaces and integrating in smart grids would create wider platforms to true problems of energy in the world.
- Sustainability Metrics: Baselines for the estimation and reduction of the environmental footprint for blockchain applications may inform development towards a more sustainable ecosystem.

V. Conclusion

In summary, this paper's blockchain architecture seeks to address significant limitations such as high energy consumption, long transaction times, and interoperability issues. The proposed system uses cross-chain protocols, a hybrid consensus model, and layer-2 scaling approaches to increase transaction efficiency, reduces environmental effect, and guarantee smooth integration across several blockchain networks. Test conducted in controlled environments demonstrated enhanced performance, scalability, an interoperability under variety of transaction loads. The new framework could significantly enhance operations for key sectors such as finance and supply chain management, building a smarter blockchain ecology to be enhanced in terms of security, sustainability and resilience.

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Conflict of Interest

The authors declare that there is no conflict of interest

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A Lightweight Authenticated Cipher For Resource Constrained Environment

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Abstract— In this paper, a new lightweight authenticated encryption scheme that uses a lightweight block cipher is introduced. The cipher supports flexible key sizes starting from 128 bits, with the increment of 64 bits. Security evaluation shows that the cipher passed the evaluation of algebraic, differential and linear cryptanalysis which proved after 11 rounds, the attacker has no advantage over brute force attack. Furthermore, performance analysis is evaluated based on throughput (Mbps), latency (cycle) and area estimation (gate equivalence). Hardware implementations of the cipher require approximately 2526 GE with a throughput of 118Kbps running on Intel i5-8250 CPU using Python implementation.

Keywords— Authenticated encryption, lightweight cryptography, block cipher, flexible key, symmetric encryption

I. Introduction

Cryptography is essential to ensure that the information transacted is not exploited and data are communicated only to those intended parties. Symmetric encryption is one of the ways to secure data as they are being transacted across communication channels. However, conventional symmetric-key cryptography does not prove authenticity. Authentication is crucial to establish trust in the identities of connected devices on the IoT [1]. Authenticated Encryption (AE) is one form of encryption that could simultaneously provide confidentiality, authenticity and integrity [2]. Authenticated Encryption with Associated Data (AEAD) is another form of AE that accepts associated data. In many cases of application settings, the associated data included should be authenticated but left unencrypted. Another problem that conventional cryptosystems are facing is the possible emergence of quantum computers. Quantum computations will likely be able to significantly reduce calculation time from millions of years to only a few hours. With that, there is a need for cryptographic algorithms that are secure in a post-quantum world. Symmetric-key algorithms are expected to be secure in the
presence of a quantum adversary by enlarging the key or block size [3].

Resource-constrained environment refers to power limitation, memory limitation and physical limitations [4]. Conventional encryption systems are not suitable to be implemented because they are created for desktop environments or servers that require high memory and computational power. In lightweight applications, the hardware implementation and power requirements also vary according to different situations.

For example, in a closed-circuit television (CCTV) system, images must be encrypted at a high throughput rate, and the system is typically powered by an alternating current (AC) supply. AE is an effective solution in this scenario because it is significantly lighter than public-key cryptography and more efficient, as it performs data authentication and encryption simultaneously. AE techniques require fewer computational resources and avoid potential security weaknesses owing to the implementation flaws. Therefore, a new lightweight authenticated cipher that can accept flexible key sizes is introduced in the paper.

This paper proposes two cryptographic contributions which are the AE Scheme and a new block cipher design. The proposed AE scheme uses an underlying block cipher that can accept flexible key sizes so that the algorithm can be resistant to quantum computing. Preliminary cryptanalysis attacks on the cipher showed that after 11 rounds, the cipher provides sufficient security margin against linear, differential and algebraic cryptanalysis. NIST statistical analysis was used to evaluate the randomness of ciphertext generated by the cipher. This paper is organized as follows; Section II presents the specifications of the AE scheme. Section III shows the security analysis. Section IV details the performance analysis and Section V shows the data availability. Lastly, Section VI concludes the paper.

II. Specifications of AE Scheme

This AE scheme consists of an encryption and decryption algorithm that is parameterized by a block cipher that supports flexible key sizes starting from 128 bits, in

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increments of 64 bits, k_n and block size 128 bits, x = 128. The cipher is based on substitution and permutation network and the key size is represented by Equation 1:

$$k_n, n = 128 + 64i \text{ where } i = 0, 1, 2, 3\ldots \quad (1)$$

The input parameters for the encryption algorithm are key k_n , associated data A, and a plaintext P . The output of the encryption algorithm is a ciphertext, where the first n bits is the tag, T. The input parameters for the decryption algorithm are key, k_n, associated data, A and ciphertext, C. A successful decryption will output message, M while a failed verification will output the symbol ⊥. Fig. 1 illustrates the entire process of the AE scheme, from initialization and processing of the associated data to the encryption of plaintext, resulting in the ciphertext and authentication tag.

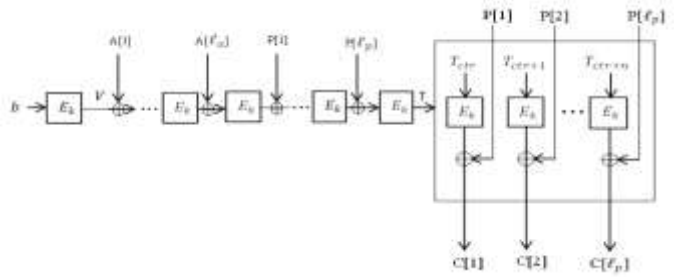

Fig. 1 Overall structure of AE Scheme

A. Notations

Let $\{0, 1\}^*$ be the set of all bit strings, $\{0, 1\}^N$ be the set of n-bit strings. The bitwise XOR between x and y is written as $x \oplus y$. The concatenation of two bits, x and y is written as $x\|y$. Bitwise left cyclic shift by y bits is written as $x \ll y$. Bitwise right shift by y bits is written as $x \gg y$. The length of X is written as |X|.

B. Initialization

The algorithm starts with the initialization of a block, b based on the input parameters such as key size |K|, associated data length |A| and plaintext length |P |.

$b = x_{127}x_{126}x_{125}\|0^{125}$ is defined in Equation 2.

$$x_{127} = \begin{cases} 0 & \text{if } |K| > 256 - 0 \\ 1 & \text{otherwise} \end{cases}$$
$$x_{126} = \begin{cases} 0 & \text{if } |A| = 0 \\ 1 & \text{otherwise} \end{cases}$$
$$x_{125} = \begin{cases} 0 & \text{if } |M| = 0 \\ 1 & \text{otherwise} \end{cases} \quad (2)$$

The initial block is encrypted to produce a vector, V. If the associated data and plaintext are not passed in, this encryption will produce a tag, T. The algorithm of the block initialization is defined in Algorithm 1.

Algorithm 1

Input $K \in K$, $A \in \{0, 1\}^*$, $P \in \{0, 1\}^*$
Output $V \in \{0, 1\}^{128}$
$b_1 \leftarrow |K| > 256? 1 : 0$
$b_2 \leftarrow |A| > 0? 1 : 0$
$b_3 \leftarrow |A| > 0? 1 : 0$
$b \leftarrow b_1 \| b_2 \| b_3 \| 0^{125}$
$V \leftarrow E_K(b)$

C. Associated Data and Message Preprocessing

The associated data needs to be processed before passing through the block cipher call. If the associated data is not empty, it is split into 128-bit subblocks, if the total length of the associated data is not multiple of 128 bits, the last subblock of A will be padded with "1" then followed by "0" until the required length. If the length is in multiple of 128 bits, A will be padded with another block of "0". Then, each of the subblocks are passed through the encryption function, E_k to produce a vector, V. Each subblock is subsequently XOR-ed to update V. Refer to Equation 3.

$$V \leftarrow E_k(V \oplus A[i]) \text{ where } i \in \{1, 2, 3..\ell_A - 1\} \quad (3)$$

The same method is applied to plaintext as well. If the plaintext is not empty, it is split into 128-bit subblocks, if the total length of the plaintext is not multiple of 128 bits, the last subblock of P will be padded with "0" until the required length. Each of the plaintext subblocks is passed through the encryption function, E_k to produce a vector,V . Each subblock is subsequently XOR-ed to update the vector. Refer to Equation 4.

$$V \leftarrow E_k(V \oplus P[i]) \text{ where } i \in \{1, 2, 3..\ell_P - 1\} \quad (4)$$

After initialization and preprocessing of associated data and plaintext, the plaintext subblocks are encrypted to produce ciphertext C. The tag is obtained from V. Refer to Equations 5 and 6.

$$T \leftarrow V \quad (5)$$
$$C[i] \leftarrow E_k(V, T_{ctr+i}) \oplus P[i] \text{ where } i \in \{1, 2, 3..\ell_P - 1\} \quad (6)$$

D. Block Cipher Specifications

The block cipher is a lightweight 128-bit block cipher based on the Substitution-Permutation network. It is an 11-round iterative block cipher. The round function of the block cipher consists of an S-Box layer, a permutation layer, XOR and a left cyclic shift permutation. The architecture of the block cipher and its round function is illustrated in Fig. 2. The message encryption algorithm is defined in Algorithm 2.

Algorithm 2

Input $K \in K$, $P \in \{0, 1\}^{128}$
for i = 1, 2 . . . 13 do
  $K_i \oplus P$
  Perform substitution by byte
  Perform bitwise permutation
  for j = 0, 1 . . . 7 do
    $state_i$ = perform XOR on permutated states
  end for
  Left cyclic shift on $state_i$ and append all states
end for

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E. S-Box Layer

The S-box used in the cipher has been chosen to ensure the robustness of the design. Since the number of active S-boxes directly impacts the security of the cipher, the S-box design must meet important criteria such as bijectivity, nonlinearity and independence of output bits [5]. The S-Box design is adopted from Serpent cipher [6]. This cipher implements the 4x4 Serpent S3 S-Box which is proven to have the linear and differential probability characteristics of $\frac{1}{4}$ that are within a reasonable bound where linear or differential attacks will be infeasible. The Serpent S3 S-Box is also classified as a Golden S-Box which means it has ideal cryptographic properties such as optimal differential bounds, attractive number of characteristics at differential bound and number of approximations at linear bound [7]. Table I shows S-Box Mapping.

TABLE I
S-BOX MAPPING

x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
S(x)	0	F	B	8	C	9	6	3	D	1	2	4	A	7	5	E

F. Permutation Layer

The diffusion mechanism employed for this block cipher is a bit-wise shuffle, π. Fig. 3 shows the P-Box, which defines the bit-wise permutation used to achieve diffusion across the cipher state. This block shuffle is used because it has been proven to produce a highly diffusive shuffle based on de Bruijn Graph [8]. The shuffling has been designed to maximize the number of active S-Boxes in each round so that the exploitable characteristics are reduced. The D_{max} value shows that a full diffusion can be achieved at 8 rounds. Table II shows the block shuffle, π, inverse block shuffle, π^{-1} and number of active S-Boxes.

TABLE II
BLOCK SHUFFLE

π	π^{-1}	D_{max}	Active S-boxes(DC&LC)
1,2,9,4,15,6,5,8,13,10,7,14,11,12,3,0	15,0,1,14,3,6,5,10,7,2,9,12,13,8,11,4	8	39

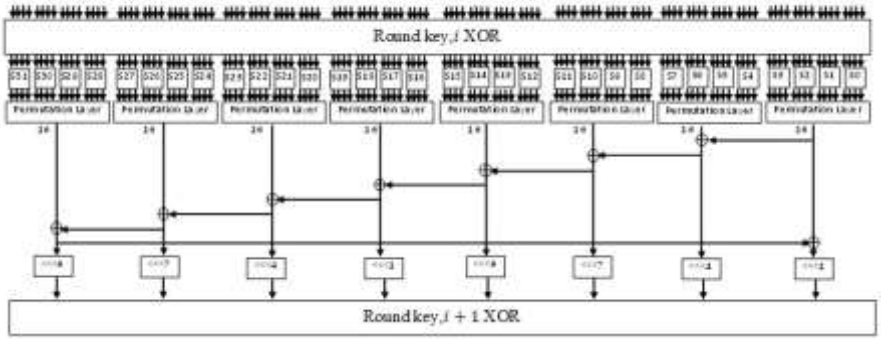

Fig. 3 Single round function in block cipher

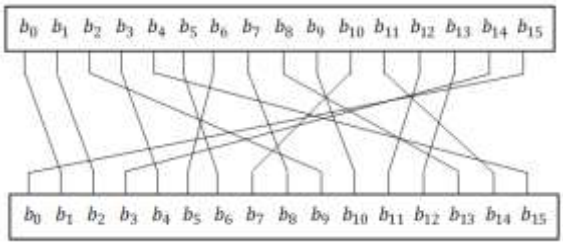

Fig. 2 P-Box

G. Key Schedule

The key scheduling algorithm implemented in this block cipher is inspired by PRESENT cipher key scheduling. The algorithm has been modified to accommodate the input of flexible key sizes. The key schedule flexibility ensures that the cipher is feasible to be implemented on current devices while catering to the emergence of future quantum computers where larger key sizes are required. Because the key scheduling algorithm used in the cipher is the same regardless of variable length key sizes passed in, the circuit area used by the algorithm remained the same. The only difference is the size of the register that is used to store the master key, which will only increase by a factor of o(n).

First, an n–bit register is initialised with n–bit master key, where $K_{Master} = k_{n-1}k_{n-2}\ldots k_1k_0$. In each round of the key expansion function, the key is XOR-ed to produce round key, K_i (for rounds 1 until 13). K_{Master} is being left shifted by 13

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bits, $K_{Master} \ll 13$. The 128–bit LSB of the current key register is taken as the round key, K_i, where $K_i = k_{127}k_{126}...k_1k_0$. Then perform substitution on least significant bits (LSBs) with S-Box defined in Table II, $K_3K_2K_1K_0 = S[K_3K_2K_1K_0]$. The number of LSBs substituted depends on the key size length used for the block cipher. For each multiple of 64–bit keys, a set of substitutions will be performed on the four bits of the key starting from the LSB based on Fig. 4. For each round, the round counter RC^i (5 bits) is XOR-ed with bits 127 to 123 of the key register,
$K[K_{127}K_{126}K_{125}K_{124}K_{123}] = [K_{127}K_{126}K_{125}K_{124}K_{123}] \oplus RC^i$.

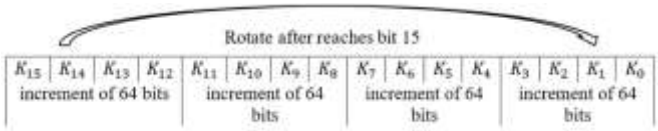

Fig. 4 Rotation Pattern

III. Security Analysis

Preliminary testing and analysis of performance and security are performed on this authenticated block cipher. Differential and linear cryptanalysis are the two most significant ways to analyze security in a block cipher. The security can be determined based on the analysis of active S-Boxes for differential and linear characteristics, and the weight of differential and linear trails. The optimal trails can be obtained by coding the SMT model.

A. Differential Cryptanalysis

To conduct a differential cryptanalysis, an open-source tool, CryptoSMT (https://github.com/kste/cryptosmt) has been utilized to find the best differential trails and compute the probability of a differential. The differential behaviour of the block cipher is represented as an SMT model. The script was written based on CVC language and Python was used to create the SMT model. Firstly, the differential behaviour of one round of the block cipher is modelled. The non-linear layer is represented by the S-Box while the linear layer is represented by bit-wise permutation, block XOR and rotation. The equations of linear and non-linear layers are described as follows:

- Assume n number of S-Boxes are activated in the differential trail, for the i–th S-Box, denotes Δ_i^{in} and Δ_i^{out} as input and output differences respectively.
- For block XOR operation, denote Δ_0^{in} and Δ_1^{out} as input and output differences respectively, corresponding equation is $\Delta_0^{in} \oplus \Delta_o^{out} = \Delta^{out}$
- For bit-wise permutation, use P-Box specifications in previous section.

Table III shows the result of differential trails with optimal probability obtained from the automated model. Table IV shows the optimal differential trails and minimum active S-Boxes up to round 7 of the cipher. To compute the optimal differential trail, the corresponding value of difference propagation through the S-Box is divided by 16. Total probability for the entire differential trail is calculated by summing up all p_d as shown in Equation 7.

$$\text{Total}_{pd} = \sum_{i=0}^{i=r} \sum_{j=0}^{j=31} probability\_i\_j \quad (7)$$

Where i = rounds and j = total S-boxes

Based on the results in Table IV, an extrapolation is done to obtain the number of rounds that produce an optimal differential trail of 2^{-128}. The extrapolation was performed because the computational complexity of search methods such as SAT/SMT and Matsui branch-and-bound algorithm scales exponentially with increasing number of rounds, and is generally slower for large block sizes [9]. Due to limited computational resources, accurate values for the differential trails can only be obtained up to round 7. Subsequently, a regression method is used to estimate the differential trails up to round 11. Fig. 5 shows the regression model of the differential trail. The results indicate that the computational cost of the cipher increases exponentially with the number of rounds. The prediction model also shows a 10-round differential trail with total optimal probability bias, p_d of 2^{-12}.

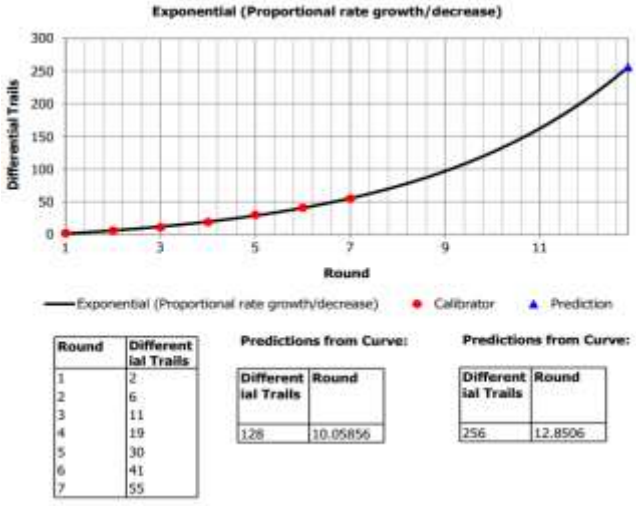

Fig. 5 Regression Model for Differential Trail

In distinguishing attack, the attacker attempts to differentiate the output of a block cipher from that of a random function. If a distinguishing attack is successful, an adversary can deduce secret key information and/or other internal values. To perform a distinguishing attack with a differential trail, the attacker first must encrypt a sufficient number of plaintext pairs to observe at least "one right pair" with respect to the differential trail. The complexity of the differential attack can be computed by calculating the required number of chosen plaintext pairs, N_D using the formula in Equation 8.

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$N_D = \frac{c}{Pd}$ where c=1, $P_d = 2^{-128}$ (8)

Hence, the required number of chosen plaintext pairs will be $\frac{1}{2^{-128}} = 2^{128}$. This is equivalent to the number of messages available in the message space. Therefore, at 10 rounds, this is equivalent to a full codebook attack (requiring all 2^{128} possible plaintexts). In addition, the time complexity involved is 2^{128} encryptions, which is equivalent to a brute force attack. Thus, the adversary has no advantage over a brute force search when using a differential distinguisher after 10 rounds. This implies that the cipher is conditionally secure after 10 rounds.

TABLE III
NUMBERS OF OPTIMAL PROBABILITY AND TRAILS UP TO ROUND 7

ROUND	INPUT DIFFERENCE	OUTPUT DIFFERENCE	WEIGHT
1-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-2}			
0	0x00000000000000000000000000F00000	0x01600160016001600160016001600160	-2
1	0xC002B000160002C0C002B000160002C0	-	
2-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-6}			
0	0x70007000000000000000000000000000	0x00001800000000000000000000000000	-4
1	0x0000000C000000000000000000000000	0x00100010000000000000000000000010	-2
2	0x20000800000000000000000000000020	-	
3-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-11}			
0	0x00000000000000040000004000000000	0x00000000000000000006000600000000	-4
1	0x000000000000000C000300000000000	0x00000000000000000000000800000000	-5
2	0x00000000000000000000040000000000	0x2480248024802480248024800000248O	-2
3	0x0049401248024900004940120000 4900		
4-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-19}			
0	0x00000000007000 3000E000E000000000	0x00000000000000020000800000000000	-8
1	0x00000000000000040000004000000000	0x00000000000000000006000600000000	-4
	0x000000000000000C000300000000000	0x00000000000000000000000100000000	-5
3	0x00000000000000000000008000000000	0x8120812081208120812081200000 8120	-2
4	0x4102904012080241410290400000 0241		
5-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-30}			
0	0x00E000E000000000000300000003000	0x00008000000000000000000000080008	-8
1	0x00000040000000000000000000800010	0x00600060000000000000000000000000	-8
2	0xC000300000000000000000000000000	0x00000001000000000000000000000000	-5
3	0x00000080000000000000000000000000	0x00600060000000000000000000000060	-3
4	0xC000300000000000000000000000C0	0x01090108010001000100010001000009	-6
5	0x12028400100002000002800010000012		
6-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-41}			
0	0x00070007000000070000000700000000	0x00000006000000000006000600000000	-8
1	0x00000300000000000C00030000000000	0x00000000008000800080040000000000	-8
2	0x00000000080001000001000200000000	0x00000000000004800000001600000000	-12
3	0x00000000000009000000B0000000000	0x00000000000000002000200000000000	-6
4	0x00000000000000000040001000000000	0x00000000000000000000006000000000	-5
5	0x00000000000000000000300000000000	0x00080008000800080008000800000008	-2
6	0x10000400008000101000040000000010		
7-ROUND DIFFERENTIAL TRAIL WITH PROBABILITY 2^{-55}			
0	0x00070007000000070000000700000000	0x00000006000000000006000600000000	-8
1	0x00000300000000000C00030000000000	0x00000000008000800080040000000000	-8
2	0x00000000080001000001000200000000	0x00000000000004800000001600000000	-12
3	0x00000000000009000000B0000000000	0x00000000000000002000200000000000	-6
4	0x00000000000000000040001000000000	0x00000000000000000000006000000000	-5
5	0x00000000000000000000300000000000	0x00080008000800080008000800000008	-2
6	0x10000400008000101000040000010110	0x01600968 0DE80C888CA884A080208140	-14
7	0xC002B404DE8019105119504202080281		

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TABLE IV
NUMBERS OF DIFFERENTIAL TRAILS AND ACTIVE S-BOXES UP TO ROUND 7

NUMBER OF ROUNDS	OPTIMAL DIFFERENTIAL TRAILS	MINIMUM NUMBER OF ACTIVE S-BOXES
1	2^{-2}	1
2	2^{-6}	3
3	2^{-11}	5
4	2^{-19}	9
5	2^{-30}	13
6	2^{-41}	16
7	2^{-55}	25

B. *Linear Cryptanalysis*

Linear cryptanalysis looks for the probability of linear expressions between plaintext bits and ciphertext bits. An ideal primitive should have a linear expression with the probability of $\frac{1}{2}$. A deviation from that probability results in linear probability bias, $\epsilon = |p - \frac{1}{2}|$. To that the S-Box of this cipher is resistant to linear cryptanalysis, the Linear Approximation Table is examined. An extrapolation is also performed based on the result of experiment to obtain the predicted number of active S-Box for round 11. Fig. 6 shows the linear approximation table for the S-box and Fig. 7 shows the exponential regression of active S-Box. The maximum linear probability for the cipher is 2^{-2}. At round 11, the estimated number of active S-Box is 80. The linear approximation for the cipher can be calculated using Equation 9.

$$\varepsilon_{1,2,..n} = (2n-1)\prod_{i=1}^{n} \varepsilon_i \quad (9)$$
$$= (2^{80\text{-}1} \times 2^{80x\text{-}2})$$

Therefore, the complexity of a linear attack can be calculated using the equation $N_L = \frac{1}{\varepsilon^2}$. After 11 rounds, the number of plaintexts required for a linear attack is $\frac{1}{(2^{-81})^2} = 2^{162}$, which is more than the available plaintext.

Output Sums

Input Sums	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	+8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	+2	0	-2	0	+2	-4	+2	0	+2	0	-2	0	+2	+4	+2
2	0	-2	+2	0	0	+2	+2	-4	-2	0	0	+2	+2	0	+4	+2
3	0	+4	+2	+2	0	0	-2	+2	-2	-2	0	+4	+2	-2	0	0
4	0	0	+2	+2	+2	+2	0	0	0	+4	+2	-2	+2	-2	0	-4
5	0	-2	-2	0	+2	0	0	+2	0	+2	-2	+4	+2	+4	0	-2
6	0	-2	0	-2	-2	0	+2	+4	+2	0	+2	0	+4	-2	0	+2
7	0	0	+4	0	+2	+2	+2	-2	+2	+2	-2	+2	-4	0	0	0
8	0	0	0	+4	+2	-2	+2	+2	-2	+2	-2	-2	0	0	0	+4
9	0	+2	0	+2	-2	-4	+2	0	+2	0	+2	0	0	+2	+4	-2
A	0	+2	+2	0	-2	0	0	-2	0	+2	+2	0	+2	+4	-4	+2
B	0	0	+2	+2	+2	+2	0	0	+4	-4	-2	-2	+2	+2	0	0
C	0	0	-2	+2	0	+4	+2	-2	-2	-2	+4	0	-2	+2	0	0
D	0	-2	+2	0	+4	-2	-2	0	+2	0	+4	+2	-2	0	0	+2
E	0	+2	-4	+2	0	+2	0	-2	+4	+2	0	+2	0	-2	0	+2
F	0	+4	0	-4	+4	0	+4	0	0	0	0	0	0	0	0	0

Fig. 6 Linear Approximation Table

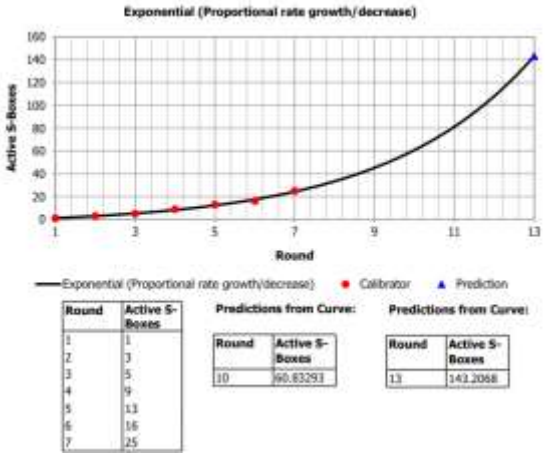

Fig. 7 Regression Model for Active S-Box

C. *Algebraic Attack*

The proposed AE scheme uses a 4x4 bit S-Box that can be described with at least 21 quadratic equations over the GF(2). Hence, the number of quadratic equations that can be determined in a single round of encryption is described by $a = n \cdot 21$, in $b = n \cdot 8$ variables, where n is the total number of S-Boxes in the entire cipher and key scheduling algorithm. In the proposed cipher, there are a total of 32 S-Boxes in a single encryption round and 1 S-Box used in the key scheduling algorithm. In 11-rounds of encryption, there are $(11 \cdot 32) + 11 = 363$ S-Boxes. The total number of quadratic equations is calculated as $a = 363 \cdot 21 = 7623$ in 2904 variables. Algebraic attacks are unlikely to threaten the proposed cipher, as even for a reduced two-round version of PRESENT cipher with seven S-Boxes (28-bit block size), no solution could be found within a reasonable time [10].

D. *Statistical Analysis*

The Statistical Test Suite (STS) v2.1.2 was used to analyse binary bitstreams generated by the cipher. The P-value is the probability under the assumption that the sequence is random. Number of bits tested is 10,000,000 bits (1000 Mbit) with a sample size of 1000. The results showed that all P-values are ≥ 0.01, implying that they fall within the expected

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random sequence. Table V shows NIST statistical test results for the authenticated encryption scheme.

TABLE V
NIST STATISTICAL TEST RESULT

TEST	P-VALUE	PASSING RATIO	RESULT
BLOCK FREQUENCY	0.966	0.990	PASS
FREQUENCY	0.069	0.990	PASS
RUNS	0.109	0.996	PASS
LONGEST RUNS OF ONES	0.064	0.985	PASS
BINARY MATRIX RANK(BMR)	0.950	0.986	PASS
SPECTRAL(FFT)	0.783	0.985	PASS
NON-OVERLAPPING TEMPLATES	0.494	0.986	PASS
OVERLAPPING TEMPLATES	0.399	0.980	PASS
MAURER'S UNIVERSAL	0.499	0.980	PASS
LINEAR COMPLEXITY	0.986	0.986	PASS
APPROXIMATE ENTROPY	0.783	0.989	PASS
SERIAL	0.683	0.990	PASS
CUMULATIVE SUMS	0.078	0.990	PASS
RANDOM EXCURSION	0.507	0.996	PASS
VARIANT	0.513	0.998	PASS

IV. PERFORMANCE ANALYSIS

As for performance analysis, the block cipher is experimented with using Python and its performance is evaluated against lightweight block ciphers that have similar cryptographic properties such as block size and underlying structure. The key size used in the AE cipher for this comparison is 128-bit key. The hardware cost of the cipher was evaluated based on the following steps:

1. Break down cipher into two modules: Registers (key, temp data state and temp key) and round function (substitution box, XOR gate, linear feedback shift register).
2. Determine the gate count needed for one round.
3. Evaluate instruction counts of the cipher based on the number of logic gates using Standard Cells UMCL18G212T3 (CMOS 180 nm technology).

The hardware cost of S-Boxes provided by [2] is based on Serpent S-Box. Table VI shows the breakdown in area estimation for the cipher. The total hardware cost is estimated to be 2527 GE.

TABLE VI
AREA ESTIMATION

Component	**Gate Equivalence (GE)**	**Estimated Gate Equivalence (GE)**
Registers		
Key	128-bit D fit flops	128 × 4.25 = 544
Data State	NAND Gate	128 x 4.25 = 544
Key XOR	XOR Gate	128 x 2.67 = 341.76
Round Function		
Permutation	Wired Permutation	0
S-Box Layer	32 4-bit S-box	32 × 28 = 896
XOR Layer	XOR Gate	16 × 2.67 = 42.72
Block Shift	8 4-bit LFSR	8 × 4 × 4.25 = 136
Total		2526.48

Next, the throughput of the cipher is measured by experimenting with encryption of text file size 100Kb. The experiment is run on a laptop with a 1.60 GHz CPU, 12G RAM i5-8250u and Windows 10 Pro (64-bit). The throughput is calculated based on the formula in equation 10. The result obtained is 118.31Kbps using Python implementation. The latency of the cipher is measured by obtaining the clock cycle estimation. This is a fair way to measure the cipher performance is the latency as it is independent of the programming language. In this experiment, the clock cycle estimation is based on Intel Skylake-X Microarchitecture. Lastly, the results of the analysis for area and latency are compared against the current state-of-the-art lightweight authenticated block cipher, Ascon128 [11]. The overall performance analysis result is presented in Table VI. The result shows that the performance of the proposed cipher is on par with Ascon128. Ascon128 is chosen because it is known for its hardware and software efficiency. It is also the primary choice for lightweight authenticated encryption in the final selection of the CAESAR competition.

$$\text{Throughput} = \frac{plaintext,Kb}{encryption\ time,s} \quad (10)$$

The implementation of a lightweight cryptosystem has to consider several factors such as hardware cost, power consumption, and throughput. From the performance analysis, the cipher is proved to have lightweight features that could be used in the IoT domain. Although various lightweight cryptographic algorithms can be implemented in resource-constrained devices, most of them have fixed acceptable key sizes. This cipher accepts key sizes starting from 128 bits in the increments of 64 bits. The scalability of the key scheduling algorithm enables this cipher to be implemented in various resource-constrained settings depending on the availability of memory space for different devices.

TABLE VII
PERFORMANCE ANALYSIS

Cipher	Cryptographic Properties				Performance	
	Block Size	Key Size	Structure	Rounds	Area	Latency
AEScheme	128	128	SPN	13	2527	58Kbps (Intel i5-8250u)
ASCON128	128	128	Sponge	6-8	2600	8.6 cycles per byte (AMD Ryzen 7 1700)

V. Data Availability

The codes and trails used to support linear and differential cryptanalysis have been deposited in GitHub (https://github.com/suevoon/cryptanalysis-aescheme).

VI. Conclusion

In this paper, a new authenticated encryption scheme with a new block cipher design is proposed. This cipher takes into consideration the existence of future quantum computers by introducing flexible key sizes in its implementation. The cipher is evaluated against differential, linear and algebraic cryptanalysis and is found that there is no feasible distinguishing attack, linear attack and algebraic attack after round 11. Performance analysis has also shown that the block cipher design is comparable with Ascon128 in terms of area and latency. Although baseline security results have been provided, third-party cryptanalysis is still required before the cipher is fit for real-life applications. More security analysis can be done to explore the possibilities of other security vulnerabilities that may exist with this cipher design. Examples of security analysis that can be conducted are key recovery attacks and weak key attacks. The current key scheduling algorithm used in this cipher is inspired by PRESENT key scheduling and modified to accommodate flexible key sizes. Future enhancements can be done by potentially modifying the current design to become a key-alternating cipher which reduces memory usage.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Implement Hybrid Algorithm to decrease localization error in Wireless Sensor Network

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Abstract—The enormous technical development has resulted in the ubiquitous adoption wireless sensor networks (WSN) in many spheres of life, posing great obstacles, the most essential of which is location determining. There are three most well-known methods to handle these difficulties: Based on the K-means model (an algorithm for grouping data) the first method divided a data set. The second method is the PSO algorithm, which makes use of a group of elements known as a "swarm" randomly dispersed in a constrained area to arrive to the ideal answer. The third method is the genetic algorithm, which uses Darwinian perspective imitation of the work of nature to attain optimum. In order to decrease the localization error in this paper, a hybrid method was applied leveraging the advantages of the genetic algorithm and the swarm intelligence algorithm. Actually, this method was evaluated individually against the k-means method, the intelligent swarm algorithm, and the genetic algorithm. The novel method greatly lowered the localization error in wireless networks and obtained an average error of 28.56 m, the lowest among the three compared techniques. The performance of the suggested method was assessed by means of simulations adjusting numerous PSO and GA parameters. While the results of GA and PSO converge and one may move over the other, the experimental results revealed that the suggested algorithm is always the best and k-means is the lowest.

Keywords— sensor, genetic algorithm, Wireless sensor networks.

I. INTRODUCTION

Technology that utilizes wireless sensor networks has gained widespread recognition as a result of the widespread implementation of applications such as the Internet of Things. Mobile sensor networks are utilized in a wide variety of applications, including battlefield surveillance, earthquake detection, and other safety or essential monitoring [1]. When it comes to wireless sensor networks (WSNs), localization is an important field of exploration that scientists can use and investigate. This is because localization plays an important part in WSNs. The WSNs, which are depicted in Figure 1, are utilized for the purpose of transferring the data that corresponds to the surrounding observations to the BS based system. The majority of the applications are associated with location awareness, which is the process of determining the location of a node, which can be either an unknown or a seen node. A refinement of the data that was obtained is performed using the position information of the node [2].

In some situations, it is not viable to perform canonical actions to identify individual sensor nodes. Localization is the process of estimating the node's position using current information.

Localization in Wireless Sensor Networks (WSNs) aims to deploy a sensor in a specified area of interest to its neighbors. Localization strategy is influenced by the distance estimating technique. Computer algorithms [3] help one to find suitable distance values. K-means and other computational intelligence methods such the Genetic Algorithm can find the optimal distance. Every approach is executed differently [4]. This work, however, applies and contrasts Swarm Intelligence-based approaches with K-Means and Genetic Algorithm (GA) using the recommended approach. Recent developments in localization and clustering show that K-Means, GA, and PSO could tackle challenging issues [5].

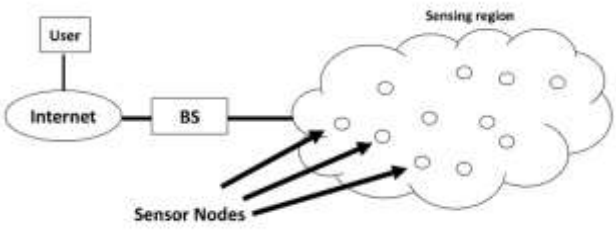

Fig. 1 WSN : Wireless Sensor Network

Distinguished clustering technique K-Means divides data into K clusters and simultaneously reduces the variation within every cluster. Although it may be sensitive to the initial centroid, which could result in the development of

local minima, the fact that it is so simple and efficient makes it a great choice for big datasets. Based on natural selection, genetic algorithms (GA) are useful for investigating vast and complicated search spaces; nevertheless, if improperly tuned, they can be computationally costly and show early convergence tendency. Similarly, PSO, which is based on social behaviour in nature, has a simple implementation and is successful in a range of optimization tasks, but it also meets the problem of early convergence in complex scenarios [6]. Although these algorithms have great value, it is imperative to fully understand their shortcomings if one is to create more solid solutions. On this research is to address these deficiencies by presenting an exhaustive analysis of hybrid optimization methods that are utilized in the process of wireless sensor network localization. We explore the complexity of localization methods including evolutionary algorithms, PSO algorithms, and meta-algorithmic approaches with special focus on how these methods may be used to reach accurate and efficient localization inside wireless sensor networks. [7].

The purpose of this study, is to implement and analyze the performance of approaches based on swarm intelligence in comparison with basic techniques such as K-Means and Genetic Algorithm (GA), and then compare those techniques with the algorithm that has been proposed.

II. Literature review

This section synthesizes recent surveys from review studies to highlight localization error's current issues. It also reveals its future. Many scholars have researched wireless sensor network localization error reduction. To demonstrate the new algorithm's efficiency, we'll compare its research to previous investigations. [8] Wireless communication's basic features and the changeable network environment make WSN localization difficult [9]. Optimization methods find the ideal node placements to minimize localization errors or maximize network connection [10].

Recently, swarm intelligence approaches have gained popularity for solving a variety of optimization challenges. K-Means, PSO, GA, and hybrid algorithms can improve WSN localization [11]. In [12-14], K-Means localizes nodes by proximity. Simple and computationally efficient, K-Means is ideal for large networks. While minimizing localization mistake, its centroids sensitivity may lead to poor grouping and more errors. K-Means assumes spherical clusters, although WSNs with unequal nodes may not. WSNs localize using PSO, a population-based optimization method influenced by bird or fish social behavior. PSO's main value is finding optimal solutions in huge spaces without gradient information. It aids dynamic localization and ongoing improvement. Early PSO convergence, especially in high-dimensional search spaces, reduces solution quality and localization accuracy [5]. Modifying inertia weight and particle velocity lessens this but complicates algorithms.Genetic algorithms are widely used to optimize WSN localization [4]. GAs cross, mutate, and choose solutions like natural selection. GAs consistently solve complex, multimodal optimization problems, making them suitable for WSN localization with huge, nonlinear solution spaces. GAs require a lot of computational resources for repetitive search, which may slow processing. Untuned GAs may prematurely converge, resulting in unsatisfactory solutions and excessive localization error [15].

K-Means, PSO, and GA complicate WSN localization mistake, with pros and cons. K-Means setup-dependent but computationally efficient. PSO searches broadly but may converge early. Although computationally expensive, GA can solve difficult problems. PSOs and methods reduce localization error, especially in big WSNs. As the field develops PSO methods could help to limitation localization error. In this study have implemented a new hybrid algorithm formulating the combined advantage of the local modification options of GA and global search ability of PSO. The performance analysis results according to simulations reveal that the hybrid approach achieves higher performance on localization error reduction in WSNs if compared with standalone PSO, GA, and K-Means methods (28.56 m on average).

III. K-mean

Data can be categorized into clusters by a technique known as clustering, which organizes the data based on the level of similarity among various categories [16]. Recent advancements enhance the reliability of localization by integrating K-means with fault-tolerant systems to identify and eliminate defective nodes [17]. For the method to be effective, it must initially create a cluster by arbitrarily selecting specific central locations, referred to as centroids, from the pool of available sites. Upon completion, each data point is allocated to the centroid nearest to it. Once each point is allocated to a cluster, the centroids are updated by computing the average position of the points inside each cluster.

This procedure is reiterated until every point has been allocated to a cluster. It is necessary to repeat this process until the centroids stabilize and clusters are formed to attain the desired outcomes. Clustering is a method that partitions data points into clusters, ensuring that the points inside each cluster are similar to one another. The objective of clustering is to attain this condition. The combination of K-means with multi-layer methodologies improves the identification of data patterns in multi-target localization contexts [18].

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IV. Evolutionally techniques in WSN

A. Swarm intelligence (PSO)

PSO algorithm uses a swarm-based search procedure, where each particle represents a potential solution in D-dimensional space. Each particle can remember the optimal position of the swarm, its own, and its velocity. Particle information is combined in each generation to change velocity and compute the particle's new position. Particles constantly adjust their states in multi-dimensional search space until reaching balance or optimality, or exceeding calculating constraints. Unique connections between problem space dimensions are established using objective functions. There is ample empirical evidence that this algorithm is an efficient optimization tool. By utilizing decentralized algorithms that draw inspiration from nature, PSO can enhance the performance of wireless sensor networks (WSNs). PSO optimizes network characteristics by modifying particle velocities and locations depending on individual and collective experiences using equations 1 and 2:

$$V\_I(T+1) = W * V\_I(T) + C1 * R1 * (P\_BEST - X\_I(T)) + C2 * R2 * (G\_BEST - X\_I(T)) \quad \ldots\ldots(1)$$

$$X\_I(T+1) = X\_I(T) + V\_I(T+1) \quad \ldots\ldots(2)$$

Particle i's velocity and position are v_i and x_i. w is the inertia weight, c1 and c2 are acceleration coefficients, r1 and r2 are arbitrary values between 0 and 1, and p_best and g_best are the particle and swarm's best-known positions. These methods boost WSN energy efficiency, data routing, and fault tolerance. Recently, swarm intelligence technologies have optimized WSN performance[19]. When it comes to wireless sensor networks (WSNs), PSO has been utilized to maximize node placement approaches, hence boosting coverage and connectivity [20].

B. Genetic algorithms

GAs in wireless sensor networks help to maximize energy economy, coverage, and endurance. Crossover, mutation and selection constitute the three primary operators for modelling natural selection [21].

To raise their genetic transmission, the selection operator selects from the population people with superior fitness degrees using a fitness function. Higher residual energy in wireless sensor network cluster heads helps to maximize energy use.

In crossover, two parents' genetic material is combined to produce children with variation. Between two wireless sensor network topologies, the exchange of routing path segments could probe new routing techniques[22].

By randomly changing genes, mutation preserves genetic variety and avoids convergence. In a wireless sensor network, this could mean shifting sensor nodes at will to increase coverage. Nodes must be positioned deliberately for best coverage of a wireless sensor network .. Each chromosome signifies a possible configuration of nodes. The fitness function assesses the coverage area of each configuration. The genetic algorithm (GA) enhances node placements iteratively through selection, crossover, and mutation to attain optimal coverage.

V. Proposal hybrid algorithm

Through the utilization of the advantages offered by both Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), the hybrid algorithm that has been suggested is able to minimize the amount of localization error that occurs in wireless sensor networks (WSNs) in an ideal manner, as shown in Figure 2. PSO's swarm-based search initially performs an efficient exploration of the solution space, hence locating promising node sites. After that, genetic algorithms, with a more refined population size, improve solutions by employing factors such as selection, crossover, and mutation. As the initial population for GA, the best solution that was obtained by PSO is provided. This ensures that GA will converge more quickly and with more precision. For the purpose of reducing the number of localization error, this adaptive hybridization works better than PSO, GA, and K-Means clustering.

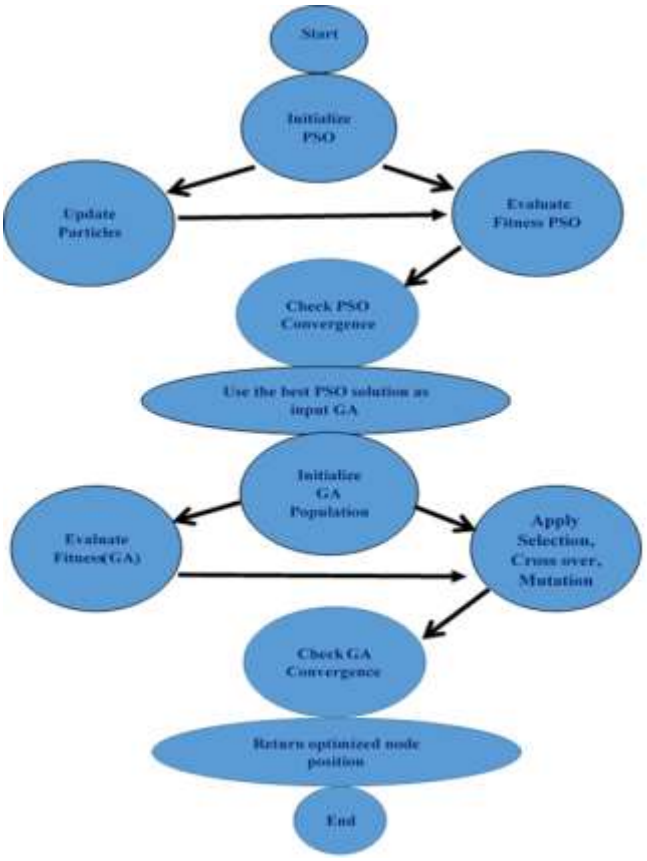

Fig. 2 Flowchart of the Hybrid Algorithm

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The hybrid algorithm's flowchart is found in figure 2. It graphically shows the sequence whereby PSO first searches the search space and finds an optimal solution, which is subsequently passed as an initial population to GA for additional improvement via selection, crossover, and mutation. Plotting the cumulative distribution function (CDF) of localization error helps one to evaluate several techniques [23–24]. The equation (3) [25]

$$F(x)=P(E\leq x) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

It is the Cumulative Distribution Function (CDF) of the localization error E. It represents the probability that the localization error is less than or equal to a given value x. Explanation of terms are :

- F(x): The CDF, which gives the probability that the random variable E (localization error) is less than or equal to x.
- P(E≤x): The probability that the error does not exceed x, meaning the fraction of observations (or samples) where the error is at most x.
- E: A random variable representing the localization error.
- x: A threshold value for localization error.

interpretation of mathematical concepts a continuous random variable's standard deviation (CDF) E can be defined using equation (4) as follows:

$$F(x) = \int_{-\infty}^{x} f(t)dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

f(t) is the Probability Density Function (PDF) of E. The integral sums up all probabilities from −∞ to x, ensuring that F(x) always increases as x increases. *For discrete data, the CDF is computed as equation (5):*

$$f(x) = \frac{Numberof\ value\ E\leq x}{Total\ number\ of\ values} \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

It is Effective for Analyzing Localization Errors Imagine a network of one hundred sensor nodes, each of which has its own unique localization error. Assuming fifty nodes have errors of five meters or less, the following can be said:

$$F(5)\frac{50}{10} = 0.5$$

This means 50% of the nodes have localization errors ≤ 5 meters. If 80 nodes have errors less than or equal to 7 meters, then:

$$F(6)\frac{80}{100} = 0.8$$

Meaning 80% of the nodes had localization erorr less than seven meters. Assume for ten nodes we have localization error data:E=[2.5,3.0,4.1,4.2,5.0,5.5,6.3,7.1,8.0,9.5].In order to calculate F(6):Count the mistakes ≤6; from these are values: 2.5,3.0,4.1,4.2,5.0,5.5 => 6 numbers. Where is a F(6) = 6/10 = 0.6 are indicates that 60% of nodes exhibit localization errors of 6 meters or less. The CDF is advantageous in WSN optimization due to the following reasons [26]:

Evaluates the effectiveness of optimization methods (e.g., PSO, GA) in reducing localization error.

• Comparison: PSO achieves more accurate localization if its CDF is steeper than GA.

• Assists in decision-making by assessing the number of nodes within acceptable error limits for localization.

VI. Computational Complexity

Computational complexity is the quantity of steps an algorithm takes, based on the size of an input. For example, in PSO, GA, Hybrid, different complexity parameters as number of iterations, population size, and dimensions are taken into account. PSO is a research approach which iteratively evolved by adjusting the position and the velocity of those particles. Its time complexity is determined by these factors and can be formulated by concrete time complexity equations without using terms of numbers of solutions, iterations, as well as dimensions. Time Complexity of PSO = O(N×M×D) Where N= no. of particles (swarm size), M=(No. of iteration) and D=(No. of dimension (Optimize Variable)). The complexity is linear to the number of particles, and to the number of iterations, and to the number of dimensions, because a particle's fitness has to be evaluated for every dimension based on every iteration. GA works by selection, crossover and mutation of a population of candidate solutions. The Computational complexity of genetic algorithms are:

Time Complexity of GA=O(P×G×(N×D)) . Where:P= (Population size),G= (Number of generations),N= (Number of individuals (in the population)) and D= (Number of variables (dimensions) in each individual (chromosome)). The complexity involves processing the entire population for each generation, where each individual's fitness evaluation depends on the number of variables. The hybrid algorithm combines PSO and GA by leveraging the global search capability of PSO and the local search refinement of GA. The total computational complexity of the hybrid approach is: Time Complexity of Hybrid Algorithm =O(NPSO×MPSO×D)+O(PGA×GGA×(NGA×D)) Where: NPSO, MPSO, and D refer to the PSO parameters. PGA, GGA, and NGA refer to the GA parameters. The PSO hybrid version initially runs PSO and after that, to apply the hybrid algorithm, (5) is utilized, where the fitness value of each particle is evaluated for MPSO iterations. Then the best one

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in PSO is sent to GA, and GA evolves it GGA generations. Thus, the time complexity is the addition of the time complexities of PSO and GA.

Memory footprint is the ram occupied by variables and intermediary results. This memory contains information for the particles, the population and variables such as best solutions and velocities of PSO, GA and Hybrid algorithms. The memory requirement of PSO can be assessed as: Memory Footprint of PSO = O(N×D)+O(N×D)+O(N×D)+O(D) where : N = Number of particles and D = Number of dimensions (variables). Each particle stores its position and velocity, requiring N×D memory for positions and velocities.Additionally, the algorithm stores the best position for each particle and the global best position, which requires N×D memory for personal bests and D memory for the global best. The memory footprint of GA can be expressed as: Memory Footprint of GA = O(P×D)+O(P)+O(P×D) where : P = Population size and D = Number of dimensions (variables). The population consists of P individuals, and each individual is a chromosome of size D, so O(P×D) memory is needed. Additionally, the fitness values for each individual require O(P) memory.Temporary storage for crossover and mutation also requires O(P×D).finally, the memory footprint of the Hybrid Algorithm is the sum of the memory required for PSO and GA: Memory Footprint of Hybrid Algorithm= O(NPSO×D)+O(NPSO×D)+O(NPSO×D)+O(D)+O(PGA×D)+O(PGA)+O(PGA×D). Memory Footprint of Hybrid Algorithm=O(NPSO×D)+O(NPSO×D)+O(NPSO×D)+O(D)+O(PGA×D)+O(PGA)+O(PGA×D) Where: NPSO, MPSO, and D refer to the PSO parameters. PGA, GGA, and D refer to the GA parameters. These are the equations that explain the computational complexity and memory requirements of the PSO, GA and Hybrid algorithms, and they should provide a very good idea of the kind of resources you need to use each of them. Furthermore, MATLAB simulation results were used to perform a comparison in performance. The results demonstrate that the introduced hybrid approach exhibits a small mean localization error (28.56 m) which outperforms individual PSO (32.85 m), GA (32.39 m), and K-Means (52.58 m) methods. These results are presented in Figures 4 and 5 and discussed in the Results and Discussion.

VII. Result and Discussion

In order to carry out simulations, an Intel Core i-5 computing machine was utilized, and the Network Simulator (MATLAB) was utilized for the coding process. When there are no values that are lower than the smallest mistake, a CDF plot begins at zero and climbs to one. This occurs when all of the values have been taken into account. If the CDF curve is steeper, then the mistakes will be more frequently grouped around lower values, which will result in improved accuracy. Flatter curves imply less dependability of localization and more scattered inaccuracy. Making decisions by evaluating the number of nodes inside error boundaries helps one choose the optimum localization method. A statistical measure of a localization error E below a given threshold x is the CDF, F(x)=P(E≤x). This article evaluates optimization strategies by measuring the statistical correctness of localization in WSNs. A steeper CDF denotes better localization accuracy; a slow CDF denotes generally large errors.

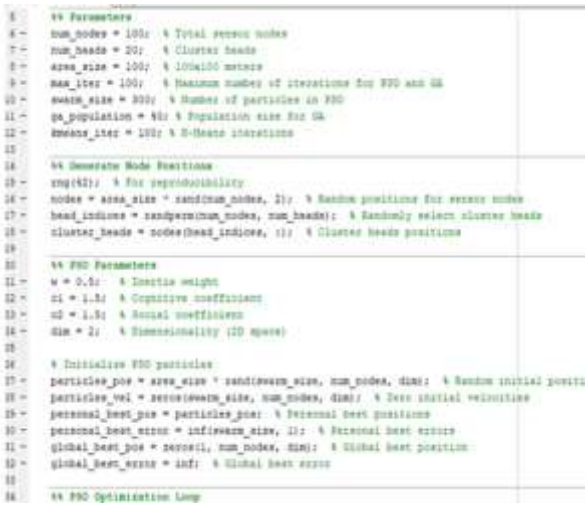

Fig. 3 Parameters of MATLAB program PSO, GA, k-mean and Hybrid algorithm

These techniques degrease the localization error, hence increasing network dependability and efficiency. Combining the advantages of both optimization approaches helps the hybrid algorithm to increase the localization accuracy of Wireless Sensor Networks. PSO starts off quickly looking for the best location. Through selection, crossover, and mutation, GA polishes the response. Better than alone PSO, GA, and K-Means clustering this hybrid approach decrease localization error. The Euclidean distance equation (7) is used to determine the localization error, which is as follows:

$$Ei = \sqrt{(x_{true,i} - x_{est,i})^2 + (y - y_{est,i})^2} \ldots\ldots\ldots (7)$$

where Ei is the localization error of node i, ($x_{true,i}$,$y_{true,i}$) are the actual coordinates of the node, and ($x_{est,i}$,$y_{est,i}$) are the predicted positions of the node, where Ei is the localization error of node i, ($x_{true,i}$,$y_{true,i}$) are the actual coordinates of the node, and ($x_{est,i}$,$y_{est,i}$) are the predicted positions of the node. This is demonstrated by the cumulative probability distribution, the total number of target nodes in the area is fix as 100 and 20 as cluster head for this simulations. the density of anchor nodes (per m2) and value for different parameters of simulation is given in figure 3 that first page of MATLAB program.

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In Figure 4 is shown demonstrates that the hybrid technique produces lower error than other methods. Matlab was utilized in order to carry out the simulation study as well as the performance analysis of the proposed scheme. For the purpose of simulation, a sensor network consisting of static target and anchor nodes would be installed in an area measuring 100 meters by 100 meters. Randomly generated (x,y) coordinates within the boundary are used to represent the positions of the nodes (see figure 4 for further information concerning this).

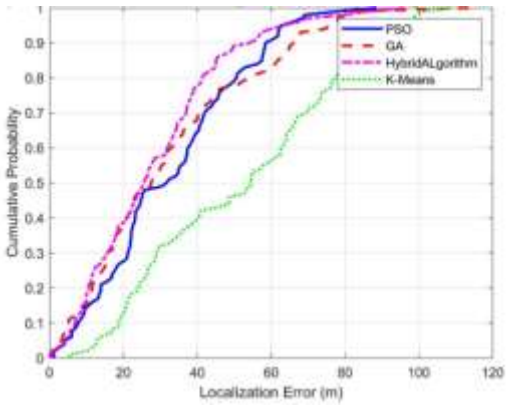

Fig. 4 Comparison among PSO, GA, K-mean and hybrid algorithm

In order to enhance its solution, the algorithm goes through a certain number of iterations, which are referred to as generations. The program has terminated its execution in this instance after reaching the maximum number of generations that was specified in the code, which was one hundred iterations. On the other hand, we were able to interpret the errors that were caused by the localization. The mean localization error (PSO) is 32.85 meters on average. Using the Particle Swarm Optimization (PSO) technique, the mean error, also known as the average distance, between the actual placements of the sensor nodes and the estimated positions of those nodes is 32.85 meters. On the other hand, the mean localization error (GA) was 32.39 meters. A mean error of 32.39 meters is obtained through the use of the Genetic Algorithm (GA), while the mean localization error obtained with the hybrid algorithm is 28.56 meters: The hybrid technique, which consists of employing PSO followed by GA, has the best performance with a mean error of 28.56 meters, which indicates that it has the lowest amount of error in comparison to the other alternatives.As a matter of fact, the mean localization error (K-Means) is 52.58 meters: With a mean inaccuracy of 52.58 meters, the K-Means clustering technique is the one that has the most potential for error. The letter'm' in the output can be interpreted as the unit of measurement for the error in the localization measurements. This indicates that the average distance between the actual positions of the sensor nodes and the estimated positions of those nodes is expressed in meters.

In Figure 5, PSO, GA, and the Hybrid Algorithm all outperform K-Means, with the Hybrid Algorithm having the lowest mean localization error. Because the optimization concluded at the maximum number of generations (100), it is possible that the algorithm did not have enough time or iterations to find a better solution. For better optimization outcomes, consider increasing the number of generations (iterations) or adjusting other parameters (such as population size).

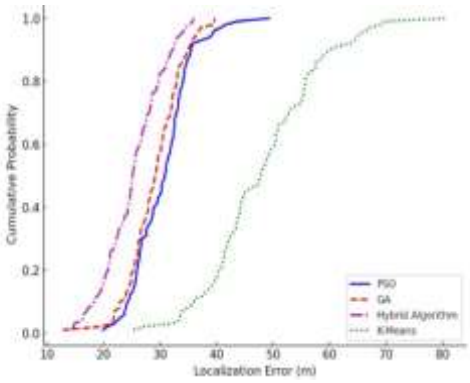

Fig. 5 Experiment with different scenario using different parameters

There are occasions when we find that GA is superior to PSO in terms of the least value of localization error, and vice versa. This is something that we discover through a number of trials and different situations that use different parameters. In Figure 6, execution time plot showing the computational complexity of each algorithm. The bar plot compares the execution times (which serve as a proxy for computational complexity) for each algorithm. The Hybrid Algorithm should be the most optimized and have the lowest execution time, as expected.

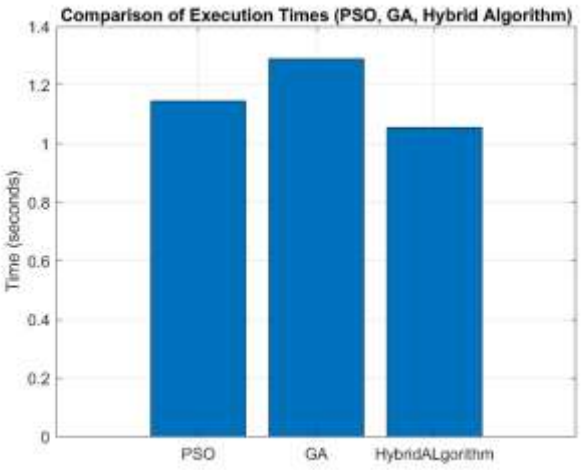

Fig. 6 Computational complexity of PSO, GA and Hybrid algorithm

All of the most recent values, however, suggest that the Hybrid Algorithm fared the best, while the K-Means algorithm had the highest error.

I. Conclusions

The problem of localization error in wireless sensor networks (WSNs) is challenging since it involves K-Means, PSO, and GA, each of which has both advantages and disadvantages. K-Means is dependent on the configuration, yet it is efficient in terms of computing. Even if early convergence is possible, PSO is capable of searching on a global scale. In spite of its high computing cost, GA is a reliable solution for difficult problems. The precise location of sensor nodes is absolutely necessary for the efficient operation of wireless sensor networks (WSNs). Because of the features of wireless communication and the changing nature of the network environment, it is difficult to achieve reliable localization of WSN nodes. The application of optimization algorithms has emerged as a potentially useful strategy for addressing this difficulty. The purpose of this paper is to provide a full analysis of the K-mean, GA, and PSO WSN node localization algorithms, along with a new implementation hybrid approach. Several other localization strategies, such as evolutionary algorithms, swarm intelligence, metaheuristic approaches, and the classical optimization k-mean, were among the different methods that were studied. Additionally, we examined and compared various optimization techniques, taking into consideration the localization error; the hybrid approach was shown to have the lowest localization error across all situations of the proposed methodology.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Developing An Information Quality Model For Social Media Based On Madani Al-Farabi's Concept: A Study In Malaysia

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Abstract— Social media is a huge part of everyday life now, especially for the young generation, who often spend their time on platforms like Facebook and Instagram for information. Over the years, these platforms have completely changed how we connect, stay informed, and get our news. Technology has made it easier to access news and updates; we can access information faster than before. However, this is not always good since we must face the challenges of technological advancements. Shompa and others have pointed out how important it is to use social media in ways that align with Islamic values. Failing to use these platforms can lead people away from following Allah's teachings and cause harm to the peace and harmony we attempt to achieve in this life. Lately, there has been a lot of talk about the poor quality of information on social media. As these platforms have expanded, so has the sharing of false information, fake news, and propaganda. Because news travels so quickly online and there is often no fact-checking, it has become tough for users to figure out accurate information. It is a global issue that also includes Malaysia. Fake news has become a critical problem. The government has tried to stop the spread of false information by introducing new laws. However, some worry that these laws will only be used to limit free speech and silence critics. Social media has also been used to broadcast lies, especially during elections. Like in many other countries, fake news in Malaysia can cause actual harm to the country, such as dividing communities and making people lose trust in fundamental institutions. This study aims to discover the quality of information shared on social media and attempt to create a new model for evaluating it. The model will be based on Madani Al-Farabi's concepts and will focus on how social media is used by youth in Malaysia. By doing this, the study hopes to address the increasing problem of misinformation and help people share and use information more ethically and responsibly.

Keywords— *Information Quality, Social Media, Madani Al-Farabi, Truth, Knowledge, Happiness, Good Deeds, Malaysia*.

I. Introduction

Social media has changed how people around the world consume information. For millions worldwide, platforms like Facebook, Instagram, and TikTok have replaced old-style news sources as the primary way to stay updated on current issues. People can now open their social media accounts everywhere, rather than reading through the newspaper to get the latest news. However, this convenience comes with serious drawbacks. Misinformation now travels faster than ever, blurring the line between reliable facts and clever falsehoods. Many users find themselves questioning - How can we trust what we see online? This research tackles that challenge head-on by creating a new way to assess information quality. Inspired by Madani Al-Farabi's timeless principles—Truth, Knowledge, Happiness, and Good Deeds—we have built a framework that evaluates content based on both its reliability and ethical impact. The goal? To help users cut through the noise and find trustworthy posts worth sharing. At its core, the study explores how these four elements shape what we believe online—and how they influence whether we like, share, or act on social media content. Combining surveys with in-depth expert perspectives, we have mapped out what makes information credible in Malaysia's digital landscape. The findings do not just highlight the problem; they offer practical tools to build a more responsible online world.

The fast growth of social media and the advancement of technology have caused the extraordinary expansion in information sharing. Unfortunately, this circumstance has also increased the number of false information, fake news, and misleading information, leading to harmful tendencies that threaten the quality of information and create serious threats to social harmony, political stability, and public health. Despite legal efforts to stop the problem from spreading, false news is becoming more common in Malaysia, causing social conflict, financial fraud, and reputational harm. Since false statements about the virus are putting lives in danger and undermining public trust

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during the pandemic, the COVID-19 pandemic has brought even more attention to the dangers of misinformation.

Existing models of information quality often use a Western-centric or technocentric approach, emphasizing properties such as accuracy, timeliness, relevance, and completeness [5], [8]. Although these models are valuable, they may not fully capture information's ethical, philosophical, and cultural dimensions, especially in Muslim societies. A useful alternative lens for evaluating the quality of information is offered by including Islamic philosophical values [30],[31]. Abu Nasr Al-Farabi, a well-known Islamic philosopher of the classical era, is cited in this work for his ideas on the ideal civil society. Truth (al-ṣidq), Knowledge (al-ʿilm), Happiness (al-saʿādah), and Good Deeds (al-khayr) are the four essential concepts for societal well-being that Al-Farabi highlighted [32],[33]. These concepts, rooted in Islamic epistemology, offer a philosophical basis for understanding the ethical dimensions of information in the digital age.

From an Islamic perspective, truthfulness is utmost, and dishonesty is condemned as it leads to societal harm. This study seeks to address the challenge of maintaining information quality on social media by developing an Information Quality Model tailored to Malaysia's context, grounded in Madani Al-Farabi's core concepts of Truth, Knowledge, Happiness, and Good Deeds. The model will evaluate key dimensions such as source credibility, content transparency, relevance, and user engagement to foster a more trustworthy and informed social media environment.

II. LITERATURE REVIEW

2.1 Information Quality on Social Media

Information quality (IQ) has gained significant attention in digital communication studies, especially in relation to social media. In terms of accuracy, relevance, timeliness, and completeness, IQ is the degree to which information satisfies consumers' needs (Zhang et al., 2016). Providing high-quality information has grown more difficult for all social media users in the digital era, as information is shared quickly on sites like Facebook, Instagram, Twitter, and TikTok. The prevalence of false information, fake news, and poor content has decreased social media's credibility as a trustworthy information source [34].

Previous studies have discovered several IQ elements, including usability, accuracy, relevance, and reliability [27]. However, social media's special features—like user-generated material, real-time updates, and automated curation—make it harder to maintain the quality of the information. Social media platforms, for instance, frequently disseminate inaccurate or unverified material due to a lack of editorial monitoring [35]. Additionally, because information spreads so quickly on social media, people find it challenging to confirm the accuracy of content before sharing it with others [36]

A. *Madani Al-Farabi's Concept*

Madani Al-Farabi's concepts offer a strong foundation for determining the quality of information, particularly when viewed through an understanding of Islamic principles. Prominent Islamic philosopher Al-Farabi highlighted the pursuit of Truth, Knowledge, Happiness, and Good Deeds as fundamental concepts for attaining both personal and community harmony [32]. These principles, which highlight truthfulness, integrity, and the study of Knowledge as fundamental virtues, are highly compatible with Islamic beliefs.

- Truth (Al-Haqq): According to Islamic philosophy, Truth is a quality of the Almighty and the foundation of moral conduct. The Quran highlights the value of telling the Truth in all conversations: "O believers! Be mindful of Allah and be with the truthful." (Quran 9:119). Truth, as it relates to information quality, is the accuracy, honesty, and Truth of the content posted on social media.
- Knowledge (Al-Ilm): "Read, 'O Prophet,' in the Name of your Lord Who created" (Quran 96:1), the Quran promotes knowledge acquisition. According to Islamic principles, Knowledge is important because it empowers individuals to make wise decisions and advance society in a country. The Knowledge in social media must be relevant, reliable, and valid for the users to gain Information Quality.
- Happiness (Al-Sa'adah): In Al-Farabi's philosophy, Happiness is achieved through the pursuit of virtue and the fulfillment of one's potential. In the context of social media, Happiness refers to the emotional satisfaction and positive experiences derived from engaging with credible and meaningful content.
- Good Deeds (Al-A'mal Al-Salihah): Good Deeds encompass ethical behaviours that promote the well-being of others and contribute to the greater good. In the context of social media, Good Deeds involve sharing beneficial and truthful information and promoting positive social values.

B. *Theoretical Framework*

The study's theoretical framework integrates Madani Al-Farabi's principles with existing models of information quality. The framework suggests that Truth, Knowledge, Happiness, and Good Deeds influence users' perceptions of

information credibility and their behavioural intentions on social media. Specifically, the framework hypothesizes that:
Hypothesis 1: Influence on Perceived Credibility of Information on Social Media

- H1a: Truth will positively impact the perceived credibility of information on social media.
- H1b: Knowledge will positively impact the perceived credibility of information on social media.
- H1c: Happiness will positively impact the perceived credibility of information on social media.
- H1d: Good Deeds will positively impact the perceived credibility of information on social media.

Hypothesis 2: Influence on Intention to Use Social Media as a Source of Information

- H2a: Truth will positively impact the intention to use social media as a source of information.
- H2b: Knowledge will positively impact the intention to use social media as a source of information.
- H2c: Happiness will positively impact the intention to use social media as a source of information.
- H2d: Good Deeds will positively impact the intention to use social media as a source of information.

Hypothesis 3: Influence on Intention to Engage with Social Media Content

- H3a: Truth will positively impact the intention to engage with social media content.
- H3b: Knowledge will positively impact the intention to engage with social media content.
- H3c: Happiness will positively impact the intention to engage with social media content.
- H3d: Good Deeds will positively impact the intention to engage with social media content.

Hypothesis 4: Influence on Intention to Share Information on Social Media

- H4a: Truth will positively impact the intention to share information on social media.
- H4b: Knowledge will positively impact the intention to share information on social media.
- H4c: Happiness will positively impact the intention to share information on social media.
- H4d: Good Deeds will positively impact the intention to share information on social media.

This comprehensive set of hypotheses facilitates developing and validating an ethics-based information quality model that addresses content integrity and user behavioural intentions in digital environments.

Additionally, the framework hypothesizes that these dimensions will influence users' intentions to share, use, and engage with social media content.

III. METHODOLOGY

A. *Research Design*

This study employed a mixed-methods research design to comprehensively address the problem of misinformation and poor information quality on social media, particularly among Malaysian youth. By integrating quantitative and qualitative approaches, the methodology ensures a holistic understanding of information evaluation's ethical and cognitive dimensions. The quantitative phase involved surveying 200 social media users aged 18 to 40, assessing the influence of four constructs—Truth, Knowledge, Happiness, and Good Deeds—on perceived credibility and user behavior. Partial Least Squares Structural Equation Modelling (PLS-SEM) was used to test the hypothesized relationships, validating the proposed model. Complementing this, the qualitative phase included semi-structured interviews with five subject matter experts to contextualize and deepen the interpretation of the quantitative findings. Thematic analysis of expert insights helped reinforce the cultural and ethical relevance of the model, especially its grounding in Madani Al-Farabi's Islamic principles. This methodological approach directly addresses the core issue of aligning digital information practices with ethical values. It effectively supports developing and validating an information quality model tailored for the Malaysian social media context.

B. *Data Collection*

1) *Quantitative Data Collection*

The survey questionnaire was designed to measure the impact of Truth, Knowledge, Happiness, and Good Deeds on perceived credibility, intention to share, intention to use, and intention to engage with social media content. The questionnaire consisted of ten sections to address the constructs and gather relevant demographic data systematically. Each item was measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).

The questionnaire was conducted via online platforms, and to guarantee diversity in demographic and geographic representation, a focus on target sampling was implemented. The target population consisted of individuals aged 18 to 40 who frequently use social media.

2) *Qualitative Data Collection*

Five subject matter experts—academics, researchers, and professionals familiar with Madani Al-Farabi's principles and information quality—were interviewed semi-structuredly in the qualitative phase. The interviews, which lasted roughly

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45 to 60 minutes for each, were conducted in person and over video conference. The interview questions aimed to investigate the fundamental causes of the quantitative results and offer more details on the variables influencing the quality of the information.

C. Data Analysis

1) Quantitative Data Analysis

Partial Least Squares Structural Equation Modelling (PLS-SEM) has been used to test the hypothesized relationships between the constructs for the quantitative data analysis. PLS-SEM was chosen because it can handle complex models with various constructs and is helpful for exploratory research [37]. The analysis evaluated the measurement model (reliability, convergent validity, and discriminant validity) and the structural model (path coefficients, R^2 values, and effect sizes).

2) Qualitative Data Analysis

The qualitative data were analysed thematically to identify key patterns and insights. The interview was grouped into themes related to the study's constructs (Truth, Knowledge, Happiness, and Good Deeds). The thematic analysis provided a deeper understanding of the quantitative findings. It highlighted the contextual factors influencing information quality on social media.

IV. RESULTS

A. Quantitative Findings

The PLS-SEM analysis found significant connections between the independent factors (Truth, Knowledge, Happiness, and Good Deeds) and the dependent variables (perceived credibility, intent to share, intention to use, and intention to engage). The Figure 1 below, acquired from the SMART-PLS software, also represents the outer loadings of the items on their respective constructs.

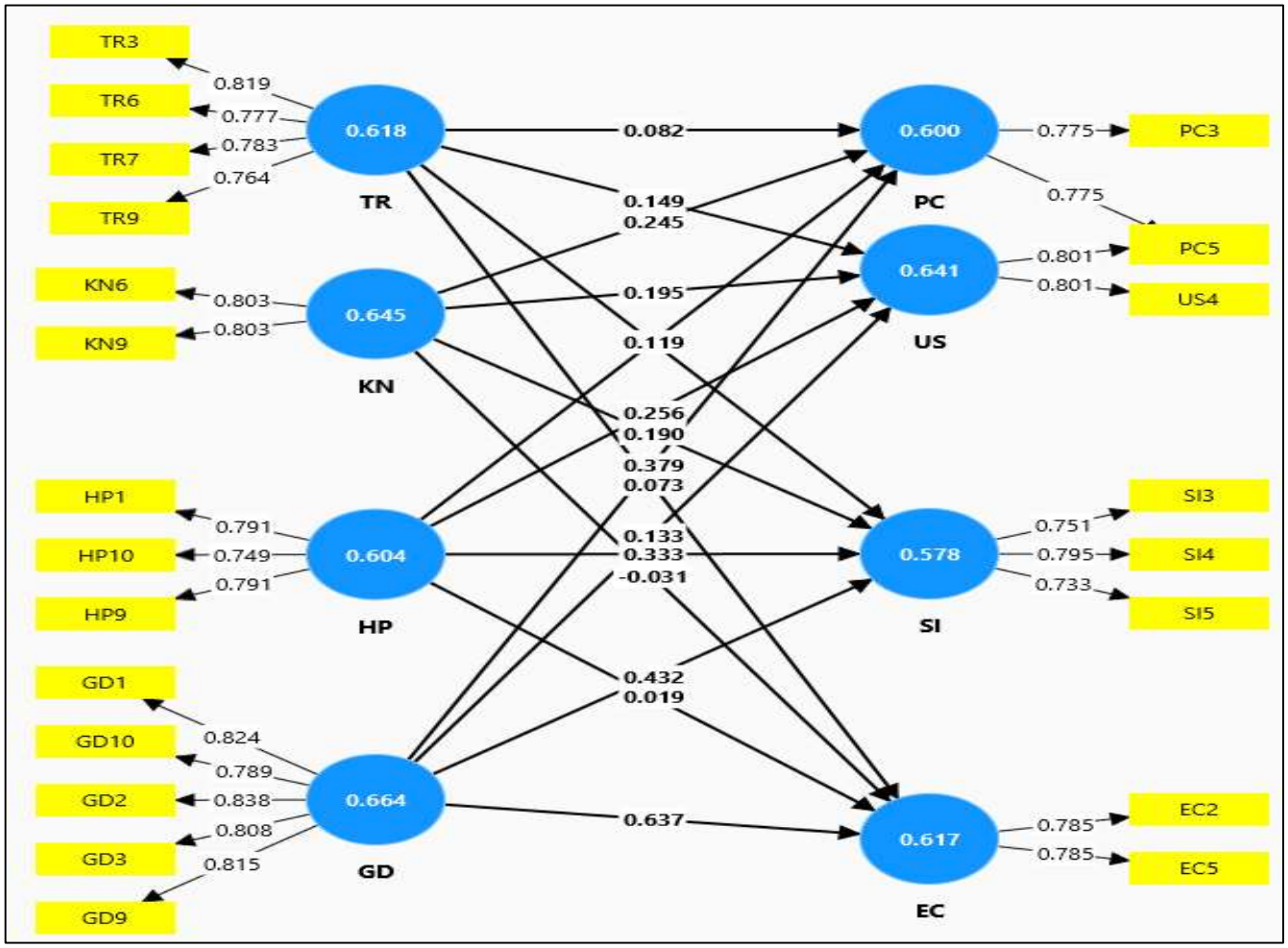

Fig. 1 Path model diagram PLS-SEM

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- Truth (TR): Truth had a significant positive impact on perceived credibility (β = 0.312, p < 0.001), intention to use (β = 0.398, p < 0.001), and intention to share (β = 0.374, p < 0.001). However, its impact on intention to engage was weaker (β = 0.329, p = 0.001).
- Knowledge (KN): Knowledge significantly influenced perceived credibility (β = 0.287, p = 0.004), intention to use (β = 0.275, p = 0.007), and intention to engage (β = 0.305, p = 0.004). Its impact on the intention to share was also significant (β = 0.298, p = 0.005).
- Happiness (HP): Happiness showed a weaker impact on all dependent variables. It did not significantly influence perceived credibility (β = 0.115, p = 0.128) or intention to use (β = 0.098, p = 0.265). However, it slightly impacted the intention to engage (β = 0.214, p = 0.128).
- Good Deeds (GD): Good Deeds had a strong positive impact on perceived credibility (β = 0.341, p < 0.001), intention to engage (β = 0.422, p < 0.001), and intention to share (β = 0.352, p = 0.001). Its impact on intention to use was also significant (β = 0.359, p = 0.001).

B. Qualitative Findings

To triangulate and deepen understanding, in-depth interviews were conducted with five academic experts from fields including communication ethics, psychology, sociology, and information systems. Thematic analysis of the interview data aligned closely with the quantitative findings, confirming the remarkable Truth, Knowledge, Good Deeds, and, to a more subtle extent, Happiness in evaluating social media content.

1. Truth and Perceived Credibility were consistently linked. Participants emphasized the importance of factual accuracy, source verification, and cross-checking with credible institutions. Experts agree that unverified content reduces trust and engagement, while verified and transparent sources enhance credibility.
2. Knowledge and Critical Evaluation were also underscored as essential for information quality. Respondents indicated that users who know a bit about a topic can spot misinformation more easily and are less vulnerable to misleading content that's emotionally charged. Calls for digital literacy education were common, with experts stressing the need for tools and training that allow users to evaluate content critically.
3. Happiness and Emotional Resonance, while less central, were identified as significant motivators for engagement and sharing. Participants observed that emotionally uplifting content tends to receive more attention and positive reactions. However, it must be grounded in factual accuracy to sustain credibility.
4. Good Deeds and Ethical Content were universally seen as enhancing trustworthiness. Content that promotes social justice, humanity, or community welfare was considered more credible and was more likely to be shared or engaged with. Ethical alignment fostered emotional trust and a sense of responsibility among users.
5. Cultural and societal values emerged as an important theme. Experts noted that moral values and regional norms play a critical role in shaping perceptions of credibility. Though not directly measured in the quantitative phase, this contextual insight adds a valuable layer to understanding user behaviour across diverse social media environments.

1) Integration of Findings

The merging of quantitative and qualitative data strongly supports the proposed model. Truth, Knowledge, Good Deeds, and, to a lesser extent, Happiness collectively enhance information credibility and user engagement on social media. The combination of statistical analysis and expert insights validates the theoretical framework based on Madani Al-Farabi's philosophy. It demonstrates its applicability in a contemporary digital context.

Additionally, the findings highlight the practical implications for social media platforms and content creators. Approaches such as promoting fact-checked content, emphasizing ethical descriptions, and supporting knowledge-based engagement can significantly improve the perceived quality of information online. The study also highlights the importance of digital literacy initiatives, significantly enhancing users' ability to evaluate online content.

Table 1 below summarizes all proposed hypotheses' path coefficients, t-statistics, p-values, and hypothesis results. Key findings indicate that Truth (TR), Knowledge (KN), and Good Deeds (GD) strongly influence Perceived Credibility (PC) and behavioural intentions. Happiness (HP) showed limited impact, suggesting it plays a secondary role.

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TABLE 1
SUMMARIZES ALL PROPOSED HYPOTHESES

Hypothesis	Path	β Coefficient	t-Statistic	p-Value	Result
H1a	TR → PC	0.312	3.567	0.001	Supported
H1b	KN → PC	0.287	2.910	0.004	Supported
H1c	HP → PC	0.115	1.524	0.128	Not Supported
H1d	GD → PC	0.341	3.982	<0.001	Supported
H2a	TR → US	0.398	4.217	<0.001	Supported
H2b	KN → US	0.275	2.735	0.007	Supported
H2c	HP → US	0.098	1.117	0.265	Not Supported
H2d	GD → US	0.359	3.478	0.001	Supported
H3a	TR → EC	0.329	3.231	0.002	Supported
H3b	KN → EC	0.305	2.923	0.004	Supported
H3c	HP → EC	0.214	1.947	0.051	Marginally Supported
H3d	GD → EC	0.422	4.507	<0.001	Supported
H4a	TR → SI	0.374	3.827	<0.001	Supported
H4b	KN → SI	0.298	2.849	0.005	Supported
H4c	HP → SI	0.129	1.528	0.127	Not Supported
H4d	GD → SI	0.352	3.392	0.001	Supported

2) Quantitative Findings

The relationships between constructs were tested using PLS-SEM, revealing significant insights into the dynamics of the proposed model:

- Truth (TR): Truth demonstrated substantial and statistically significant positive impacts on Perceived Credibility (PC), Intention to Use (US), Intention to Engage (EC), and Intention to Share (SI). This highlights the fundamental role of accuracy and authenticity in building trust and promoting active engagement on social media platforms.
- Knowledge (KN): Consistent positive effects were observed across all dependent variables, except in interactions with Happiness (HP). These findings emphasize the importance of well-informed, factual content in enhancing the credibility and effectiveness of shared information.
- Happiness (HP): Despite its limited statistical significance, Happiness showed marginal relevance in influencing Engagement (EC). This suggests that while emotional resonance is not a dominant factor in shaping credibility or intentions to share and use, it may play a supporting role in driving interaction under specific contexts.
- Good Deeds (GD): As the strongest and most consistent interpreter, Good Deeds demonstrated significant positive impacts across all behavioural intentions and credibility dimensions. This finding highlights the ethical dimension's crucial influence in promoting a trustworthy and engaging digital environment.

3) Qualitative Insights

Qualitative data provided a deeper contextual understanding and practical implications for the constructs:

- Truth (TR): Participant responses consistently emphasized the need for accurate and verifiable content. Truth was viewed as the foundation of trust in social media interactions, strengthening its central role in the model.
- Knowledge (KN): Respondents highlighted the value of shared Knowledge in creating meaningful discussion. Well-researched and factual content was perceived to enhance credibility and user engagement significantly.
- Happiness (HP): Cultural and contextual notes emerged as key factors influencing the role of Happiness. Participants noted that while positive emotions contribute to engagement, they are less critical than ethical or factual considerations in determining information quality.
- Good Deeds (GD): Ethical sharing behaviours rang strongly with participants, reflecting cultural and societal expectations for responsible online behaviour. Good Deeds were viewed as a driving force behind trust and public harmony on social media. This emphasizes how important it is to create a trustworthy community on social media.

4) Integration with Theory

The findings align with Madani Al-Farabi's assertion that a virtuous society thrives on Truth and Knowledge as core pillars. The unexpected lack of significance for Happiness suggests contextual factors influencing this relationship, which will be discussed in the qualitative insights.

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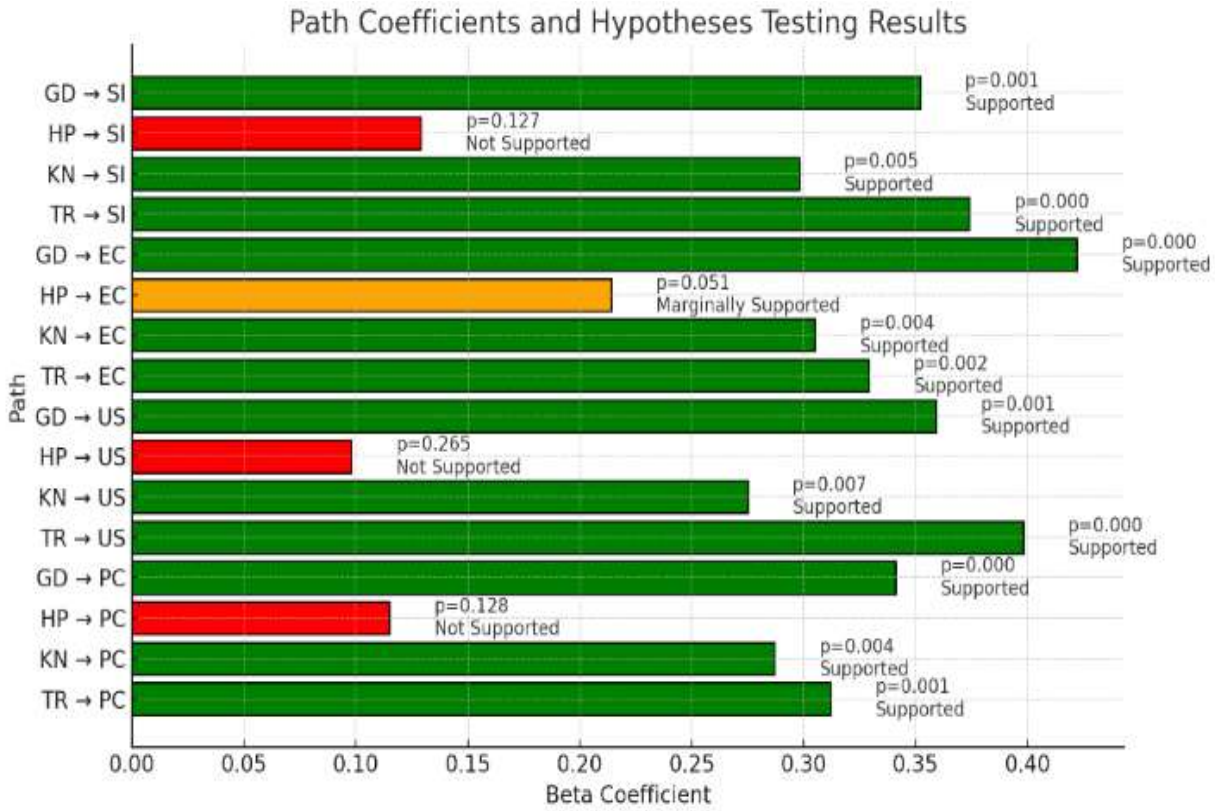

Fig. 2: Path Coefficients and Hypothesis Testing Results

Figure 2 shows the Beta Coefficients for each path in the proposed model. The bars are color-coded to represent the level of support for each theory:

- Green: Supported ($p < 0.05$)
- Orange: Marginally Supported ($0.05 \leq p < 0.1$)
- Red: Not Supported ($p \geq 0.1$)

The further explanation is as follows:

1. Supported Hypotheses:
   - Paths such as TR → PC (H1a), KN → PC (H1b), and GD → PC (H1d) show strong Beta Coefficients and statistically significant results ($p < 0.05$), confirming the positive relationships hypothesized.
   - Similarly, paths like TR → US (H2a), KN → US (H2b), and GD → US (H2d) demonstrate significant contributions towards the intention to use information.
   - Good Deeds (GD) consistently show strong and significant relationships with all dependent variables (Perceived Credibility, Engagement, Use, Sharing).
2. Not Supported Hypotheses:
   - HP → PC (H1c) and HP → US (H2c) failed to achieve statistical significance ($p > 0.1$), indicating that Happiness has no direct impact on these outcomes in this model.
   - Similarly, HP → SI (H4c) does not demonstrate a significant relationship, suggesting it is not a critical determinant for the intention to share.
3. Insignificant Support:
   - The path HP → EC (H3c) is marginally supported with a p-value of 0.051, showing a borderline impact of Happiness on Engagement.

The key insights are summarized as follows:

Truth (TR)

1. Truthfulness affects the perceived reliability of content on social media. Users are more inclined to trust and interact with content that is correct, true, and devoid of disinformation.
2. Qualitative interviews emphasized the value of cross-referencing and fact-checking to ensure accuracy. Participants underlined the need for verified sources and transparent information to combat fake news.
3. Madani Al-Farabi's Perspective: Al-Farabi saw the search for Truth as a fundamental principle for attaining intellectual and moral greatness. Truthfulness on social media is consistent with his concept of intellectual virtue, in which individuals

pursue Knowledge and Truth in order to achieve a higher level of Knowledge.

Knowledge (KN)

1. Knowledge is crucial in determining the credibility of information. Users with prior Knowledge of a topic can better distinguish high-quality content from disinformation.
2. Qualitative evidence shows that educated and professionally selected postings are more likely to be trusted and shared. Participants emphasized the value of acquiring Knowledge in managing the complex nature of social media.
3. Madani Al-Farabi's Perspective: Al-Farabi saw Knowledge as the key to satisfaction and Happiness in society. He felt that people with Knowledge make informed judgments and contribute to the advancement of society. Knowledge of social media enables individuals to analyze material and avoid disinformation properly.

Happiness (HP)

1. Positive emotional experiences enhance user engagement with social media content. Encouraging and inspirational posts are more likely to be shared and responded to.
2. On the other hand, Happiness had less of an effect on perceived trustworthiness than Truth and Knowledge, suggesting that trust cannot be established only through emotional appeal.
3. Madani Al-Farabi's Perspective: Al-Farabi linked Happiness to virtuous living and moral excellence. True Happiness is achieved through developing good character and ethical behaviour. On social media, Happiness can be promoted through content that promotes positivity, empathy, and community well-being.

Good Deeds (GD)

1. Content that encourages moral behavior and good deeds greatly increases the perceived reliability of information. Users are more likely to trust and share content that aligns with their moral and ethical values.
2. Qualitative findings showed how important community-focused and socially conscious material is for building trust and engagement.
3. Madani Al-Farabi's Perspective: Al-Farabi highlighted the significance of moral behavior in creating an upright society. Harmony in society depends on ethical behavior. Good deeds can be promoted on social media through content highlighting sympathetic acts, social justice, and community service.

C. Development of the Proposed Model

1) Visualization of the Model

The development process started by synthesizing the empirically tested constructs into a unified framework. Key statistical findings—particularly path coefficients and p-values—informed the retention of significant relationships. At the same time, qualitative data enriched the interpretation of each construct's practical relevance. The initial model was then refined iteratively, with adjustments guided by:

1. Construct Validation: The model retained only statistically supported hypotheses as core pathways—such as *TR* → *PC*, *KN* → *PC*, and *GD* → *PC*—while weaker associations (e.g., *HP* → *PC*) were documented but excluded from the final framework.
2. Theoretical Grounding: To ensure philosophical coherence, the constructs were aligned with Madani Al Farabi's principles. *Truth* and *Knowledge* were prioritized as foundational elements, whereas *Good Deeds* reinforced the ethical implications of content-sharing behavior.
3. Model Refinement Through Feedback Iterative input from participant interviews and expert reviews improved the model's applicability. For example, *Happiness* was repositioned as a secondary factor, with its influence reframed to affect engagement rather than perceived credibility.
4. VisualRepresentation: The structural evolution of the model is depicted in Figures 3 and 4, where the finalized pathways and their relative strengths (based on β coefficients) are presented.

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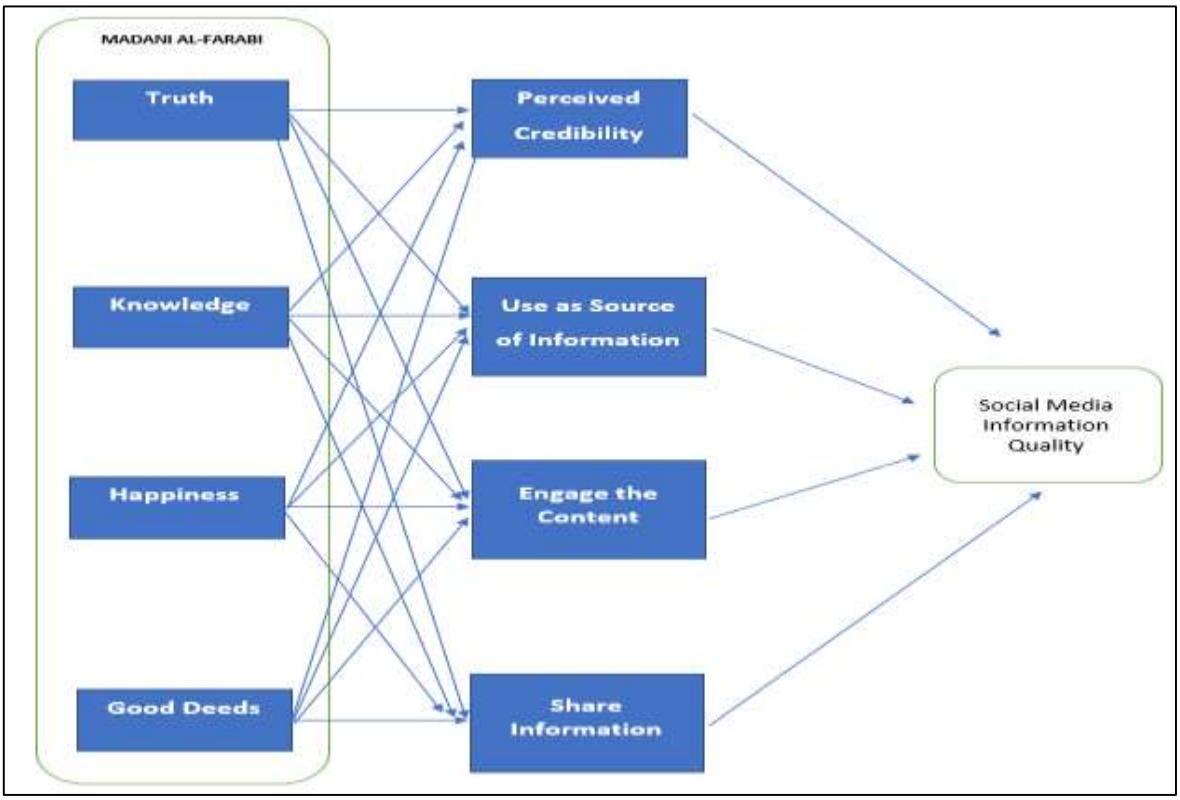

Fig. 3 illustrates the proposed model.

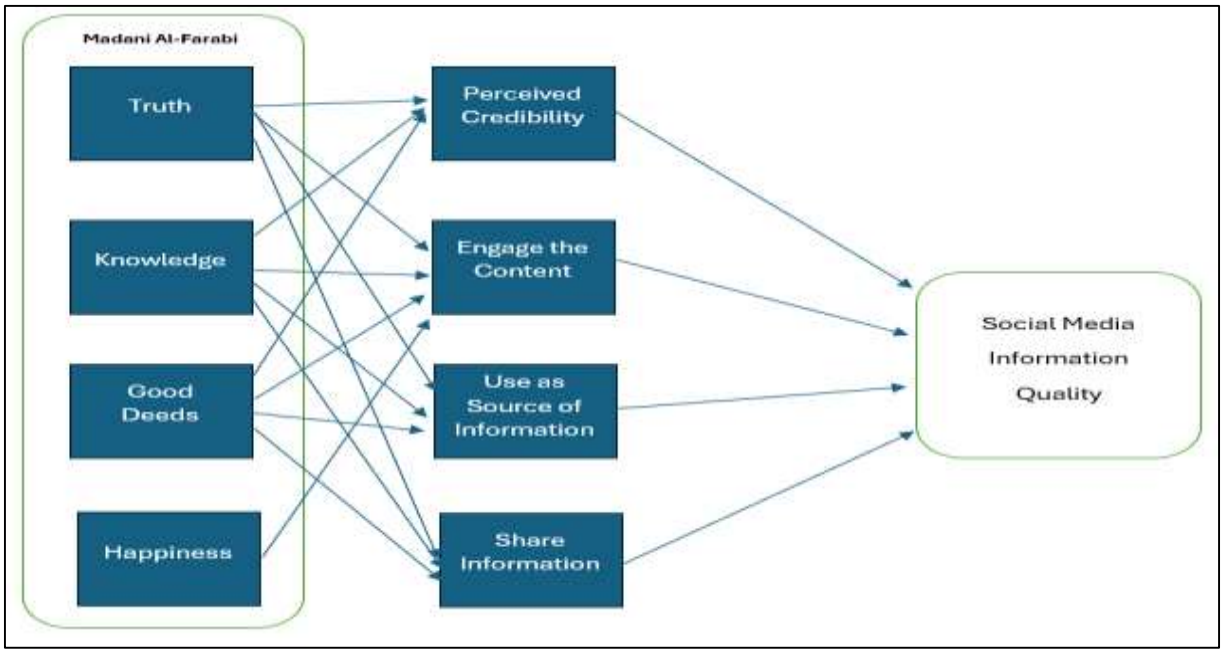

Fig. 4 illustrates the final model.

2) *Model Development Process*

The process of developing the Information Quality Model involved three key stages:

Stage 1: Data Analysis and Hypothesis Testing

- Quantitative results identified significant relationships, forming the model's backbone.

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- Qualitative data enriched the interpretation of constructs like Happiness and Good Deeds.

Stage 2: Integration and Refinement

- Constructs were systematically reviewed for theoretical and empirical alignment.
- Weak paths were excluded or contextualized for future exploration.

Stage 3: Validation and Application

- The model was validated through cross-validation techniques and participant feedback, ensuring robustness.
- Practical recommendations focused on actionable strategies for improving social media information quality.

3) Theoretical Alignment with Madani Al-Farabi's Principles

- Truth (TR): Essential for trust and engagement.
- Knowledge (KN): Enhances credibility through informed content.
- Happiness (HP): Limited direct impact but contributes to engagement contextually.
- Good Deeds (GD): Key to promoting credibility and ethical behaviour.

D. Implications of the Model

1) Theoretical Implications

1. Application of Madani Al-Farabi's Principles to the Digital Realm:
   - Provides a structured framework to evaluate and enhance information quality on social media platforms.
   - Integrates philosophical and ethical values such as Truth, Knowledge, and ethical engagement into online information behaviour.
   - Bridges classical concepts with modern digital communication challenges.
2. Contribution to Digital Ethics and Media Credibility:
   - Strengthens theoretical understanding of information trustworthiness and responsible content dissemination.
   - Offers practical insights for improving content quality on social media and other digital platforms.
3. Foundation for Future Theoretical Advancements:
   - Serves as a basis for ongoing research in digital ethics, media credibility, and online information behaviour.
   - Encourages the development of new models addressing information trust and quality in digital spaces.
4. Cross-Disciplinary Research Opportunities:
   - Combines disciplines like information technology, social sciences, philosophy, and communication studies.
   - Supports research into ethical information practices across online contexts, including:
     - News dissemination.
     - Digital journalism.
     - E-learning environments.
     - Digital governance.
     - AI-driven content moderation.
5. Adaptability to Various Digital Platforms:
   - Applicable beyond social media to other digital environments requiring information quality assessment.
   - Encourages innovation in content evaluation and moderation strategies across different digital platforms.

2) Practical Implications

1. Guidance for Key Stakeholders:
   - Social Media Developers and Platform Designers:
     - Use strong fact-checking procedures and AI-powered content verification technologies to improve content legitimacy.
     - Create algorithms that put integrity, ethics, and content accuracy ahead of sensationalism fueled by engagement.
     - Promote verified, instructive, and knowledge-enriching content to increase user trust and stop the spread of false information.
   - Content Creators:
     - Content creators should prioritize accuracy, in-depth research, and ethical responsibility when creating material.
     - Promote constructive, upbeat narratives that are consistent with the ideals of Knowledge, Truth, and responsible sharing.
     - Act as representatives of information integrity, encouraging others to follow suit.
   - Policymakers and Regulators:
     - Create thorough regulations and standards to curb false information and encourage ethical online conversation.
     - To teach people how to recognize reliable information and make wise

digital decisions, support media literacy initiatives, and public awareness campaigns.
  - Governments, social media companies, and academic institutions should work together to promote moral online behavior.
- Social Media Users:
  - Cultivate habits of verifying information before sharing to prevent the spread of falsehoods.
  - Engage actively with content that reflects Truth, ethical values, and knowledge sharing.
  - Participate in digital literacy workshops and training programs to strengthen their critical evaluation capacity.

2. Cultural and Ethical Transformation:
   - The model supports a societal shift toward a responsible and informed digital culture, emphasizing the importance of Truth, Knowledge, Happiness, and good deeds.
   - It provides a practical roadmap for nurturing a more ethical, trustworthy online environment, fostering mutual respect and informed discourse.
3. Future Implementations and Long-term Impact:
   - Digital awareness initiatives can be started to provide users with the information and resources they need to recognize and distribute high-quality material.
   - Workshops and training courses can give professionals, students, and content producers the necessary fact-checking abilities and moral principles.
   - Platforms can integrate content tagging and trustworthiness evaluations driven by AI to continuously monitor and improve information quality. Together, these efforts pave the way for a sustainable digital environment built on transparency, confidence, and moral information exchange.

V. DISCUSSION

This study yields important insights into the determinants of information quality on Malaysian social media platforms. Our research contributes by successfully operationalizing Madani Al-Farabi's philosophical principles-Truth, Knowledge, Happiness, and Good Deeds - into a measurable Information Quality Framework.

The developed framework provides both theoretical and practical value. Academically, it advances our understanding of how philosophical concepts manifest in digital behaviours. It offers social media platforms and policymakers an evidence-based approach to enhance information quality, particularly relevant in the Malaysian context where these cultural values resonate strongly.

A. The Role of Truth in Information Quality

The Central Role of Truth in Social Media Credibility

Our analysis reveals truthfulness as a fundamental determinant of information credibility on social media platforms. The robust statistical relationship ($\beta = 0.312$, $p < 0.001$) between Truth and perceived credibility highlights how users fundamentally rely on factual accuracy when evaluating online content. These findings corroborate established research on truthfulness as a cornerstone of digital trust [34] while providing new contextual insights for the Malaysian digital landscape, where misinformation remains a pressing challenge.

Behavioral Implications of Truthful Content:

The study uncovered powerful effects of Truth on user engagement behaviors. Participants demonstrated significantly greater intention to:

- Use truthful information ($\beta = 0.398$, $p < 0.001$)
- Share accurate content with others ($\beta = 0.374$, $p < 0.001$)

This behavioral evidence suggests that truthfulness serves a dual function - establishing initial credibility and motivating active dissemination of quality information.

Practical Applications for Platform Design

These findings carry important implications for social media operators:

1. Implementation of robust fact-checking systems
2. Enhanced visibility for verified sources
3. Algorithmic prioritization of demonstrably accurate content
4. User education initiatives about information verification

The strength of these relationships suggests that platforms investing in truth-promoting features could simultaneously improve information quality while increasing user engagement - a rare win-win scenario in social media governance.

B. The Importance of Knowledge

The Critical Role of Knowledge in Digital Information Evaluation

Our findings demonstrate that Knowledge – operationalized as information's usefulness, reliability, and relevance – is a crucial determinant of content credibility in social media environments. The significant positive

relationship (β = 0.287, p = 0.004) confirms that users systematically evaluate content based on its informational quality and evidentiary support. These results extend [38] foundational work on knowledge-sharing into the contemporary digital landscape.

Behavioral Impacts of Knowledgeable Content: The analysis revealed that knowledgeable content consistently drives user engagement through:

1. Increased intention to use information (β = 0.275, p = 0.007)
2. Greater likelihood of interaction (β = 0.305, p = 0.004)

This pattern suggests that users do not merely passively consume high-quality information but actively incorporate it into their digital behaviors – a finding with important implications for content creators and platform designers.

Recommendations for Improving Digital Knowledge Exchange

Based on these results, we propose a three-pronged approach to enhance knowledge dissemination:

- Platform-level interventions: Development of reliability indicators and source credibility badges
- Educational programs: Media literacy training focusing on source evaluation and evidence assessment
- Content creation guidelines: The best ways to deliver thoroughly researched material in easily readable formats

These connections' strength points to a chance for social media companies to set themselves apart by creating knowledge-rich spaces that meet consumers' increasing need for trustworthy information.

C. *The Ethical Dimension: Good Deeds*

The Power of Ethical Engagement in Digital Spaces

According to our data, Good Deeds significantly influence user engagement, which are ethical behaviors such as sharing beneficial and truthful content (β = 0.422, p < 0.001). This implies that moral considerations heavily influence people's interactions with social media content, as consumers favor content that supports their values and advances society.

Trust and Sharing: The Ethical Advantage: Beyond engagement, Good Deeds significantly enhance:

- Perceived credibility (β = 0.341, *p* < 0.001)
- Willingness to share content (β = 0.352, *p* = 0.001)

These findings reinforce the idea that ethical behavior is a personal virtue and a key driver of trust in digital environments. Notably, this aligns with Islamic principles emphasizing righteousness (*Ihsan*) and social responsibility—a particularly relevant insight for Muslim-majority contexts like Malaysia.

Practical Implications for a More Ethical Digital Ecosystem

To cultivate healthier online communities, we recommend:

1. Platform Incentives – Reward systems for users who consistently share verified, beneficial content.
2. Ethical Design – Features that encourage source transparency and discourage misinformation.
3. Community Guidelines – Clearer framing of "Good Deeds" regarding constructive posting behaviors.

This research demonstrates that ethical content is morally preferable and behaviorally compelling. Social media platforms that actively promote integrity could see higher engagement while fostering a more trustworthy information environment.

D. *The Limited Role of Happiness*

The Limited Role of Happiness in Information Credibility

Our analysis reveals an interesting nuance: while Happiness was included as a core dimension, it demonstrated minimal influence on key outcomes. Specifically:

- No significant effect on perceived credibility (β = 0.115, *p* = 0.128)
- No meaningful impact on intention to use content (β = 0.098, *p* = 0.265)
- Only marginal association with engagement (β = 0.214, *p* = 0.128)

This suggests that while positive emotional experiences may slightly encourage interaction, they play a secondary role compared to Truth, Knowledge, and Good Deeds in shaping credibility judgments.

Contrasting with Existing Literature

These findings partially diverge from prior work (e.g., Kross et al., 2013) emphasizing emotional appeal's role in engagement. The discrepancy may stem from:

1. Cultural Priorities – Malaysian users may weigh ethical/factual rigor more heavily than emotional resonance.
2. Contextual Differences – Cognitive and moral factors likely dominate information quality (vs. entertainment/viral content).

Key Implications: For platforms targeting similar demographics:

- Fact-based and ethical content strategies may outperform emotion-centric approaches.
- Happiness-driven features (e.g., reaction buttons) could be deprioritized in favor of credibility indicators. This culturally situated insight helps refine digital engagement models, showing that not all drivers of "likes" translate to trust.

E. Implications for Social Media Platforms and Policymakers

Practical Implications for Building a More Trustworthy Digital Ecosystem: This study yields actionable insights for multiple stakeholders invested in improving social media's information landscape:

1. For Social Media Platforms: Truth and Knowledge as Design Imperatives

- Fact-Checking Integration: Embed real-time verification systems to flag or demote unsubstantiated claims.
- Algorithmic Prioritization: Reward *truthful* and *knowledge-rich* content (e.g., expert sources, peer-reviewed citations) in recommendation engines.
- Transparency Tools: Give users contextual cues (e.g., "Source Reliability Ratings") to assess credibility at a glance.

Rationale: The robust effects of Truth (β = 0.312) and Knowledge (β = 0.287) on credibility signal that users inherently value accuracy and depth—platforms that institutionalize these values could gain a competitive edge.

2. For Policymakers: Ethical Frameworks for Digital Citizenship

- Incentivize "Good Deeds": Partner with platforms to recognize ethical sharing (e.g., badges for users who consistently cite reputable sources).
- Combat Misinformation: Leverage the strong linkage between ethics and engagement (β = 0.422) to design public campaigns framing *responsible sharing* as a social good.
- Cultural Tailoring: Adapt guidelines to local values (e.g., aligning with Islamic principles in Malaysia to resonate with users' moral frameworks).

3. For Educators: Media Literacy as a Foundational Skill

- Critical Evaluation Training: Teach users to interrogate sources using the study's dimensions (*Truth, Knowledge, Good Deeds*).
- Behavioral Nudges: Use the weak role of Happiness to debunk the myth that "viral = credible," redirecting focus to evidence-based judgment.
- Community Workshops: Partner with platforms to scale literacy programs, emphasizing how ethical sharing benefits collective well-being.

VI. CONCLUSION

This study introduces a new way to evaluate information quality on social media based on the timeless principles of philosopher Madani Al-Farabi. By testing four key factors - Truth, Knowledge, Happiness, and Good Deeds - we discovered what really matters when people judge online content. Our findings show that Truth and Knowledge are the most important for making information credible. When content is accurate (Truth) and well-supported (Knowledge), people trust it more and are more likely to share it. Good Deeds - like sharing helpful, ethical content - also play a strong role in building trust. Interestingly, while Happiness matters somewhat for engagement, it does not affect credibility much.

These insights are especially relevant for countries like Malaysia, where ethical values strongly influence online behavior. The results suggest that social media platforms should focus more on promoting truthful, knowledgeable, and ethical content rather than just chasing viral, feel-good posts. For everyday users, we should pay the most attention to whether the information is accurate, well-supported, and shared for good reasons, not just whether it makes us happy or gets lots of likes. The study gives social media companies, educators, and policymakers clear guidance on improving online information quality by focusing on what truly matters to users.

A. Key Contributions

The study makes several important contributions to information quality and social media literature. In the first place, it incorporates Madani Al-Farabi's ideas into a thorough framework for assessing the quality of information, offering a distinct viewpoint consistent with moral and ethical standards. Second, the study provides valuable insights for enhancing the caliber of information on social media by highlighting the important roles that Truth, Knowledge, and Good Deeds play in influencing users' attitudes and actions. Lastly, the study adds empirical data from the Malaysian context to the expanding quantity of studies on the quality of information in non-Western contexts.

B. Practical Implications

The results significantly affect educators, legislators, and social media companies. To increase the legitimacy of information, platforms should prioritize fact-checking and highlighting reputable sources. Policymakers' main priorities should be promoting moral content sharing and raising user media literacy. To prevent the spread of false information, give users the ability to assess material, and promote a critically informed online community, educators can play a significant role.

C. Limitations and Future Research

It is important to take into account the limitations of this study. Initially, it was limited to Malaysian youth and middle-aged adults (18–40 years old). This implies that older persons or people from different cultural backgrounds may be unable to use the results. Future studies should test the

model in other places and with different age groups to see if it works everywhere. Another limitation is that we only asked people what they thought about information quality. People sometimes do not answer these questions honestly or accurately. Future research could see how people actually behave online instead of just asking them. This would give more reliable results.

The study looked at four main qualities of information (Truth, Knowledge, Happiness, and Good Deeds), but there are other important factors too. Things like how up-to-date the information is, whether it tells the whole story, and whether it is fair could also affect credibility. Future versions of the model should test these factors. We also mainly talked to experts about the qualitative part. Next time, including regular social media users in discussions would also be good. This would help us understand better how different people judge information online.

These limitations do not mean the study is useless - it still gives us important new Knowledge. However, fixing these issues in future research will help make the model even better and more useful for different situations. The findings are a good starting point, but more work must be done to fully understand the quality of social media information.

D. Final Thoughts

This research gives us a practical, ethics-based approach to improving social media content. By putting Madani Al-Farabi's timeless wisdom to work, we have created a model that highlights what really matters online: Truth, Knowledge, and good deeds. The findings show that focusing on these core values can make social media more reliable and valuable for everyone. While the study focused on Malaysia, its lessons about truthful information and ethical sharing matter to users everywhere. As we move forward, this research provides guidance to social media companies, educators, and policymakers. By designing platforms that reward accurate information and responsible sharing, we can fight misinformation while building online spaces people can trust. The digital world does not have to be a wild west of fake news and viral lies. This study proves there is another way - one that brings out the best in both technology and human nature.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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The Study of Social Media Contribution to Knowledge Sharing in Maqasid Al-Shariah

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Abstract— The need to obtain information quickly has driven the development of social media technology innovation and the establishment of digital communications. People worldwide use social media extensively, seeing it as an important tool in their daily lives. In organizations, Knowledge has always been a valuable resource. As social media becomes more advanced, it can become one of the tools for sharing Knowledge or information. However, regarding content and connectivity, Social Media usage for information sharing has produced a difficult circumstance. According to research by Shompa et al., a person should be careful to use social media properly from an Islamic viewpoint. Inappropriate Social Media usage causes us to take us away from Allah and His command. Despite the social benefits provided by social media, it may create a burden for the user. It may create some issues that are incompatible with Maqasid Al-Shariah (Islamic objectives), such as fake news, misinformation, malinformation, violation of privacy, incitement to hatred, some electronic fraud, children's extortion, and people's adverse judgment. In this research, the researcher will present the contribution of social media to knowledge sharing and the Islamic objectives of the Protection of Aql (Mind/intellect). To protect the intelligence on Social Media, by spreading false knowledge-related material and throwing derogatory comments against those in disagreement that can harm their intellect, Muslims are ordered to prevent evil actions.

Keywords— Knowledge Sharing, Knowledge Management, Social Media, Maqasid Al-Shariah, Protection of Aql (Mind/Intellect).

I. INTRODUCTION

Globalization and internet development make it easy to connect with people worldwide. Nowadays, in a world that has become more interconnected, technologies are spreading faster and throughout many platforms. The need to obtain information quickly has driven the development of social media technology innovation and the establishment of digital marketing communications. In an accessible exchange of information and communication through Facebook, WhatsApp, Twitter, and many other platforms, Social Media's growth has linked East and West, North and South. Social media is a comprehensive platform that connects people and enables companies to grow, find jobs, and share information around the world. It has changed people's behavior, transforming their lives and ways of thinking.

One of the solutions that has overcome many limitations in current technologies is the utilization of social media. Furthermore, Social Media is an evolving and diverse technological infrastructure that transforms and supports how people collaborate and communicate in the organization. Allah mentioned in the Quran to speak and know each other by the following verse (Surah Al-Hujurat, 49:13); "Oh humankind, certainly We have made you from man and woman and complete you peoples and clans that you may recognize each other. To be sure, the politest of you in the prospect of Allah is your best honor. Truly, Allah is deliberate and familiar."

Knowledge management requires technological elements [1]. Information and communication technologies are implemented to enhance people-to-people connections and people-to-document availability [2]. Several social media applications have been built to encourage knowledge-sharing (e.g., online forums and blogs) and knowledge management (e.g., wikis and crowd-sourcing) [3]. Platforms like Facebook, Instagram, and LinkedIn were designed to keep people connected [4].

From an Islamic viewpoint, a study by Shompa et al. [35] suggests that a person should be careful to use Social Media correctly. Inappropriate Social Media usage takes us away from Allah and His command. Islam's message sets forth an ethical structure that maintains harmony and peace in human life. Therefore, transmitting positive news encourages benefits while preventing statements that can harm life and belief. Rosidi et al. [46] highlighted the application of Hifz al-Aql (Protection of intellect) in guiding ethical digital behavior. They argued that this principle can mitigate the spread of misinformation online. Similarly, Azlan and Zainudin [47] analyzed post–COVID-19 social media usage in Malaysia, noting a growing trend toward

information literacy and ethical sharing based on Islamic teachings. Shamsuddin [48] further extended this discourse by proposing ethical guidelines for Muslim social media influencers grounded in Maqasid al-Shariah, focusing on key principles such as intention (niyyah), ethical method (al-Ada'), and consequence (al-Ma'al). The objectives of Shariah, commonly known as Maqasid al-Shariah, are to protect humanity's faith, existence, intelligence, integrity, and wealth. Therefore, these studies focus on Social Media's contribution to Knowledge Sharing in Maqasid al-Shariah and the Protection of Aql (Mind/Intellect).

II. PROBLEM STATEMENT

In our daily lives, the sharing of Knowledge is an important aspect. The growth of the internet and various electronic devices such as smartphones, laptops, and tablets make it easier to share Knowledge that can be achieved without time and place constraints. Nowadays, gathering and sharing Knowledge and keeping in touch with other people through social media is easy. Social media has become more critical for sharing Knowledge and information. According to the Hootsuite and We Are Social Report 2025 [40], the data regarding global Social Media use is 63.9 percent (5.24 billion) of active Social Media users from the total population (8.20 billion).

Social media is influencing the practice of online networking for knowledge sharing. Social Media has evolved from the latest technologies like artificial intelligence, big data, machine learning, the Internet of Things, augmented reality, and cloud computing. Social Media's strategic capabilities positively impact brand technology development. They are a moderating variable between acquiring Knowledge, business performance, and brand innovative thinking. Social Media sites are increasingly used in organizations to communicate and interact with people. People can give the info explicit Knowledge over traditional communication and the tacit understanding that is hard to convey through the written method. People who utilize social media will get information to solve problems and challenges by exchanging information and sharing Knowledge.

Despite the social benefits provided by social media, it may create a burden for the user. It may create some incompatible issues with Maqasid Al-Shariah (Islamic objectives), such as fake news, violation of privacy, incitement to hatred, some electronic fraud, children's extortion, and people's adverse judgment. In this research, the researcher will present social media for knowledge sharing and the objectives of the Islamic religion. The effect of Knowledge Sharing using Social Media will be identified and derived from five Maqasid al-Shariah in Arabic, named Protection of al-Nafs (Life), al-Din (Religion), al-'Aql (Intellect), al-Nasb (Posterity/Lineage), and al-Mal (Wealth). It is highly suggested to prioritize Maqasid al-Shariah's Social Media application to preserve reliability, privacy, safety, respect, dignity, and many others. As stated by Imam Al-Shatibi, Islam's objective serves as a regulatory philosophy to ensure all actions, including Social Media events, are final to achieve the objective of the Shariah. The researcher will concentrate on the Protection of Mind/Intellect for Islam's objective (Maqasid al-Shariah).

III. RESEARCH QUESTIONS AND RESEARCH OBJECTIVE

In line with the problem statement stated before, the following questions are created:

RQ1: What type of Knowledge is shared on social media?

RQ2: What are the main problems facing Social Media usage for Knowledge Sharing?

RQ3: How does social media impact the Protection of Maqasid al-Shariah and the Protection of Aql (Mind/intellect)?

The primary objective of this study is to recognize Social Media's contribution to Knowledge Sharing. To achieve this primary objective, sub-objectives can be expressed:

RO1: To determine the type of Knowledge shared in Social Media.

RO2: To investigate the main problem facing Social Media usage for Knowledge Sharing.

RO3: To develop a framework of knowledge sharing according to Maqasid al-shariah, protecting Aql (Mind/intellect) in social media.

Based on the research objectives and questions, the following hypotheses were developed:

H1: Social Media significantly contributes to the sharing of news-type Knowledge.

H2: Social Media usage poses significant risks to identity and mental well-being.

H3: Social Media positively impacts the Protection of Aql (Intellect) when used responsibly.

IV. METHODOLOGY

This research is a quantitative study that uses a questionnaire as a tool for data collection. The data were collected through convenience sampling by distributing the questionnaire via the researcher's social media platforms (e.g., WhatsApp, Facebook). This approach was chosen due to its accessibility and ability to reach many respondents quickly. The target population consisted of Malaysian netizens aged 18 years and above who are active social media users.

Out of approximately 400 individuals who received the questionnaire link, 300 valid responses were obtained, resulting in a response rate of 75%. The research aimed to

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investigate the contribution of social media to knowledge sharing, specifically within the framework of Maqasid al-Shariah, focusing on the Protection of Aql (intellect).

A questionnaire is a data collection tool. It is a collection of questions that respondents have to answer. Those questions are designed with the research objectives in mind and should help to answer the research questions. Usually, those questionnaires contain questions that must be answered in a scaled format like the Likert scale. Questionnaires are the most suited tools for collecting primary data [5].

In the data collection process, the questionnaire plays a significant role. A self-administered questionnaire was developed to determine the contribution of Social Media to Knowledge Sharing in Maqasid al-Shariah.

This questionnaire consists of five sections. The first section, section 1, consists of five questions covering demographic information, including age, gender, occupation, and other demographic information. This section tries to give background information on the respondents. Section 2 consists of 6 questions that cover different topics regarding Social Media usage for Knowledge Sharing.

Section 3 consists of 5 questions about the Perception of Social Media usage. These questions must be answered in a Likert scale format that varies from "strongly disagree" to "strongly agree." This type of scale will better represent the opinions of the respondents. Section 4 covers the main problems of social media usage for the knowledge-sharing topic.

Respondents must also answer six questions in a Likert scale format. The last section covers the topic of Social Media's impact on the Protection of Maqasid al-Shariah. Section 5 consists of 9 questions focusing on one area of Maqasid al-Shariah, Protection of Mind/Intellect. Respondents also need to answer using a Likert scale format.

A. *Data Analysis Techniques*

Data collected were analyzed using SPSS Version 26. The analysis included:

- Descriptive statistics (frequency, percentage, mean, and standard deviation)
- Reliability tests (Cronbach's Alpha)
- Inferential statistics, including Pearson correlation analysis to test relationships between constructs such as perception and the Protection of intellect.

These methods addressed the study's objectives and validated the relationships between variables.

B. Reliability Analysis

To ensure the internal consistency of the constructs, Cronbach's Alpha was calculated for Sections 2 through 5 using SPSS. The results are summarized in Table 1.

TABLE I
THE RESULT OF THE INTERNAL CONSISTENCY OF THE CONSTRUCTS

Construct	Cronbach's Alpha (α)
Type of Knowledge Shared	0.79
Perception of Social Media Usage	0.82
Problems in Social Media Usage	0.85
Protection of Aql (Mind/Intellect)	0.87

V. FINDING

The study includes the demographic characteristics of the netizens living in Malaysia regardless of gender, age, nationality, education, and occupation. The participants' categorical variables are discussed in detail below, based on the data collected from the first section of the questionnaire. Data were analyzed using both descriptive and inferential statistics (Pearson correlation) via SPSS.

A. *Demographic Characteristics*

The study collected data from 300 respondents in Malaysia, as shown in Table 2. The gender distribution shows more participation from females (68.3%) than males (31.7%). Age-wise, the 26–30 age group dominated the sample (54.7%), followed by 21–25 (14.7%), under 20 (13.0%), 31–35 (10.7%), and 36–40 (7.0%).

In terms of education, most respondents had a bachelor's degree (60.0%), followed by diploma holders (15.7%), high school (13.0%), master's (10.0%), and Ph.D. holders (1.3%). Nationally, the vast majority were Malaysians (90.7%), with a small representation of non-Malaysians (9.3%). Regarding occupation, 76.0% were employed, 17.7% were students, 3.3% were unemployed, and 3.0% were self-employed.

TABLE II
DEMOGRAPHIC CHARACTERISTICS

Demographic	Category	Frequency	Percentage (%)	Cumulative (%)
Gender	Male	95	31.7	31.7
	Female	205	68.3	100.0
Age	< 20	39	13.0	13.0
	21–25	44	14.7	27.7
	26–30	164	54.7	82.3
	31–35	32	10.7	93.0
	36–40	21	7.0	100.0
Education	Diploma	47	15.7	15.7
	Degree	180	60.0	75.7
	Master	30	10.0	85.7
	PhD	4	1.3	87.0
	High School	39	13.0	100.0
Nationality	Malaysian	272	90.7	90.7
	Non-Malaysian	28	9.3	100.0
Occupation	Student	53	17.7	17.7

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	Employee	228	76.0	93.7
	Self-employed	9	3.0	96.7
	Unemployed	10	3.3	100.0

B. *Type of Knowledge/Information Usually Shared or Found on Social Media*

RQ1: What type of Knowledge is shared on social media? The first research question is intended to define the type of Knowledge sharing in social media. Based on Table 3, the most popular type of knowledge/information usually shared on Social Media is news, with 89.7%, followed by entertainment, with 81.7%. Meanwhile, 74% share 'life experiences.' 36% of respondents who stated 'Humour/ Funny content' is the content usually shared on their Social Media, followed by 'education' with 30%, and 'Jobs and networking' with 29.3%. However, 'Books/Publications' and 'Marketing' have the exact percentages at 15%.

TABLE III
TYPE OF KNOWLEDGE/INFORMATION USUALLY SHARED OR FOUND ON SOCIAL MEDIA

		Frequency	Percent	Cumulative Percent
News	Yes	269	89.7	89.7
	No	31	10.3	100.0
	Total	300	100.0	
Education	Yes	92	30.7	30.7
	No	208	69.3	100.0
	Total	300	100.0	
Books/ Publications	Yes	51	17.0	17.0
	No	249	83.0	100.0
	Total	300	100.0	
Life Experiences	Yes	222	74.0	74.0
	No	78	26.0	100.0
	Total	300	100.0	
Humor/ Funny content	Yes	108	36.0	36.0
	No	192	64.0	100.0
	Total	300	100.0	
Entertainment	Yes	245	81.7	81.7
	No	55	18.3	100.0
	Total	300	100.0	
Marketing	Yes	51	17.0	17.0
	No	249	83.0	100.0
	Total	300	100.0	
Jobs and Networking	Yes	88	29.3	29.3
	No	212	70.7	100.0
	Total	300	100.0	

C. *Perception Of Social Media Usage For Knowledge Sharing*

Consequently, the descriptive analysis (frequency, percentage, standard deviation, and mean) shows the response at the level and the general outcome at the end. This data provides insights into the perception of Social Media usage for Knowledge Sharing. Five-point Likert scale of 1 = Strongly Disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; and 5 = Strongly Agree. The level of perception of Social Media usage for Knowledge Sharing will be determined based on the meaningful interpretation of scores, whereby for low (1-2.33), for moderate (2.34-3.67), and high (3.68-5) (see Table 4).

TABLE IV
THE PERCEPTION OF SOCIAL MEDIA USAGE FOR KNOWLEDGE SHARING

	SD	D	N	A	SA	M	Std(X)
1. I believe it is helpful to use Social Media to communicate with other individuals to share Knowledge	0	0	5	49	246	4.80	.438
	0%	0%	1.7%	16.3%	82.0%		
2. I believe connecting with others using Social Media to share Knowledge is easy.	0	2	6	76	216	4.69	.544
	0%	0.7%	2.0%	25.3%	72.0%		
3. I believe using Social Media gives me valuable Knowledge about my everyday activities.	0	2	27	92	179	4.49	.687
	0%	0.7%	9.0%	30.7%	59.7%		
4. I believe Social Media provides me with reliable and trustworthy data.	4	33	130	96	37	3.43	.891
	1.3%	11.0%	43.3%	32.0%	12.3%		
5. I believe that Social Media provides me with fast information.	0	1	5	63	231	4.75	.493
	0%	0.3%	1.7%	21.0%	77.0%		
Average total	0.3%	2.5%	11.5%	25.1%	60.6%	4.43	.611

SD - Strongly Disagree, D – Disagree, N – Neutral, A – Agree, SA - Strongly Agree, M – Mean, std(X) – Standard Deviation

Based on Table 4, five items indicate the perception of Social Media usage for sharing Knowledge. Item 1, "I believe it is helpful to use Social Media to communicate with other individuals to share knowledge." Most respondents strongly agreed with statement 246 (82%) and 49 (16.3%). The minority responded as neutral, with only five respondents (1.7%). For this item, the average total mean score is M=4.80. So, the whole outcome shows that most of the respondents

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in this study agreed that it is helpful to use social media to communicate with other individuals and share Knowledge.

For item 2, "I believe it is easy to connect with other people using Social Media to share knowledge." Most respondents strongly agreed with statement 216 (72%) and 76 (25.3%). However, the minority responded disagree only 2 (0.7%), and responded neutral, only six respondents (2.0%). For this item, the average total mean score is M=4.69. Hence, the whole outcome shows that most of the respondents in this study agreed that it is easy to connect with other people using social media to share Knowledge.

For item 3, "I believe that using Social Media gives me valuable knowledge about my everyday activities." The majority of respondents reported strongly agreeing with statement 179 (59.7%) and agreeing with statement 92 (30.7%). However, the minority responded disagree only 2 (0.7%) and responded neutral to only 27 respondents (9.0%). For this item, the average total mean score is M=4.49. Therefore, the whole outcome shows that most of the respondents in this study agreed that using social media provides valuable Knowledge about everyday activities.

For item 4, "I believe Social Media provides me with reliable and trustworthy data," the majority of the respondents reported neutral with the statement 130 (43.3%), agree with 96 (32%), and strongly agree with 37 (12.3%). The minority responded strongly disagreed 4 (1.3%) and disagreed 33 (11%) respectively. For this item, the average total mean score is M=3.43. So, the whole outcome shows that the opinion is divided into two parts, and not all respondents agree with the statement that social media provides reliable and trustworthy data.

For item 5, "I believe that Social Media provides me with fast information.", the majority of respondents reported strongly agree with statement 231 (77%) and agree 63 (21%). However, the minority responded disagree only 1 (0.3%), and responded neutral, only five respondents (1.7%). For this item, the average total mean score is M=4.75. Therefore, the whole outcome shows that most of the respondents in this study agreed that social media provides fast information. Generally, it can be inferred that the majority of respondents expressed clear agreement that Social Media can be beneficial for exchanging information. In line with the interpretation of mean scores, this pattern is 4.43 from the total mean score for all five items, suggesting that respondents strongly view Social Media usage for Knowledge Sharing.

D. The Main Problems Facing Social Media Usage For Knowledge Sharing

RQ2: What are the Main Problems Facing Social Media Usage for Knowledge Sharing?

Based on Table 5, six items represent the main problems facing Social Media usage for Knowledge Sharing. Item 1, "Social Media can have your identity stolen." The majority of the respondents reported strongly agree with statement 201 (67%) and agree with 79 (26.3%). Meanwhile, the respondents reported neutral with statement 18 (6%). The minority responded that they disagreed with only two respondents (0.7%). For this item, the average total mean score is M=4.60. So, the whole outcome shows that most of the respondents in this study agreed that social media could have their identities stolen.

TABLE V
THE MAIN PROBLEMS FACING SOCIAL MEDIA USAGE FOR KNOWLEDGE SHARING

	SD	D	N	A	SA	M	Std(X)
1. Social Media can have your identity stolen.	0 0%	2 0.7%	18 6.0%	79 26.3%	201 67.0%	4.60	.634
2. Social Media can accidentally be letting stalkers find you.	0 0%	2 0.7%	13 4.3%	81 27.0%	204 68.0%	4.62	.602
3. Social Media intends to give you wrong information/fake news.	0 0%	4 1.3%	18 6.0%	72 24.0%	206 68.7%	4.60	.664
4. Social Media is used for spreading spam and malware.	0 0%	8 2.7%	42 14.0%	126 42.0%	124 41.3%	4.22	.783
5. Social Media increases the incidence of anxiety and depression.	0 0%	9 3.0%	49 16.3%	101 33.7%	141 47.0%	4.25	.834
6. I notice that my real social interaction has been reduced compared to the time before using Social Media.	6 2.0%	30 10.0%	86 28.7%	102 34.0%	76 25.3%	3.71	1.019
Average total	0.3%	3.1%	12.6%	31.2%	52.8%	4.33	.756

SD - Strongly Disagree, D – Disagree, N – Neutral, A – Agree, SA - Strongly Agree, M – Mean, std(X) – Standard Deviation

For item 2, "Social Media can accidentally be letting stalkers find you.", the majority of respondents reported strongly agree with statement 204 (68%) and agree 81 (27%). However, the minority responded that they disagreed only 2 (0.7%) and that they responded neutrally with only 13 respondents (4.3%). For this item, the average total mean score is M=4.62. Hence, the whole result shows that most of

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the respondents in this study agreed that social media could accidentally let stalkers find you.

For item 3, "Social Media intends to give you wrong information/fake news.", the majority of respondents reported strongly agree with statement 206 (68.7%) and agree 72 (24.0%). However, the minority responded disagree only 4 (1.3%) and responded "neutral" only 18 respondents (6.0%). For this item, the average total mean score is M=4.60. Therefore, the whole outcome shows that most of the respondents in this study agreed that Social Media intends to give you wrong information/fake news.

For item 4, "Social Media is used for spreading spam and malware," the majority of the respondents reported agree with statements 126 (42%) and strongly agree with 124 (41.3%). The minority respondents disagree with 8 (2.7%) and responded neutral with 42 respondents (14.0%). For this item, the average total mean score is M=4.22. Hence, the whole outcome shows that most of the respondents in this study agreed that social media is used to spread spam and malware.

For item 5, "Social Media increasing the incidents of anxiety and depression.", the majority of respondents reported strongly agree with statement 141 (47%) and agree 101 (33.7%). However, the minority respondents disagree with only 9 (3%) and responded with neutral, 49 respondents (16.3%). For this item, the average total mean score is M=4.25. Therefore, the whole outcome shows that most of the respondents in this study agreed that Social Media increases the incidence of anxiety and depression.

For item 6, "I notice that my real social interaction has been reduced compared to the time before using Social Media," the majority of the respondents reported agree with the statement 102 (34%), neutral with 86 (28.7%), and strongly agree with 76 (25.3%). The minority responded strongly disagree 6 (2%) and disagree 30 (10%) respectively. For this item, the average total mean score is M=3.71. The whole outcome shows that most of the respondents in this study noticed that real social interaction had been reduced compared to the time before using Social Media. Generally, it can be concluded that most respondents are aware of the problems facing Social Media usage for Knowledge Sharing. In line with the interpretation of the mean score, this pattern can be seen from the overall mean score of 4.33 for all six items. This suggests that respondents are highly concerned about the problems faced when using Social Media for Knowledge Sharing.

E. Social Media Impact On The Protection Of Maqasid Al-Shariah (Protection Of Intellect)

RQ3: How does Social Media impact the Protection of Maqasid al-Shariah?

Based on Table 6, nine items represent the Social Media impact on the Protection of Maqasid al-Shariah (Protection of Intellect). Item 1, "Before I create any knowledge/information post on Social Media, I check the accuracy of the knowledge/information facts."

TABLE VI
SOCIAL MEDIA IMPACT ON THE PROTECTION OF MAQASID AL-SHARIAH (PROTECTION OF INTELLECT)

	SD	D	N	A	SA	M	Std(X)
1. Before I create any knowledge/information post on Social Media, I check the accuracy of the knowledge/information facts.	0 0%	0 0%	20 6.7%	85 28.3%	195 65.0%	4.58	.615
2. Before I upload any knowledge/information post on Social Media, I check the accuracy of the knowledge/information facts.	0 0%	2 0.7%	16 5.3%	102 34.0%	180 60.0%	4.53	.630
3. I will not easily believe every piece of knowledge/information posted on Social Media without any references.	0 0%	1 0.3%	20 6.7%	101 33.7%	178 59.3%	4.52	.636
4. I will check the accuracy of the knowledge/information I've been looking for on Social Media.	0 0%	1 0.3%	28 9.3%	98 32.7%	173 57.7%	4.48	.676
5. I will evaluate the quality of the knowledge/information that I post or share on Social Media.	0 0%	1 0.3%	26 8.7%	116 38.7%	157 52.3%	4.43	.663
6. I have shared other people's posts on Social Media (text, music, photos, videos, graphics, etc.) only if I get their permission	2 0.7%	12 4.0%	64 21.3%	101 33.7%	121 40.3%	4.09	.912

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and take credit for it.							
7. Social media has helped me to use my free time and entertain me in any pressure moment.	0 0%	6 2.0 %	53 17.7%	124 41.3%	117 39.0 %	4.17	.787
8. The positive impacts of Social Media overcome its negative effects.	1 0.3 %	19 6.3 %	98 32.7 %	92 30.7 %	90 30.0 %	3.84	.941
9. High interest in people's lives by following their Social Media profiles increases the possibility of depression and dissatisfaction in society.	1 0.3 %	9 3.0 %	69 23.0 %	95 31.7%	126 42.0 %	4.12	.888
Average total	0.14 %	1.88 %	14.60%	33.87%	49.51%	4.31	.750

SD - Strongly Disagree, D – Disagree, N – Neutral, A – Agree, SA - Strongly Agree, M – Mean, std(X) – Standard Deviation

The majority of the respondents reported strongly agree with statement 195 (65%) and agree with 85 (28.3%). Meanwhile, the respondents reported neutral with statement 20 (6.7%). For this item, the average total mean score is M=4.58. Therefore, the whole outcome shows that most of the respondents in this study agreed that before creating any knowledge/information post on social media, the accuracy of the knowledge/information facts must be checked.

For item 2, "Before I upload any knowledge/information post on Social Media, I check the accuracy of the knowledge/information facts.", the majority of respondents reported strongly agree with statement 180 (60%) and agree 102 (34.0%). However, the minority responded disagree only 2 (0.7%), and responded neutral, only 16 respondents (5.3%). For this item, the average total mean score is M=4.53. Therefore, the whole outcome shows that most of the respondents in this study agreed that before uploading any knowledge/information post on social media, the accuracy of the knowledge/information facts must be checked.

For item 3, "I will not easily believe every knowledge/information posted on Social Media without any references.", the majority of respondents reported strongly agree with statement 178 (59.3%) and agree 101 (33.7%). However, the minority responded disagree only 1 (0.3%), and responded neutral, only 20 respondents (6.7%). For this item, the average total mean score is M=4.52. Hence, the whole outcome shows that most of the respondents in this study agreed that they would not easily believe every knowledge/information posted on Social Media without any references.

For item 4, "I will check the accuracy of the knowledge/information I've been looking for on Social Media.", the majority of respondents reported strongly agree with statement 173 (57.7%) and agree 98 (32.7%). However, the minority responded disagree only 1 (0.3%), and responded neutral, only 28 respondents (9.3%). For this item, the average total mean score is M=4.48. Therefore, the whole outcome shows that most of the respondents in this study agreed to check the accuracy of the knowledge/information they were looking for on Social Media.

For item 5, "I will evaluate the quality of the knowledge/information that I post or share on Social Media." The majority of respondents reported strongly agreeing with statement 157 (52.3%) and agreeing with 116 (38.7%). However, the minority responded disagree only 1 (0.3%), and responded neutral, only 26 respondents (8.7%). For this item, the average total mean score is M=4.43. Hence, the whole outcome shows that most of the respondents in this study agreed to evaluate the quality of the knowledge/information posted or shared on Social Media.

For item 6, "I have shared other people's posts on Social Media (text, music, photos, videos, graphics, etc.) only if I get their permission and taken credit for it.", the majority of the respondents reported strongly agree with the statement 121 (40.3%), agree with 101 (33.7%), and neutral with 64 (21.3%). The minority responded strongly disagree 2 (0.7%) and disagree 12 (4.0%) correspondingly. For this item, the average total mean score is M=4.09. Therefore, the whole outcome shows that most of the respondents in this study agreed to share other people's Social Media posts (text, music, photos, videos, graphics, etc.) only if they get their permission and take credit for it.

For item 7, "Social Media has helped me to use my free time and to entertain me in any pressure moment." Most respondents reported agreeing with statement 124 (41.0%) and strongly agreeing with statement 117 (39.0%). However, the minority of respondents disagreed with only 6 (2.0%) and responded as neutral, 53 respondents (17.7%). For this item, the average total mean score is M=4.17. Therefore, the whole outcome shows that most of the respondents in this study agreed in this regard. Social media has helped me use my free time and entertain myself under pressure.

For item 8, "The positive impacts of Social Media overcome its negative effects," the majority of the respondents reported neutral with the statement 98 (32.7%), agree with 92 (30.7%), and strongly agree with 90 (30.0%). The minority responded strongly disagree 1 (0.3%) and

disagree 19 (6.3%) correspondingly. For this item, the average total mean score is M=3.84. Therefore, the whole outcome shows that most of the respondents in this study agreed that the positive impacts of Social Media overcome its negative effects.

For item 9, "High interest in people's lives by following their Social Media profiles increases the possibility of depression and dissatisfaction in society," the majority of the respondents reported strongly agree with the statement 126 (42.0%), agree with 95 (31.7%), and neutral with 69 (23.0%). The minority responded strongly disagree 1 (0.3%) and disagree 9 (3.0%) correspondingly. For this item, the average total mean score is M=4.12. Therefore, the whole outcome shows that most of the respondents in this study agreed that a high interest in people's lives by following their Social Media profiles increases the possibility of depression and dissatisfaction in society. Generally, most of the respondents are aware of the impact of social media on the Protection of Maqasid al-Shariah (Protection of Aql). In line with the interpretation of the mean score, this pattern can be seen from the overall mean score of 4.31 for all nine items, which suggests that respondents are highly concerned about the impact of Social Media on the Protection of Maqasid al-Shariah (Protection of Aql)

E. Correlation Analysis Between Key Constructs

To strengthen the empirical basis of the findings, a Pearson correlation analysis was conducted to examine relationships among the three primary constructs:

- Perception of Social Media Usage
- Problems in Social Media Usage
- Impact on the Protection of Aql

TABLE VII
THE RESULTS OF THE CORRELATION AMONG THE CONSTRUCT

Constructs	**1**	**2**	**3**
1. Perception of Social Media Usage	1		
2. Problems in Social Media Usage	.251**	1	
3. Protection of Aql (Mind/Intellect)	.433**	.317**	1

Note: Correlation is significant at the 0.01 level (2-tailed).

A moderate positive correlation was found between perception and Protection of Aql ($r = 0.433$, $p < .01$) (see Table 7), indicating that respondents who positively perceived social media for knowledge sharing were more likely to engage in behaviors that align with the Protection of intellect.

Problems in social media usage were also significantly correlated with Protection of Aql ($r = 0.317$, $p < .01$), suggesting that awareness of social media risks contributes to more responsible behavior.

V. FINDING AND DISCUSSION

This research on Malaysian netizens has provided findings that spotlight Malaysian netizens' perception of using social media for knowledge sharing on Maqasid al-Shariah and the Protection of Aql (Mind/intellect). The conclusions are summarised and discussed regarding how they answered the corresponding research questions.

A. Finding of Type of Knowledge Shared In Social Media.

RO1: To Determine the Type of Knowledge Shared in Social Media.

Research objective number one, "to determine the type of knowledge shared in Social Media," was achieved based on analysis and findings. The majority of the respondents picked 'News' as the most popular knowledge/information usually shared on Social Media. With 89.7% of the respondents, it shows that people seek more news on Social Media than other Knowledge. Nowadays, the trend is just one click away. Social Media makes it easier to find the news and has become the most used platform to seek the latest news. With advanced technology, people can watch live streaming to get the latest news from any social media platform, such as YouTube Live or Facebook Live.

The finding shows that 81.7% of the respondents also use Social Media for Entertainment content. More people are using social media as a source of entertainment instead of watching television or watching movies. Individuals, companies, or agencies create and post entertainment content daily on social media. Then, 74% of the respondents used Social Media to share their life experiences and look at other people's experiences. People tend to share their life experiences on their social media accounts, such as travel photos, cooking skills, singing of cover songs, workout routines, current issues, etc. This is usually content that is very famous on any social media platform. People create and share their life experiences, and at the same time, they influence others to have the same lifestyle. Some may have a harmful effect, and some can be used as an inspiration to others. That depends on how people acquire Knowledge and information.

The findings reveal that people also use social media for other things. There were 36% chosen for 'Humour/Funny content,' 30% for 'education,' 29.3% for 'Jobs and networking,' and 'Book/Publications' and 'Marketing have the exact percentages of 15%. Social Media has become increasingly valuable for almost all fields (Entertainment, Education, Corporate, Marketing, etc.) that can benefit from Social Media platforms. People believe it is helpful to use Social Media in their daily lives. It is to communicate with

other individuals to share their Knowledge and connect with them by using social media platforms and providing fast information.

Generally, it can be inferred that the majority of respondents expressed clear approval that Social Media can be beneficial for exchanging and sharing information. In line with the interpretation of mean scores, this pattern is 4.43 from the total mean score for all five items, suggesting that respondents strongly view Social Media usage for Knowledge Sharing. This shows that research objective no.1, "to determine the type of knowledge shared in Social Media," has been achieved.

B. Finding The Main Problems Facing Social Media Usage For Knowledge Sharing

RO2: To Investigate the Main Problem Facing Social Media Usage for Knowledge Sharing.

Research objective number two, "To investigate the main problem facing Social Media usage for Knowledge Sharing," based on analysis and findings, achieved the objective. The majority of the respondents expressed explicit approval of all the problems stated in section 4 of the questionnaire. The first statement on the questionnaire, "Social Media can have your identity stolen.", is one of the issues people may experience by having Social Media accounts. Identity theft is a common act by a 'bad person' or a hacker taking other people's pictures and names and using them to make different accounts. It becomes dangerous once the hacker uses your name and photo to do bad things.

The second statement, "Social Media can accidentally let a stalker find you," shows that this problem can happen to everyone with Social Media accounts. Some people like to publicize their social media accounts even if they have a private feature. They then upload every detail of their location and activities at that time by posting photos or videos on their Social Media account. This situation will give any stalker the opportunity for any stalker to see their account. Then, stalkers or strangers can keep up to date with their daily activity. This may lead to crimes such as robbery, kidnapping, and so on because the stranger gets the information from Social Media. As stated in Surah Al-Baqarah verse 195, the Quran stressed this: "And spend on Allah's sake and do not plunge yourself into ruin (by investing your riches on Allah's cause) and do great." Allah loves (people who do the nice thing) Al-Muhsinin.". In addition, to secure their lives with safety and Protection, Muslims should not share their details on Social Media platforms to fulfill the greater objective of saving a life.

Other than that, the third statement, "Social Media intends to give you wrong information/fake news," shows that this problem occurs around the world. Some people or organizations use Social Media to share fake news for their own sake. According to MIT's Twitter study, spreading fake news is six times faster than the facts. This happens when people intend to share and believe whatever they read on social media without checking the source. The same goes for the fourth statement, "Social Media is used for spreading spam and malware.". Spam, malware, and fake news could be inevitable on Social Media. However, by thinking logically, people can help prevent the spread. Sustain a fair degree of interest in what people read on their feed, consider that what they see is curated by Social Media outlets, and often use investigative approaches. Social Media is a powerful tool for both organizations and individuals when used with proper purpose and thought. Always check the validity of the content before sharing it with others.

Next, "Social Media is increasing the incidence of anxiety and depression." According to the fifth statement, this situation frequently happens because of the excessive use of social media. People, especially teenagers and young adults, easily feel insecure, envious, anxious, and many other things about what they see on social media. However, it can significantly increase well-being by reducing Social Media usage to around 30 minutes per day [19]. For statement 6, "I notice that my real social interaction has been reduced compared to the time before using Social Media." This is also one of the main problems. Social Media makes people addicted to using it. Many fun things happen on Social Media that make people like to spend their time scrolling through their Social Media feeds. Real social interaction will be reduced when too much time is spent on Social Media.

Generally, it can be concluded that most respondents are aware of the problems facing Social Media usage for Knowledge Sharing. In line with the interpretation of the mean score, this pattern can be seen from the overall mean score of 4.33 for all six items. This suggests that respondents are highly concerned about the problems faced when using Social Media for Knowledge Sharing. With this finding, research objective two, "To investigate the main problem facing Social Media usage for Knowledge Sharing," has been achieved.

C. Finding How Social Media Impacts The Protection Of Maqasid Al-Shariah (Protection Of Intellect)

The finding for the third research question, which is "How does Social Media impact the protection of Maqasid al-Shariah (Protection of Mind/Intellect?", shows that the behavior of people toward how they use Social Media indicates the Protection of Aql (Mind/Intellect). Statements of items 1 to 6 in the questionnaire show that people's decisions, whether good or bad, will indicate the final result. All social media users need to check and evaluate the accuracy and quality of their Knowledge before creating,

uploading, or sharing any information and posting it to social media. Users also should not easily believe every Knowledge or information on Social Media without any references. Getting permission from the knowledge content owner before posting on Social Media is also important. The majority of the respondents agreed with this statement. Misusing social media happens when people make the wrong decisions or choices without judging their minds and thinking correctly about the cause and effect. That is how Social Media impacts the Protection of the Mind/Intellect.

From item 7, "Social Media has helped me to use my free time and to entertain me in any pressure moment." Most respondents agree with the statement. Nowadays, people like to spend their free time on Social Media. They use social media to find interesting and entertaining content, like songs, videos, and so on, to release stress. Not only does Islam allow entertainment, but it indeed recommends it! In Nahjul Balagha, Imam Ali (peace be upon him) says: "The time of the believer has three periods: the time when he is in fellowship with Allah, the time when he handles his livelihood, and the time when he can enjoy what is permissible and good." The last part is a sweetener for the other pieces and is relaxing. However, everything needs to be limited. The overuse of Social Media will lead to another problem. So, people must go back to Islam's objective for the Protection of Aql (Mind/Intellect).

From item 8, "The positive impacts of Social Media overcome its negative effects," most respondents reported having a balanced response to this statement. Since the survey result may be inaccurate sometimes, almost equal numbers choose neutral, agree, and strongly agree with this statement. The average total mean score is M=3.84. Therefore, the whole outcome shows that most of the respondents in this study agreed that the positive impacts of Social Media overcome its negative effects. This shows that people still believe that the positive impact of Social Media has overcome its negative side, according to UKEssays 2018, social media has many positive impacts, like staying in touch with friends, making new friends, offering educational advantages, and easing web access. There are also several negative impacts, including identity theft, cyberbullying, reduced real-life social contact, and social isolation. A rise in mobile social networks may cause future health issues.

The final item, "High interest in people's lives by following their Social Media profiles increases the possibility of depression and dissatisfaction in society." Therefore, the whole outcome shows that most of the respondents in this study agreed that a high interest in people's lives by following their Social Media profiles increases the possibility of depression and dissatisfaction in society. The recent Documentary released on Netflix, titled "The Social Dilemma," directed by Jeff Orlowski, uncovers the impact of smartphones and social media on human activity. The way people view Social Media, in general, has been affected by this Documentary as individuals have become addicted to these technologies that reveal a false reality. Some studies have associated Social Media use with suicide, depression, and anxiety (see Figure 1).

Generally, most respondents were aware of the impact of social media on Maqasid al-Shariah and the Protection of Aql (Mind/intellect). In line with the interpretation of the mean score, this pattern can be seen from the overall mean score of 4.31 for all nine items, which suggests that respondents are highly concerned about the impact of Social Media on the Protection of Maqasid al-Shariah (Protection of Intellect).

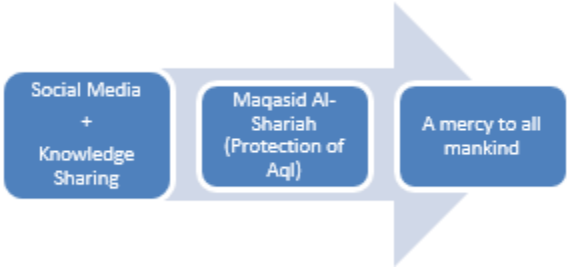

Fig. Social Media and Knowledge Sharing on Protection of Aql (Mind/Intellect)

D. The Solutions of Social Media Contribution For Knowledge Sharing In Maqasid Al-Shariah

RO3: To Develop a Framework of Knowledge Sharing According to Maqasid Al-Shariah, Protection of Aql (Mind/Intellect) in Social Media.

Research objective three, "To develop a framework of Knowledge Sharing according to Maqasid al-shariah, Protection of Aql (Mind/Intellect) in Social Media," was achieved based on analysis and findings. Based on the findings from the respondents' opinions, to maintain the positive side of Social Media's contribution to Knowledge Sharing, the researcher suggests the practice of Maqasid al-Shariah, Protection of Aql (Mind/Intellect). For Muslims, everything goes back to the Quran and Sunnah. The Qur'an is a primary source of Knowledge for Muslims in all their spiritual, religious, ethical, social, and legal matters. In order to learn and spread the Knowledge of Allah, it is therefore important for all Muslims to study and teach the Qur'an. Allah's most extraordinary acts of worship are studying and understanding the Qur'an and transmitting its wisdom by educating others honestly. As said by the Prophet Muhammad (PBUM)."

"The best among you are those who learn the Qur'an and teach it to others" (Al-Wahidi, 2008).

This research can give some awareness about how people would be associated with the law of Islam on social

media for knowledge sharing and how to use social media to share Knowledge in a balanced and reasonable way to protect Aql (Mind/intellect). As Hanifah et al. [17] emphasized, the most tacit Knowledge should be recorded to ensure that the Knowledge can be exchanged among others and that knowledge sharing can be fully implemented in the organization. This is because their research has shown that the exchange of information occurs when the data or Knowledge is recorded clearly. With advanced technologies, Knowledge sharing using social media will give people many advantages in finding practical Knowledge from any other world's expertise.

These are the things people can practice when using Social Media to share Knowledge. Firstly, always make sure the content shared on social media is accurate. Islam orders Muslims to be truthful and dependable in all situations and actions. Muslims should always be honest in creating and sharing correct info, check the correctness, and assess the value of the Knowledge. Secondly, do not spread fake news. People are prohibited from spreading fake news on Social Media, whatever it is. This disrupts the Protection of the intellect. Thirdly, do not share personal information on social media. People must not share their personal data on Social Media, such as their address, phone number, locations, pictures, and videos. People need to be extra alert about what they share on Social Media, and even their first intention is to share the Knowledge. Similarly, people should not share or post other people's knowledgeable content and detailed info without their consent.

Next, people should obey Allah's order and avoid His bans. A Muslim who has inside him or herself some degree of Taqwa, then he or she will not be doing the things that Islam does not permit. He or she can just do accountable and ethical things. Consequently, a Muslim must have decent ethics when using Social Media and protect themself against all wickedness and incorrect manners on Social Media. Muslims must also do their utmost to speak and only do things Allah pleases, adhere to His orders, and escape His prohibitions. Muslims must decide based on Maqasid al-Shariah and the priorities of their lifetime. Also, using the right words to share Knowledge on Social Media. People must not use disrespectful language in making content or sharing information that has no benefit to other people.

Lastly, in Islam, promoting good deeds is very necessary. Sharing rightful Knowledge on Social Media is a good deed because it benefits others. All Muslims must do the right deeds for Allah's sake every time. Allah has assured us in this world and the afterlife that righteous deeds are honored. Allah mentioned in the Quran, "So whoever performs goodness, either man or woman when he or she is a real follower of Islamic polytheism), certainly, We will give him a good life (with dignity, fulfillment, and legitimate provisions in this world), and Then we will definitely give them a prize to what they had been doing (i.e. Heaven in the Henceforth" (Surah An-Nahl, verse 97). Therefore, research objective three, "To develop a framework of Knowledge Sharing according to Maqasid al-shariah, Protection of Aql (Mind/Intellect) in Social Media," has been accomplished.

VII CONCLUSION

A. Conclusions Based On The Findings

The research objectives can be restated as follows:

RO1: To determine the type of Knowledge shared in Social Media.

RO2: To investigate the main problem facing Social Media usage for Knowledge Sharing.

RO3: To develop a framework of knowledge sharing according to Maqasid al-shariah, protecting Aql (Mind/intellect) in social media.

To fulfill the above research objectives, extensive literature was consulted to provide a background to Social Media and Knowledge Sharing, as well as Maqasid al-Shariah's definition. In the pursuit and implementation of all research studies, this research uses a questionnaire as a tool for data collection. The outcome was gathered using an online survey by Google.

Following the first research objective, the results reveal that most respondents picked 'News' as the most popular knowledge/information usually shared on Social Media. It can be inferred that most respondents expressed explicit approval that Social Media can be beneficial for exchanging and sharing information. Concerning the second research objective, the study's results confirm that most respondents expressed clear approval of all the problems stated in section 4 of the questionnaire—most respondents were aware of the problems facing Social Media usage for Knowledge Sharing.

Lastly, the results reveal that most respondents were aware of the impact of social media on Maqasid al-Shariah and the Protection of Aql (Mind/intellect). To maintain the positive side of the Social Media contribution to Knowledge Sharing, the researcher suggests the practice of Maqasid al-Shariah, the Protection of Aql (Mind/Intellect).

In this paper, the researcher found that it is very clear from the previous study that Social Media has become a massive part of people's lives in this era of advanced technology. This paper aims to develop a knowledge-sharing framework, according to Maqasid al-shariah, for social media. The study results suggest how social media use for knowledge sharing includes ethics in the Maqasid al-Shariah, Protection of Aql (Mind/Intellect) framework. This paper guarantees that people's actions to share Knowledge on social media are not uninvolved in bad outcomes and harm.

This study successfully addressed three research objectives:

RO1 – Type of Knowledge Shared: Social media is extensively used to disseminate news and entertainment, but less for structured academic Knowledge.

RO2 – Problems Identified: Users are aware of social media's risks, including misinformation, identity threats, and emotional harm—factors that threaten the integrity of Knowledge and intellect.

RO3 – Protection of Aql: Users show awareness of ethical sharing practices aligned with Maqasid al-Shariah, especially in checking for content accuracy and minimizing harm to others' intellect.

The results were further validated through reliability tests (Cronbach's Alpha > 0.7) and Pearson correlation analysis, establishing empirical support for the framework proposed.

B. Future Work

The findings of this research will help in the innovation of an exposition for Muslims to use social media to share Knowledge in Maqasid al-Shariah that will foster attentiveness and endorse harmless and accountable practices. Muslim scholars must continue to write more research that may help solve problems and threats of Social Media and promote the positive values provided by these platforms. Hence, extra effort is required to deeply discover the impact of Social Media's Contribution to Knowledge Sharing in other Muslim countries. This research contributes to understanding the intersection of Islamic ethics and digital knowledge sharing. By grounding the discussion in Maqasid al-Shariah, specifically Hifz al-Aql, the study offers a novel model for ethical engagement on social media. It also provides a conceptual foundation for future empirical validation using more advanced statistical techniques such as PLS-SEM.

C. Limitations And Future Work

This study has some limitations:

- The use of convenience sampling may limit generalizability.
- The framework was not statistically validated (e.g., no confirmatory factor analysis).
- The study focused only on the Protection of Aql. In contrast, other maqasid dimensions (e.g., al-Mal, al-Din) also deserve exploration.

Future research should:

- Test the proposed framework using PLS-SEM or SEM techniques
- Include other Muslim-majority countries for cross-cultural insights
- Explore qualitative interviews to complement quantitative findings
- Considering a longer observation time, as it only takes a 1-month observation. By having longer experimental and observation time, the number of participants who took the test will also increase, and this will also increase the accuracy of the research.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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Event-Based Cybersecurity Risk Assessment: Identifying Potential Cyber-Attacks in Organisations

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Abstract— Cybersecurity risk assessment is crucial for organisations since cyber threats are becoming increasingly sophisticated and dynamic. This study investigates how organisations identify potential cyber-attacks within an event-based risk assessment context. Using a qualitative approach, semi-structured interviews were conducted with ten cybersecurity experts from diverse organisations. The experts possess extensive strategic, technical, and advisory expertise in the field. Thematic analysis of the data revealed four key practices: (i)collaborative brainstorming involving diverse stakeholders, (ii)referring to historical data and past incident logs, (iii)staying updated on current cyber-attacks trends, and (iv)using established frameworks such as ISO/IEC 27005 supplemented with dynamic resources. These findings underscore the importance of integrating diverse methods and perspectives into event-based cybersecurity risk assessments to address evolving threats. The study contributes to theory and practice by offering actionable insights for organisations to identify potential cyber-attacks within an event-based cybersecurity risk assessment framework. Limitations are acknowledged, including reliance on self-reported data and a small sample size, with recommendations provided for future research.

Keywords— Cybersecurity Risk Assessment, Event-Based Approach, Cyber Attack Identification

I. Introduction

In an increasingly digital world, the complexity and frequency of cyber-attacks continue to grow rapidly. This phenomenon poses critical challenges to organisations globally. The stakes are particularly high for public and private sector organisations, where the impact of a successful cyber-attacks can lead to severe financial, operational, and reputational losses. As organisations modernise, their computing systems become increasingly vulnerable, with even minor weaknesses potentially being exploited [1]. Consequently, digital transformation has not only accelerated innovation but also heightened organisational exposure to cyber risks [2].

Cybersecurity risk management encompasses a comprehensive process to protect organisations from cyber risks [3], [4], [5]. At the heart of this process lies the cybersecurity risk assessment, a fundamental exercise to identify and assess potential cyber threats [6], [7]. An event-based cybersecurity risk assessment focuses on identifying potential cyber-attacks or events that may compromise an organisation's systems [6], [7]. This approach emphasises the identification of potential cyber-attacks or possible events and their impact, enabling organisations to prepare for and mitigate risks properly [7].

Despite the increasing sophistication of cyber-attacks, there is a lack of clarity on how organisations systematically identify these threats. This gap is due to the existing cybersecurity framework that lacks comprehensive guidance on identifying potential cyber-attacks and response mechanisms [8]. Furthermore, many organisations still struggle with situational awareness regarding the threat landscape, which is crucial for risk assessment [9].

This study aims to address this gap by examining how organisations identify potential cyber-attacks or events in the context of event-based cybersecurity risk assessment. The qualitative data was collected through interviews with ten well-qualified cybersecurity experts across diverse organisations. The study employs thematic analysis based on [10], [11], and [12]. The findings provide valuable insights into organisational approaches to identifying potential cyber-attacks. These findings contribute to the development of event-based cybersecurity risk assessment strategies. By focusing on the identification of potential cyber-attacks, this study offers practical recommendations and theoretical contributions to enhance the efficacy of event-based cybersecurity risk assessments.

II. Literature Review

This section presents the reviews of academic literature to understand event-based cybersecurity risk assessment, including the definitions, key elements and its focus on identifying potential cyber-attacks or events.

Cybersecurity risk assessment is a critical component of organisational risk management, focusing on safeguarding operations, assets, reputation, and national security. It plays a central role in managing risks at multiple levels [13]. It as an integrated approach that combines identification,

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analysis, and assessment into a unified strategy for simplifying and managing cybersecurity risks [14]. There are two main approaches for risk assessment: an event-based approach and an asset-based approach [7]. In an event-based approach, the underlying concept is that risks can be identified and assessed through an evaluation of events and consequences [7].

An event-based approach can establish high-level or strategic scenarios without spending a considerable amount of time on the identification of assets on a detailed level [7]. This allows the organisation to focus its risk treatment efforts on the critical risks. The key elements in event-based cybersecurity risk assessment encompass three (3) primary processes: risk identification, analysis and evaluation [6], [7], [14]. An event-based approach to cybersecurity risk assessment focuses on identifying potential cyberattack scenarios by considering risk sources and their impact on organisations [6], [7]. It specifically recommends referring to examples and typical attack methods, such as those summarised in Table 1, to assist organisations in systematically identifying potential cyber-attacks [7]. This structured approach supports organisations in recognising vulnerabilities and preparing for possible attack scenarios.

TABLE 1:
THE EXAMPLES AND USUAL METHODS OF ATTACK [7]

Risk Source	Examples and Usual Method of Attacks
State-related	States, intelligence agencies
	Method: Attacks generally conducted by professionals, working under a calendar and a method of attack that are predefined. This attacker profile is characterized by its ability to carry out an offensive operation over a long period of time (stable resources, procedures) and to adapt its tools and methods to the topology of the target. By extension, these actors have the means of purchasing or discovering 0-Day vulnerabilities and some are able to infiltrate isolated networks and to conduct successive attacks in order to reach a target or targets (e.g. by means of an attack aimed at the supply chain).
Organized crime	Cybercriminal organizations (mafias, gangs, criminal outfits)
	Method: Online scams or in person, ransom request or attack via ransomware, use of bot-nets, etc. Due in particular to the proliferation of attack kits that are readily available online, cybercriminals are conducting increasingly sophisticated and organized operations for lucrative or fraudulent purposes. Some have the means of purchasing or discovering 0-Day vulnerabilities.
Terrorist	Cyber-terrorists, cyber-militias
	Method: Attacks that are usually not very sophisticated but which are conducted with determination for the purposes of destabilization and destruction: denial of service (aimed for example at making the emergency services of a hospital centre unavailable, untimely shutdowns of an energy production industrial system), exploitation of vulnerabilities of Internet sites and defacement.
Ideological activist	Cyber-hacktivists, interest groups
	Method: The methods of attack and sophistication of the attacks are relatively similar to those of cyber-terrorists but are motivated by less destructive intentions. Some actors conduct these attacks in order to convey an ideology, a message (e.g. massive use of social networks as a sounding board).
Specialized outfits	"Cyber-mercenary" profile with IT capacities that are generally high from a technical standpoint. Because of this, it should be distinguished from script-kiddies with whom it shares however the spirit of a challenge and search for recognition but with a lucrative objective. Such groups can be organized as specialized outfits that propose veritable hacking services.
	Method: This type of experienced hacker is often at the origin of the designing and creating of attack kits and tools that are available online (possibly for a fee) which can then be used "turnkey" by other groups of attackers. There are no particular motivations other than financial gain.
Amateur	Profile of the script-kiddies hacker or who has good IT knowledge; motivated by the quest for social recognition, fun, challenge.
	Method: Basic attacks but with the capacity of use the attack kits that are available
Avenger	The motivations of this attacker profile are guided by a spirit of acute vengeance or a feeling of injustice (e.g. employee dismissed for serious fault, discontented service provider following a contract that was not renewed, etc.).
	Method: This attacker profile is characterized by its determination and its internal knowledge of the systems and organizational processes. This can make it formidable and provide it with substantial power to do harm.
Pathological attacker	The motivations of this attacker profile are of a pathological or opportunistic nature and are sometimes guided by the motive for a gain (e.g. unfair competitor, dishonest client, scammer, and fraudster).
	Method: Here, either attackers have a knowledge base in computing that leads them to attempt to compromise the IS of their target, or they use the attack kits available online, or decide to subcontract the IT attack by calling upon a specialized outfit. In certain cases, attackers can direct their attention to an internal source (discontented employee, unscrupulous service provider) and attempt to corrupt the latter.

The potential for cyber-attacks is based on a variety of factors, including the capabilities and intentions of the attacker [15]. Besides that, risk identification can also involve historical data, theoretical analysis, informed and expert opinions, and interested parties' needs [7].

Organisations are suggested to determine which type of potential cyber-attacks or events to consider during risk assessments [6]. The level of detail needed to describe such events. Descriptions of potential cyber-attacks can be expressed in highly general terms, in more descriptive terms

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using tactics, techniques, and procedures, or in highly specific terms [6].

Therefore, it is important to understand risk and threat sources to recognise potential cyber-attacks [6], [7]. It is recommended to use examples and typical attack methods to guide organisations in systematically identifying threats [7]. It also incorporates historical data, expert opinions, and stakeholder needs. It is also suggested to vary levels of detail in describing potential attacks, from general overviews to specific tactics and techniques [6].

III. Methodology

This research adopts a qualitative approach to explore how organisations identify potential cyber-attacks within the context of event-based cybersecurity risk assessment. A qualitative methodology was considered appropriate for this study as it enables a rich and in-depth exploration of expert perspectives and practices, particularly valuable in a rapidly evolving field like cybersecurity. In an interdisciplinary domain such as cybersecurity, qualitative approaches are essential for capturing the diversity of knowledge, experiences, and contextual insights that may not be evident through quantitative methods alone [16]. Moreover, qualitative research allows for a deeper understanding of complex, real-world issues by examining how participants interpret them within their organisational contexts [17].

Research Design: The study is focused on uncovering the strategies and methods organisations use to identify potential cyber-attacks within the event-based cybersecurity risk assessment framework. Data were collected through semi-structured interviews with cybersecurity experts, allowing flexibility to probe deeper into participants' insights while maintaining a structured alignment with the research objectives and questions.

Participants: Participants are experts who were selected using purposive sampling based on predefined criteria: at least 10 years of experience, involvement in organisational-level cybersecurity, and decision-making roles. Expert interviews are a widely used qualitative interview method, often aiming at gaining information about or exploring a specific field of action [18]. The sampling strategy was guided by the principle of information power, which posits that the more relevant and information-rich the participants are in relation to the study objectives, the fewer participants are required to generate meaningful data[19]. The selected participants, outlined in Table 2, were recruited via professional networks and referrals to ensure their relevance and expertise in the field.

TABLE II
IDENTIFIED PARTICIPANTS

Participants	Organisation Specialisation	Gender	Portfolio	Total Years of Service
Participant 1	Specializes in national cybersecurity policies, strategies, and incident management	Female	Officer, Expert, Consultant	20
Participant 2	Focuses on construction, public works, and infrastructure development	Male	Officer, Expert	17
Participant 3	Responsible for coordinating national policies, strategic planning, and high-level governance	Female	Officer, Expert	15
Participant 4	Specializes in public sector training and professional development	Female	Officer, Expert, Consultant	16
Participant 5	Oversees human resources, policies, and operations for the Malaysian civil service	Male	Officer, Expert, Consultant	17
Participant 6	Manages cross-ministerial coordination, national projects, and strategic initiatives	Male	Officer, Expert, Consultant	21
Participant 7	Focuses on immigration management, passport services, and border control.	Female	Officer, Expert	15
Participant 8	Responsible for driving national digitalization and ICT development	Female	Officer, Expert, Consultant	24
Participant 9	Manages national finances, budgeting, and economic policy	Female	Officer, Expert, Consultant	21
Participant 10	Oversees national security, law	Female	Officer, Expert	18

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Participants	Organisation Specialisation	Gender	Portfolio	Total Years of Service
	enforcement, and internal affairs.			

The participants represent a mix of strategic, technical, and advisory roles. These criteria make them ideal contributors to understanding how organisations identify potential cyber-attacks within the event-based cybersecurity risk assessment framework. Their responsibilities include shaping, supporting, and implementing cybersecurity risks in their respective organisations.

Data Collection: The primary method of data collection was semi-structured interviews conducted with the selected experts. Each interview was guided by open-ended questions designed to explore their approaches, experiences, and challenges in identifying potential cyber-attacks or events. The interviews were audio-recorded, transcribed verbatim, and anonymised to ensure participant confidentiality. Follow-up questions were asked where necessary to gain further clarification or depth in responses.

Data Analysis: Thematic analysis was employed to analyse the interview data. This method was chosen for its ability to systematically identify, organise, and interpret patterns (themes) within qualitative data. The data in this study were analysed using the following steps [10], [11], [12]:

i. Preparing the transcriptions
ii. Reading, understanding and translating the transcripts
iii. Highlighting the key statements that are relevant to the research objectives
iv. Grouping and coding the key statements
v. Deriving the themes and sub-themes
vi. Finalising and writing the results

The themes and sub-themes were directly aligned with the research objective and question. It provides a structured and meaningful interpretation of the data.

Trustworthiness: To ensure the trustworthiness of the study, a credibility strategy is employed. Credibility refers to confidence in the truth of the findings. One effective method to enhance credibility is through data triangulation [16]. Data triangulation was achieved by including diverse participants from different organisations and roles. By including diverse participants from various organisations and roles, researchers can obtain a more comprehensive understanding of the phenomenon under study [16], [20]. This approach helps to mitigate biases that may arise from relying on a single source of data.

Ethical Considerations: Ethical approval was obtained before data collection to ensure the study adhered to ethical research principles. All participants were provided with detailed information about the study and signed an informed consent form before participating. Confidentiality and anonymity were strictly maintained throughout the research process. This practice aligns with the ethical principle of confidentiality, which mandates that researchers safeguard participants' private information [21].

IV. Findings

This section presents the findings of this study, which explores how organisations identify potential cyber-attacks in the context of event-based cybersecurity risk assessment. Thematic analysis of the data collected from ten expert participants yielded four primary themes: (i)brainstorming and collaboration, (ii)referring to past incidents and logs, (iii)staying updated on current trends and (iv)using ISO/IEC 27005 and other relevant references.

1. Collaborative Brainstorming

A collaborative brainstorming approach to identify potential cyber-attacks is essential. 6 out of 10 participants explicitly agreed that brainstorming sessions involving multiple stakeholders help provide a well-rounded perspective on cybersecurity risks. Participant 1 emphasised the importance of cross-department collaboration: *"Brainstorming with all the officers involved, including top management. Each person has their views and experiences, so there needs to be collaboration in this process"*. Different departments may face unique cybersecurity risks, making their input valuable. Participant 5 reinforced this point: *"Through collaborative brainstorming sessions involving officers at all levels, each department can contribute unique perspectives on the specific threats they encounter"*. Additionally, Participant 9 suggested including specialised cybersecurity personnel to provide technical insights: *"Brainstorming sessions should involve all relevant stakeholders, including the IT team, cybersecurity experts, and even top management"*. By fostering brainstorming and collaboration, organisations can have a comprehensive understanding of potential cyberattack scenarios, ensuring no critical threats are overlooked.

2. Referring to Past Incidents and Logs

Analysing historical cybersecurity incidents provides valuable insights into recurring attack patterns and vulnerabilities. 9 out of 10 participants agreed that analysing historical cybersecurity incidents provides valuable insights into recurring attack patterns and vulnerabilities. Participant 1 stressed the need for historical data review: *"Refer to the history of past events. Look back at the records of previous cyber-attacks and check the log records"*. Similarly, Participant 2 emphasised leveraging previously documented incidents to improve threat detection: *"Organisations can also refer to past incidents. Look at past attack records or log records for attempted attacks"*. Beyond internal records, organisations should also study global cybersecurity incidents and emerging threat trends. Participant 9 recommended expanding the scope of reference:

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"Organisations should always refer to past incidents, both locally and internationally, and keep an eye on the latest cyberattack trends". By analysing past incidents, organisations can better understand the evolving threat landscape, allowing them to strengthen defences against future attacks.

3. Staying Updated on Current Trends

The cybersecurity landscape evolves rapidly, with new threats emerging daily. 9 out of 10 participants agreed on the necessity of staying informed about current attack trends at both domestic and international levels. Participant 1 highlighted the importance of cybersecurity awareness: *"We must stay alert to current issues, both domestically and internationally. Cyber-attacks are constantly evolving, so we need to stay up-to-date"*. Similarly, Participant 5 reinforced the need for continuous monitoring: *"We also need to stay aware of current issues, both locally and internationally, because cyber threats evolve rapidly"*. To support real-time threat identification, organisations should integrate threat intelligence feeds, advisories, and cybersecurity reports into their risk assessment processes. Participant 6 emphasised the importance of using threat intelligence: *"It's important to incorporate threat intelligence into this process to ensure we stay updated on the latest threats"*. By staying informed on evolving cyber threats, organisations can identify vulnerabilities early and implement proactive event-based cybersecurity risk assessment.

4. Using Usual Methods of Attack by ISO/IEC 27005 and Other Relevant Sources as References

All participants acknowledged the examples and commonly used attack methods outlined in ISO/IEC 27005 (as presented in Table 1) as a valuable reference for identifying typical cyberattack techniques. However, 7 out of 10 participants also stressed the importance of supplementing it with additional resources to keep up with dynamic and emerging threats. Participant 5 pointed out that ISO/IEC 27005 alone is insufficient: *"ISO/IEC 27005 is a good reference, but we need to combine it with up-to-date information from other sources as well"*. To enhance cyberattack identification, participants recommended integrating MITRE ATT&CK and other intelligence platforms for a more comprehensive approach. Participant 6 supported this view: *"ISO/IEC 27005 is a good reference, but we also need to refer to other sources, such as the MITRE ATT&CK matrix. Combining references can provide a more complete picture of the potential threats"*. Similarly, Participant 9 reinforced the need for multiple sources to improve cybersecurity risk assessments: *"ISO/IEC 27005 is a good reference, but agencies should also refer to platforms like MITRE ATT&CK or other intelligence sources"*. By referring to multiple sources of threat intelligence, agencies can implement a risk identification that stays aligned with evolving cyber risks.

V. Discussion Of Findings

This section presents the discussion of this study, which explored how organisations identify potential cyber-attacks within an event-based cybersecurity risk assessment framework. Our findings highlighted a multifaceted approach encompassing brainstorming and collaboration, historical data analysis, staying updated on current trends, and using established frameworks.

According to our findings, a collaborative approach is useful for identifying potential cyber-attacks. Based on the majority of the participants' feedback, brainstorming sessions involving multiple stakeholders, including technical teams and top management, offer diverse perspectives that contribute to a more accurate and comprehensive understanding of risk. This aligned with [22] and [23], which encourages consultation with both senior management and process owners to help identify relevant threat events and consequences.

Our findings show that analysing historical cybersecurity incidents is a valuable practice. Based on the majority of the participants' feedback, reviewing past incidents provides critical insight into recurring attack patterns, vulnerabilities, and organisational weaknesses. We found that it allows organisations to better anticipate and address similar threats in the future. This aligned with [24], [25], [26] and [27], who argue that the evolving nature of cyber threats demands a historical understanding of incidents to effectively categorise and mitigate risks.

Our findings also emphasise the importance of staying current with emerging cybersecurity threat trends. Based on the majority of the participants' feedback, organisations should actively monitor the threat landscape to ensure their defences and response strategies remain effective. This aligned with [22], [28] and [29], who argue that by understanding these trends, organisations can adopt a forward-thinking and innovative approach to cybersecurity that strengthens long-term resilience. Our findings also align with [30], who reinforces advocating cyber threat intelligence for automated threat analysis across all levels of an organisation to combat increasingly sophisticated cyber threats. However, while participants emphasised the value of real-time cyber threat intelligence, implementation may be hindered by cost, staffing, or technological readiness, especially in resource-constrained organisations [31].

Based on our findings, the ISO/IEC 27005 standard was acknowledged as a valuable reference for identifying common cyberattack methods (as shown in Table 1). However, our findings also stressed the importance of supplementing this with dynamic and up-to-date sources such as the MITRE ATT&CK framework. We found that the MITRE ATT&CK framework is a globally accessible knowledge base of adversary tactics and techniques based

on real-world observations. This aligned with [32], [33] and [34], who highlight the role of MITRE ATT&CK in helping organisations assess risks and understand adversarial behaviour. Combining multiple references fosters a collaborative, informed, and adaptive approach that allows organisations to strengthen their cybersecurity posture.

We found that identifying potential cyber-attacks requires a multidimensional approach. While established frameworks offer structured guidance, proactive practices such as collaborative brainstorming, historical incident analysis, and monitoring emerging threat trends are equally vital to effective cybersecurity risk assessment.

Contribution to Theory: This study contributes to the body of knowledge on event-based cybersecurity risk assessment. It identifies practical strategies that organisations can employ to identify potential cyber-attacks. It bridges the gap between theoretical frameworks and practical implementation, offering a roadmap for organisations to enhance their event-based risk assessment practices.

Practical Implications: The study provides actionable recommendations for organisations to improve their event-based cybersecurity risk assessments:

i. Regularly conduct brainstorming sessions involving diverse stakeholders.
ii. Develop and maintain comprehensive logs of past incidents and use them to anticipate future threats.
iii. Keeping up with emerging cyber threats and, if possible, investing in real-time threat intelligence tools to stay updated on emerging trends.
iv. Combine established frameworks with dynamic resources to ensure a robust and adaptive approach to risk assessment.

By adopting these practices, organisations can enhance their ability to identify potential cyber-attacks proactively within event-based cybersecurity risk assessment. This study highlights the importance of integrating collaboration, historical insights, current trends, and authoritative references into event-based cybersecurity risk assessments, providing a comprehensive and adaptive approach for mitigating evolving cyber threats.

VI. Limitations

This study is subject to several limitations. First, it employed a qualitative research design, relying on semi-structured interviews with ten cybersecurity experts. Although the participants were carefully selected for their expertise and experience, the relatively small sample size may constrain the generalisability of the findings to the broader organisational context. Second, the study's reliance on self-reported data introduces the potential for biases, such as recall bias and social desirability bias, which could influence the accuracy of the responses.

Future research could expand the sample size to include a broader and more diverse range of stakeholders across multiple organisations. In addition, incorporating quantitative methods or a mixed-methods approach could offer more robust validation and enable better triangulation of data. To address potential biases in self-reported data, future research could incorporate direct observations, document analysis or simulation-based assessments to complement interview findings.

VII. Conclusion

This study explored how organisations identify potential cyber-attacks within an event-based cybersecurity risk assessment framework. Through qualitative analysis of interviews with ten cybersecurity experts, key practices and considerations were uncovered. The findings reveal that organisations rely on a combination of brainstorming and collaboration, leveraging historical data, staying updated on current trends, and using established frameworks such as ISO/IEC 27005, supplemented with dynamic threat intelligence platforms like MITRE ATT&CK. These practices highlight the importance of a multifaceted and proactive approach to managing cybersecurity risks.

The study contributes to both theory and practice by addressing the gap in understanding how organisations identify cyber threats within an event-based risk assessment context. It emphasises the value of integrating static and dynamic resources, fostering cross-departmental collaboration, and maintaining a forward-looking approach to mitigate evolving cyber threats. These insights provide a practical roadmap for organisations aiming to enhance their cybersecurity risk assessment strategies and align them with the demands of an ever-changing threat landscape.

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Conflict of Interest

The authors declare that there is no conflict of interest

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Efficient Skyline Query Processing in Incomplete Graph Databases Using Machine Learning Techniques

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Abstract— Skyline queries play a critical role in multi-criteria decision-making systems by retrieving non-dominated data points from large datasets. In recent years, the rapid growth of graph-structured data across various domains has introduced challenges in efficiently processing skyline queries over incomplete and large-scale graph databases. Processing skyline queries in such massive, incomplete graphs is computationally intensive due to missing values and high-dimensional data. Traditional techniques often fail to scale or effectively handle data imperfections. There is a pressing need for a scalable, intelligent framework that can manage missing data, reduce computational overhead, and improve skyline query efficiency. This study adopts the Design Science Research Methodology (DSRM) to design and implement an optimisation framework that integrates machine learning techniques, including domination score ranking, dimension-based filtering, K-Means clustering and quicksort. These methods collectively reduce the search space and redundant comparisons. Experimental evaluation on real graph datasets demonstrates significant improvements in skyline computation time and accuracy, with clear reductions in pairwise comparisons and improved processing efficiency on large-scale graphs. By leveraging machine learning techniques for sorting, filtering and clustering, the approach reduces computational complexity and enhances scalability. These results show promising directions for applying intelligent query optimization in big data environments.

Keywords— Skyline queries, Incomplete graph database, Machine learning, Graph database

I. INTRODUCTION

These Skyline queries are used in database systems to retrieve non-dominated tuples data points that are not dominated by any other nodes [1]. In graph databases, this means identifying nodes that are optimal based on attributes such as distance, cost or relevance, making skyline queries particularly useful in applications like recommendation systems, e-commerce, road networks and urban planning.

A big challenge happens when graph databases contain incomplete data [2] [3] [4]. These missing values fail the transitivity of dominance relationships, which is foundational to skyline computations. This can lead to cyclic comparisons and ambiguous dominance, significantly increase the complexity of processing queries. Despite the widespread use of skyline queries in practice, limited research has addressed how to efficiently compute skylines when dealing with incompleteness in graph-based datasets.

Graphs in real-world applications are often dynamic and sparse, where nodes frequently lack values in one or more dimensions. For example, in a hotel recommendation system, a user may want to identify hotels near the beach with affordable prices. If some hotels are ratings or price information, they still might be valuable candidates depending on the available data. Traditional skyline algorithms often leave out these incomplete entries, which potentially eliminates useful information from the results.

Processing skyline queries efficiently over incomplete graph databases thus requires innovative techniques which can reduce the computational cost, handle missing values without compromising the accuracy of results and adapt to high-dimensional and constantly changing data. This study aims to tackle these challenges by proposing a method which integrates machine learning techniques particularly clustering to enhance skyline query performance. Machine learning can help infer patterns from incomplete data, cluster similar nodes to narrow the search space and dynamically adapt to query updates, thus making skyline processing more accurate and scalable.

To address the limitations of existing approaches, the following objectives and contributions of the study are proposed:

- To design and develop an efficient data pruning approach tailored for incomplete graph databases.

- To leverage machine learning techniques for enhanced performance and scalability.
- To evaluate the effectiveness of the proposed pruning technique through empirical experiments, comparing its performance with existing baseline methods in terms of accuracy, efficiency and computational cost.

A. *Summary of Contribution*

- The proposed study has introduced a unified framework which combines quick-sort based domination scoring, threshold-filtering and K-Means clustering to optimize skyline query processing.
- A development of a clustering mechanism which groups nodes based on missing dimensions to enable effective skyline computation with requiring data imputation.
- A proposed local and global skyline identification method which reduces unnecessary pairwise comparison to ensure transitivity while avoiding cyclic dominance.
- A demonstration on the improvements in processing time and data pruning with experiments on different datasets of varying sizes.

II. Related Works

A skyline query optimization in graph databases has been advanced significantly especially for static environments. The pruning technique in [5] uses hierarchical labels to reduce overhead but is limited by its need for re-computation in dynamic graphs. The study by [6] supports dynamic queries with local distance functions but suffers from high computational costs as graph complexity grows. Similarly, a hybrid approach in [7] combines subgraph isomorphism with dual traversal however, scalability in high-dimensional graphs remained a challenge.

Moreover, the algorithmic divide-and-conquer method in [8] improves on nested loop approaches by partitioning the problem space and minimizing redundant comparisons thus boosting performance and accuracy. Compared to pruning in [9] and subgraph merging in [7], [8] which demonstrates superior efficiency especially in large-scale and moderately dynamic graphs. However, it lacks adaptability to real-time changes and user-defined preferences which increasingly demands an interactive application. This comparison reveals that while algorithmic performance remains a core priority, practical implementations must also factor inflexibility and dynamic responsiveness.

Furthermore, the handling of incomplete data in skyline queries possesses a unique challenge particularly in ensuring accurate dominance comparisons. The method in [8] utilizes Approximate Functional Dependencies (AFDs) to infer missing values followed by ranking based on dependency strength which is a technique that enhances the semantic richness of imputations. While effective in preserving skyline correctness however, this method can be computationally expensive due to repeated AFD generation. On the other hand, [16] adopts a more parallel-friendly framework by clustering nodes with similar missing patterns and applying bitwise skyline filters. This not only improves processing speed but also upholds the transitivity of skyline dominance, a property often lost in simpler imputation methods. Also, building on these foundations, [17] introduces a dominance-aware clustering and pruning technique that further scales skyline computation by minimizing redundant comparisons. Despite their differences, these methods reflect a shared emphasis on balance precision, performance and scalability, though none fully resolves the complexities of high-dimensional or real-time incomplete data handling.

Real-time skyline path queries in dynamic networks require algorithms that are both fast and responsive. The PSQ+ algorithm from [10] has introduced a refined pruning mechanism which discards non-skyline paths during graph traversal thus maintaining real-time efficiency even in bicriteria networks. This method marks a significant departure from more static approaches like those in [8] or [11], as it actively adapts to the changing cost landscape of paths. Supporting this, [11] improves the credibility of skyline query results through POI signature-based authentication, ensuring the integrity of results in outsourced databases. Meanwhile, [12] tackles user-centric issues such as incomplete skyline results by implementing a reverse-query mechanism that identifies potential missing tuples based on adjusted preferences. While these methods collectively push skyline path queries closer to real-time user-aware applications however, they also introduce new overheads in preprocessing, verification and system complexity that must be managed carefully.

In distributed environments, skyline computation must balance network communication, data partitioning and computation cost [20]. Approaches like BDS and IDS optimize node access and reduce comparisons, but struggle with dynamic networks. More advanced methods, such as PDS and iSky, use probabilistic models and adaptive filters to prune irrelevant data early and improves performance. However, their effectiveness depends on initial data distribution and network topology which are not always controllable. Despite having a progress, full scalability and fault tolerance in dynamic scenarios remains open challenge.

Skyline query processing under uncertainty becomes more complex in dynamic settings with frequent updates. The method in [13] extends skyline queries to uncertain graphs using expected distances and probabilistic pruning, enhancing decision but increase computational costs (See Table 1). The IDSA algorithm[14] handles dynamic changes

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with multi-phase pruning and block nested loops, but exhaustive dominance checks can hinder performance on large graphs. While effective in real-time, noisy environments, these methods highlight the need for lighter or incremental models to improve scalability and responsiveness.

TABLE I
EXISTING LIMITATIONS AND GAP ANALYSIS

	Limitation	Gaps
[9]	High memory usage, lacks support for dynamic graphs	Needs optimization for non-Euclidean and real-time use
[6]	Computationally expensive, lacks general graph support	Scalability and real-time processing
[7]	Struggles with large graphs, complex constraints	Unified large-scale graph handling
[5]	Inefficient nested loop, compute-heavy	Optimization for complex graph queries
[8]	Heavy preprocessing, not scalable with many POIs	Large dataset handling with missing data
[2]	Expensive in complex networks	Lightweight path skyline algorithms
[11]	Preprocessing burden, slow with many POIs	Scalable authentication methods
[12]	Not efficient for large-scale data	Better performance for big data
[3]	Struggles with cycle dominance and dimensionality	Real-time complex missing data handling
[17]	Poor performance on high-dimensional datasets	Optimization for high complexity
[16]	Complexity in distance calculations across layers	Scalability in multi-layer graphs
[17]	Underperforms with anti-correlated data, dimension bottlenecks	Dimensionality handling
[18]	Scalability and communication bottlenecks	Robust-distributed skyline methods
[13]	Multi-phase algorithm complexity	Simplified dynamic skyline algorithms
[15]	Complex, constrained by time and label ranges	Scalable temporal skyline querying
[19]	MapReduce overhead, partition imbalance	Balanced distributed skyline computing
[20]	Struggles with sparse data, normalization issues	Effective QoS partitioning
[21]	Not memory-efficient for large datasets	Support for dynamic updates
[22]	Inter-bucket comparison slows things down	Efficient global skyline merging

Also, the temporal and attribute-rich graphs require advanced skyline processing. The TMP algorithm [15] uses bidirectional search and time-aware indexing to efficiently find skyline paths under temporal and label constraints outperforming traditional methods. The probsky [19] built on mapreduce, handles probabilistic skyline queries using slab partitioning and reference-point acceleration for scalability, though it suffers from high signature generation costs. These methods highlight the need to combine temporal awareness, uncertainty handling and distributed computing, while also raising concerns about preprocessing overhead and integration complexity.

III. METHODOLOGY

This study adopts the design science research methodology (DSRM) [23] (see Figure1), which is a structured framework to design, develop, and evaluate innovative IT artefacts to address real-world problems. This study utilizes DSRM to propose a machine learning-based approach for skyline query optimization in a large-scale incomplete graph database. It emphasized both practical relevance and theoretical contribution. The proposed methodology aligns with the six stages of DSRM to address the objective and goals of this study.

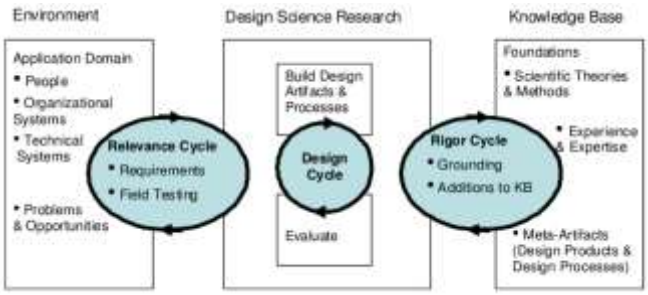

Fig 1. DSRM Process ([23])

A. *Design and development*

This phase of skyline query optimization comprises five key components as shown in Fig 2 and Table 2. Each component plays an important role in ensuring computational efficiency and maintaining the accuracy of the skyline query optimized results.

1) Dataset development: A synthetic dataset was developed to evaluate the proposed skyline solution. The reason for using the synthetic dataset is due to the lack of availability of a real dataset concerning the skyline query problem. The dataset was designed to include missing values randomly, simulating data incompleteness, which is common in large-scale graph databases. The dataset comprises 51 nodes connected to form a graph. The dataset simulates a hotel booking scenario to assist customers in finding recommendations for the best hotel room.

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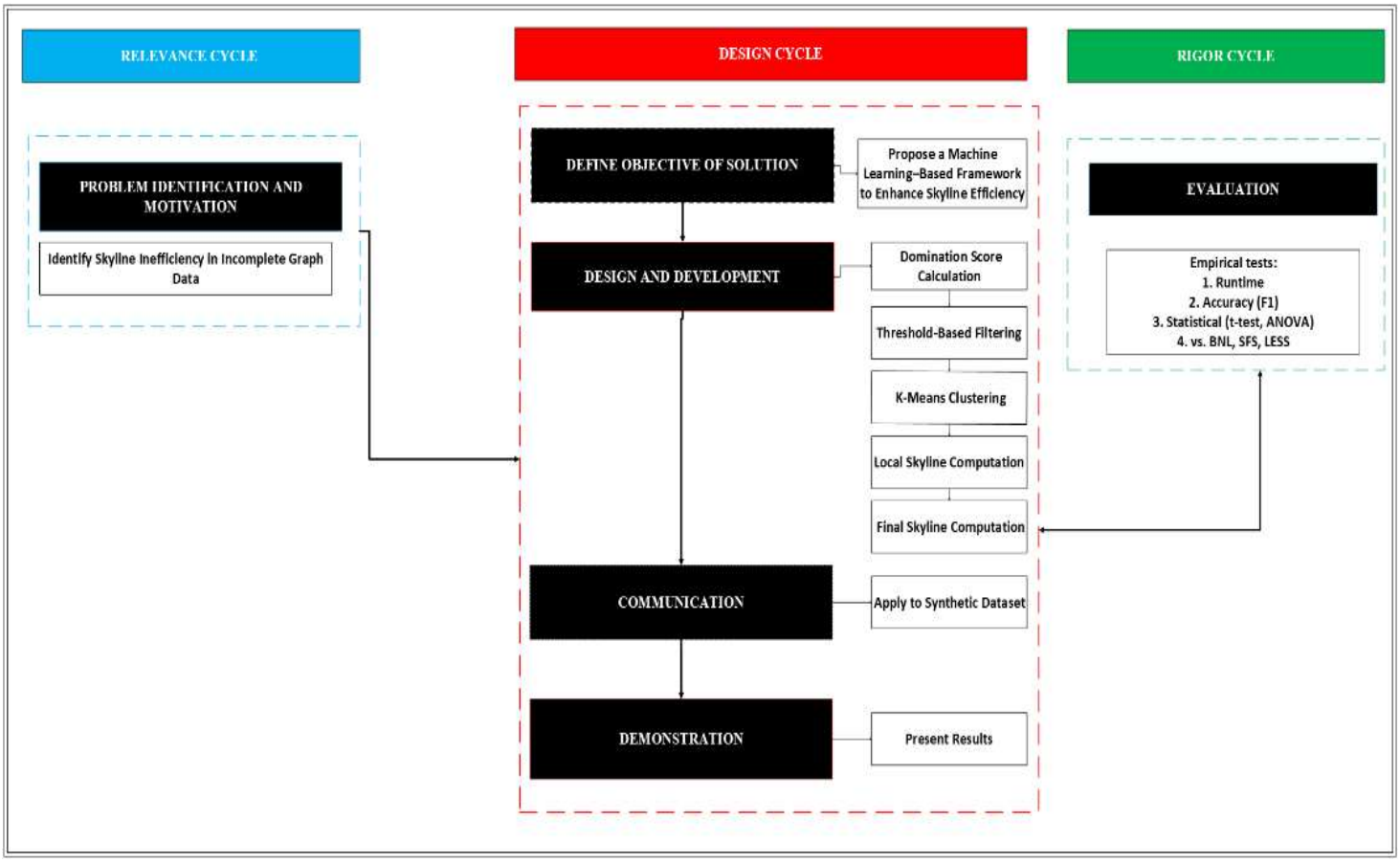

Fig 2. Proposed Methodology based on DSRM

The attributes of the dataset include price, rating, distance, and hotel service. The dataset has a comprehensive number of nodes, each comprised of systematically randomized values, achieving the major objective of the dataset development. Also, the dataset development aligns with its application to be used in machine learning algorithms, to make sure that the data preprocessing was performed earlier during the dataset development phase, addressing null value duplication and irrelevant data, respectively. The dataset is highly suited for machine learning purposes, particularly concerning the skyline query problem and its potential optimization solution for graph databases.

2) *Sorting and filtering:* This phase arranges the data nodes in descending order based on their domination power, which reflects the total number of other nodes that dominate across all dimensions. A round-robin traversal method is used to calculate domination scores, considering only non-missing values to ensure fairness and accuracy. The framework enables the early elimination of less relevant nodes, reducing the number of pairwise comparisons required during skyline computation. This significantly lowers computational overhead and ensures that only the most promising candidates proceed to the next stages.

TABLE II
STAGES OF PROPOSED METHODOLOGY

1	Problem identification and motivation	Inefficient skyline queries in incomplete graph databases present significant challenges, primarily due to missing data and scalability concerns.
2	Design objective of a solution	This study proposes a machine learning–based pruning and clustering framework aimed at improving accuracy and performance.
3	Design and development	A five-step framework was developed, consisting of sorting, filtering, clustering, local skyline detection, and final skyline computation.
4	Demonstration	The proposed framework was evaluated using synthetic graph datasets to assess its practical utility.
5	Evaluation	Experimental results have indicated that the proposed framework significantly reduced processing time and improved scalability.
6	Communication	This research presents the findings to support further exploration within academic and technical communities.

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Similarly, the filtration process excludes nodes whose domination power falls below a user-defined threshold, as such nodes are unlikely to contribute meaningfully to the skyline. This threshold-based pruning complements the sorting phase by reducing unnecessary computations early in the process. The threshold can be adjusted based on dataset characteristics or user requirements to balance precision and efficiency. Moreover, the framework remains adaptable and other sorting or filtering can be integrated, as long as they align with the core principles. This design ensures robustness and flexibility across varied, incomplete graph datasets.

3) Clustering: The objective of this phase is to establish clusters among data items based on their domination power, which enables a more efficient skyline query processing. The data items with similar domination power are grouped, resulting in the formation of distinct clusters. The K-Means clustering was considered due to its real data points consideration as representatives of each cluster. This feature is particularly useful in ensuring that the clusters accurately reflect the dataset and make the skyline computation more precise. To validate the clustering model, k-fold cross-validation is used in which the dataset is split into *k* subsets, and the model is trained on *k - 1* subsets and tested on the remaining one. The model performance is evaluated using the silhouette score and Davies-Bouldin index to assess the quality of the clusters formed, ensuring that the final skyline computation is robust and accurate. Lastly, the search space significantly reduces the gaps, which helps to avoid unnecessary comparisons while maintaining the accuracy of the final skyline results.

4) *Identifying Local Skyline:* It is intended to retrieve local skylines for each of the constructed clusters, which leads to prevents many dominated data items from further processing, resulting in a reduction in the processing time. Also, it ensures the transitivity property of the skyline solution holds as all data items in one cluster have a similar namespace. The parallel process will be in all clusters, which will reduce the processing time between the data elements.

5) Final Skyline: The last component is responsible for determining the final skyline. The process starts by comparing those local skylines generated earlier and retrieving those undominated data items as the final skylines of the entire incomplete graph database. This component ensures that any reported global skylines are the skylines over the entire database, and no other data items might dominate them.

B. *Evaluation*

This phase aims to determine how well the framework meets the objectives set out in this study, particularly in the context of skyline query optimization for incomplete graph databases. The evaluation is carried out by comparing the proposed framework with traditional skyline query methods and evaluating key performance metrics such as scalability, accuracy, and efficiency. Similarly, the integration of sorting and filtering techniques will be evaluated to understand their performance in reducing the dataset size before skyline computation. By prioritizing more influential nodes and eliminating irrelevant data points, the proposed framework will be evaluated on the reduction of its search space for efficient skyline processing. Moreover, the framework will be evaluated further by applying threshold-based filtering to remove dominated nodes early in the process. By evaluating these nodes, which are less likely to contribute to the final skyline result, the proposed framework will be analyzed in terms of the computational cost required for skyline computation.

IV. Experimental Analysis and Results

The proposed framework was implemented using Python, leveraging a range of machine learning libraries to support the required functionalities. Similarly, to implement clustering and support data processing tasks, the Scikit-learn package was used for clustering with the K-means model, data processing, and model evaluation. The pandas and numpy packages were utilized for efficient data manipulation, specifically in handling the incomplete dataset having one missing dimension. The numpy provided support for numerical operations, while pandas facilitated data cleaning, sorting and filtering, ensuring seamless integration across the different steps in skyline query optimization. Moreover, the implementation was modular, allowing each technique to be independently tested and optimized. The next step was to execute a series of experiments to assist its performance. These experiments were conducted on datasets of varying sizes to evaluate how well the framework performs under different conditions.

	Node	Dim1	Dim2	Dim3	Dim4
0	1	2	8	0	4
1	2	3	0	8	1
2	3	3	2	0	2
3	4	5	0	2	8
4	5	8	1	0	6
5	6	4	0	7	3
6	7	0	8	2	9
7	8	7	0	8	4
8	9	0	6	4	2
9	10	5	2	6	0
10	11	8	6	4	0

Fig. 3. Initial Dataset

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Algorithm 1 Quick Sort Nodes

```
Input: An array A of n nodes
Output: Sorted array A
function QuickSort(A, low, high)
    if low < high then
        p ← Partition(A, low, high)
        QuickSort(A, low, p − 1)
        QuickSort(A, p + 1, high)
    end if
end function
function Partition(A, low, high)
    pivot ← A[high]
    i ← low − 1
    for j ← low to high − 1 do
        if A[j] ≤ pivot then
            i ← i + 1
            Swap A[i] and A[j]
        end if
    end for
    Swap A[i + 1] and A[high]
    return i + 1
end function
```

Fig. 4. Quicksort algorithm implementation

A. *Sorting and filtering analysis*

The process starts by sorting the items in each distinct list based on values of each dimension on the dataset as shown in Fig. 3 The quick sort algorithm was used in this experiment as shown in Fig. 4 for its divide-and-conquer strategy. The partitioning step efficiently divides the dataset into manageable subsets, reducing operational complexity. Using the last element as a pivot ensures consistency and minimizes redundant operations. Node 1 is read with its domination power, which is increased by 1, which means it is compared with other nodes in the given dimension. The dimension 1 as shown in Fig. 5(a), Nodes 5 and 11 have the highest score of 8, followed by Node 8 with a score of 7. The dimension 2 as shown in Fig. 5(b), Nodes 1, 7, and 6 dominate while in dimension 3 as shown in Fig. 5(c), Nodes 2, 8, and 6 take the lead. The dimension 4 as shown in Fig. 5(d), Nodes 7 and 4 have the highest domination scores. The process terminated after dimension 4 with Node 11. The total number of iterations comprises 44th in number. The lowest score of 0 is assigned to Node 9 in dimension 1, where no comparison can be made due to its value being zero or empty. The constructed lists are scanned round-robin style for each data item to determine its domination power. Domination scoring of all nodes occurs one after the other until each node receives its dominance value.

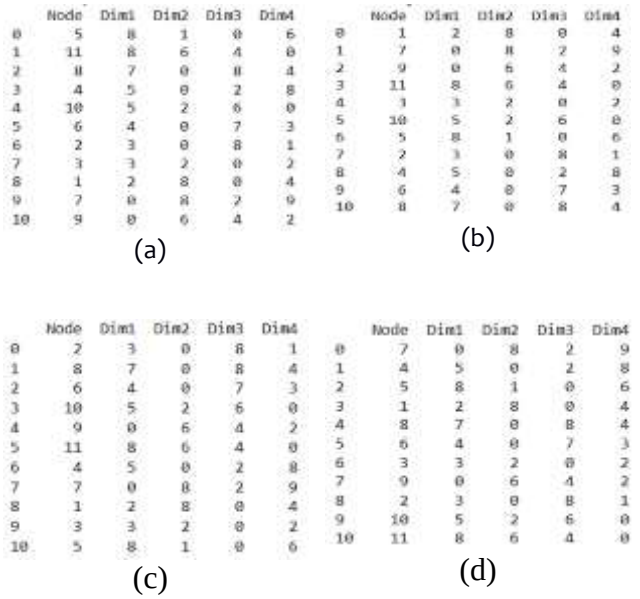

Fig. 5. Domination power calculation

B. *Threshold-based filtering*

This process has removed the nodes which comprise of low domination score and had minimal impact on the skyline computation. Also, it reduces the size of the data which is essential in decreasing computational overhead and enables faster processing. Moreover, the removal of less influential nodes makes skyline query processing more significant and efficient. Additionally, filtration is an equally crucial step aimed at narrowing the search space by discarding nodes which are unlikely to contribute to the skyline. The experiment uses a threshold-based approach which maximizes efficiency while ensuring relevant candidates are retained as shown in Fig. 6 and the algorithm is shown in Fig. 7. The focus is on a limited subset of nodes on each dimension; this approach efficiently controlled the exponential growth of pairwise comparisons. Moreover, the stopping condition introduced a mechanism for early termination to ensure runtime was minimized without compromising accuracy.

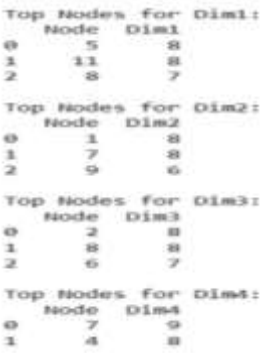

Fig. 6. Top threshold nodes

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Algorithm 2 Filter Nodes with Threshold

```
Input: Dictionary sorted_nodes, where each value has sorted nodes
Output: Dictionary nodes_with_threshold, containing nodes for each dimension
nodes_with_threshold ← empty dictionary
for all Dimensions, sorted_nodes in sorted_nodes do
    top_nodes ← empty list
    top_values ← empty set
    value_counts ← empty dictionary
    for all row in sorted_nodes do
        value ← row[Dimensions]
        node ← row["Node"]
        if value not in value_counts then
            value_counts[value] ← 0
        end if
        if value_counts[value] < 2 then
            Append (node, value) to top_nodes
            value_counts[value] ← value_counts[value] + 1
            Add value to top_values
        end if
        if len(top_values) == 2 then
            break
        end if
    end for
    nodes_with_threshold[dim] ← DataFrame of top_nodes with columns ["Node", Dimensions]
end for
    return nodes_with_threshold
```

Fig. 7. Threshold-based filtering

The threshold-based filtration eliminates the data items with a domination power lower than a user-defined threshold. These data items are discarded because their domination score indicates that they perform well in no more than one dimension, making them unlikely to be part of the skyline result. Dimension 1 with Nodes such as Nodes 5, 11 and 8 remain there, while in dimension 2, Nodes 1, 7 and 9 are still considered. Dimension 3 with Nodes 2, 6, and 8 have domination powers greater than the threshold, and in dimension 4, Nodes 7 and 4 are still in consideration. These nodes have domination powers greater than the threshold value and thus remain in consideration for the skyline result.

Algorithm 3 Final Nodes Filtered with Threshold

```
Input: Dictionary nodes_with_threshold, containing nodes for each dimension
Output: DataFrame final_filter_nodes, containing the final nodes without duplicates
final_filter_nodes ← Empty DataFrame with column "Node"
for all Dimension, Nodes in nodes_with_threshold do
    for all row in Nodes do
        if row["Node"] not in final_nodes["Node"] then
            Create a new DataFrame with row["Node"]
            Concatenate the new DataFrame to final_filter_nodes
        end if
    end for
end for
    return final_top_nodes
```

Fig. 8. Final nodes filtered with a threshold algorithm

In the example from Fig. 8, after applying the algorithm in Fig. 9, the filtration process and setting a threshold value, there were identified 9 nodes as eligible for the skyline as shown in Fig. 10. These nodes represent approximately 81.82% of the total 11 nodes in the dataset. The remaining nodes, which didn't meet the threshold criteria are not considered in the skyline calculation.

Algorithm 4 Final Nodes with Threshold Assigned with Actual Values

```
Input: Dictionary sorted_nodes, where each value is a DataFrame
Output: Dictionary final_nodes_with_threshold, containing top nodes for each dimension
final_nodes_with_threshold ← empty dictionary
for all Dimensions, sorted_nodes in sorted_nodes do
    top_nodes ← empty list
    top_values ← empty set
    value_counts ← empty dictionary
    for all row in sorted_nodes do
        value ← row[Dimensions]
        node ← row["Node"]
        if value not in value_counts then
            value_counts[value] ← 0
        end if
        if value_counts[value] < 2 then
            Append (node, value) to top_nodes
            value_counts[value] ← value_counts[value] + 1
            Add value to top_values
        end if
        if len(top_values) == 2 then
            break
        end if
    end for
    final_nodes_with_threshold[Dimensions] ← DataFrame of top_nodes with columns ["Node", Dimensions]
end for
    return final_nodes_with_threshold
```

Fig. 9. Final nodes with dataset values

	Node	Dim1	Dim2	Dim3	Dim4
0	5	8	1	0	6
1	11	8	6	4	0
2	8	7	0	8	4
3	1	2	8	0	4
4	7	0	8	2	9
5	9	0	6	4	2
6	2	3	0	8	1
7	6	4	0	7	3
8	4	5	0	2	8

Fig. 10. Results of eligible nodes for clustering

C. *Machine learning-based clustering*

This process aims to group nodes that exhibit zero values in specific dimensions. The nodes with zero values often hold distinctive properties that warrant separate analysis. The algorithm in Fig 11 begins with nodes containing dimensional values and a list of dimensions to analyze. It iteratively examines each dimension to identify nodes with zero values, excluding any nodes which are excitingly assigned to clusters. Also, for the nodes which are isolated, the algorithm performs K-Means clustering to organize the nodes into clusters depending on the number of nodes available. This clustering step ensures that the nodes are grouped based on their similarity in dimensional values making subsequent processing more efficient. The final clusters annotated with their labels are stored in a structured format which develops the basis for further analysis. The example from the experiment as shown in Fig. 12 results of clustering based on the proposed model.

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Algorithm 5 Cluster Nodes Based on Zero Values

Input: DataFrame `final_top_nodes_with_values`, List of dimensions `["Dim1", "Dim2", "Dim3", "Dim4"]`
Output: Dictionary `clusters`, containing the nodes clustered by each dimension
`clusters` ← Empty dictionary
`used_nodes` ← Empty set ▷ To keep track of nodes already assigned to clusters
for all `Dimensions` in `["Dim1", "Dim2", "Dim3", "Dim4"]` **do**
  `zero_values` ← Rows in `final_top_nodes_with_values` where `Dimensions` is 0 and `Node` not in `used_nodes`
  if `zero_values` is not empty **then**
    `n_clusters` ← Minimum of 4 and the length of `zero_values`
    Perform KMeans clustering with `n_clusters` on the columns `"Dim1", "Dim2", "Dim3", "Dim4"`
    `cluster_labels` ← Result from KMeans clustering
    Assign `cluster_labels` to the `zero_values` DataFrame in a new column `Cluster`
    `clusters[Dimensions]` ← Subset of `zero_values` with columns `"Node", "Dim1", "Dim2", "Dim3", "Dim4", "Cluster"`
    Update `used_nodes` by adding the nodes from `zero_values["Node"]`
  end if
end for
return `clusters`

Fig. 6. Clustering algorithm

Clusters for Dim1 (Nodes with Zero Values):

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
4	7	0	8	2	9	0
5	9	0	6	4	2	1

Clusters for Dim2 (Nodes with Zero Values):

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
2	8	7	0	8	4	2
6	2	3	0	8	1	0
7	6	4	0	7	3	3
8	4	5	0	2	8	1

Clusters for Dim3 (Nodes with Zero Values):

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
0	5	8	1	0	6	0
3	1	2	8	0	4	1

Clusters for Dim4 (Nodes with Zero Values):

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
1	11	8	6	4	0	0

Fig. 7. Clustering results

D. *Local skyline computation*

This step enables the identification of the local skyline node from each cluster, simplifying the clustered data into a small set of candidates for local skyline query processing. The local skyline is determined by identifying nodes that are not dominated by any other node within the cluster. The node with the highest score in each cluster is selected as the representative, which captures the most important characteristics of that cluster, as shown in Fig 13.

Applying clustering techniques while identifying the local skyline phase assists in eliminating many dominated data nodes. Based on the given example it is obvious that 4 nodes are left out of the remaining 9 nodes as shown in Fig. 14. This represents the 44.44% reduction in the dataset.

E. *Final skyline computation*

This final skyline aggregation approach mainly addresses the issue of skyline query processing on incomplete graph data. The goal is to select the final skyline of the entire dataset. In the experiment, a set of nodes were retrieved which stand out in at least one dimension and are not inferior in all dimensions to any other node. These final skyline nodes are the most significant for further analysis and decision-making. The process compares each node as shown in Fig. 15 in the dataset with every other node to derive these final skyline nodes.

s illustrated in Figure 16, Node 7 was compared with Nodes 5, 11, and 8, and was found to be dominated by Nodes 5 and 9. Node 11 dominated Node 8, while neither Node 7 nor Node 11 dominated each other qualifying both for inclusion in the final skyline. This step, central to machine learning–driven skyline analysis, filters out redundant nodes and retains only distinct, high-value candidates, thereby reducing noise and supporting effective decision-making. This final step ensures that only the nodes that are not dominated by any others across the entire dataset are included in the skyline, representing the best or most significant nodes in the context of the skyline query.

Algorithm 6 Identify Single Nodes on each Cluster

Input: Dictionary `clusters`, where each value contains cluster information for nodes
Output: DataFrame `final_result`, containing the final selected nodes from each cluster
`final_clusters` ← Empty dictionary
for all `Dimensions`, `cluster_nodes` in `clusters` **do**
  `scores` ← Empty dictionary ▷ To store scores for each node
  for all `node_n` in `cluster_nodes` **do**
    `scores[node_n["Node"]]` ← 0 ▷ Initialize score for the current node
    for all `node_n` in `cluster_nodes` **do**
      if `node_n["Node"]` ≠ `node_n["Node"]` **then**
        for all `col` in `["Dim1", "Dim2", "Dim3", "Dim4"]` **do**
          if `node_n[col]` > `node_n[col]` **then**
            `scores[node_n["Node"]]` ←
            `scores[node_n["Node"]]` + 1
          end if
        end for
      end if
    end for
  end for
  `max_score_node` ← Node with the highest score from `scores`
  `final_clusters[Dimensions]` ← Subset of `cluster_nodes` where `Node` equals `max_score_node`
end for
`final_result` ← Concatenation of `final_clusters`
return `final_result`

Fig 8. Single node cluster identification algorithm

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
4	7	0	8	2	9	0
2	8	7	0	8	4	2
0	5	8	1	0	6	0
1	11	8	6	4	0	0

Fig. 9. Local skyline results

F. *Performance evaluation*

The performance evaluation of the experimental results of skyline queries in incomplete graph databases was performed on synthetic datasets. This set of experiments aims at examining the effect of data size on datasets, and on the processing time that needs to be performed during the skyline query process over an incomplete graph database.

1) Effect on Size of Dataset: The proposed method reduces the dataset size by an average of 50% before the

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final skyline selection. It evaluates node comparisons in a synthetic dataset using two sizes: 11 and 51 nodes as shown in Fig. 17 and Fig. 18. The results have shown that larger datasets require more pairwise comparisons, increasing processing time. However, the approach effectively prunes ineligible nodes, systematically reducing computational workload and maintaining high efficiency. Despite dataset growth, the method shows minimal impact on processing time, demonstrating strong scalability and robustness for incomplete skyline processing in graph databases.

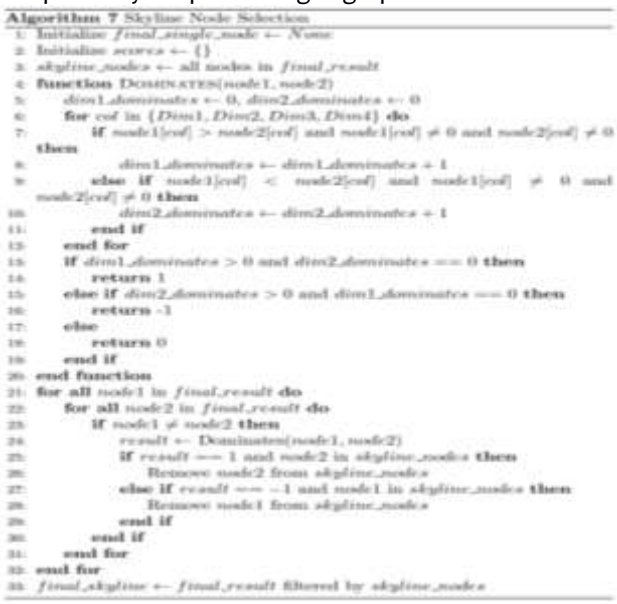

Fig 10. Selecting the final skyline node algorithm

	Node	Dim1	Dim2	Dim3	Dim4	Cluster
4	7	0	8	2	9	0
1	11	8	6	4	0	0

Fig. 11. Final Skyline results

2) Effect on Processing Time: The proposed machine learning-based approach reduces query processing time by 30–50% compared to traditional methods. This is achieved by clustering the dataset, allowing skyline queries to operate on smaller, more relevant subsets, thus minimizing unnecessary pairwise comparisons. This streamlines computation and ensures quicker, optimized execution. The approach also demonstrates high scalability, maintaining efficiency as dataset size grows unlike traditional methods, which face exponential increases in processing time. This makes the proposed method well-suited for large-scale, dynamic environments with expanding data.

As shown in Fig. 18 for the 51-node dataset, processing time decreases as data size increases. The proposed approach consistently outperforms previous methods in all scenarios, showing minimal sensitivity to data size. By effectively pruning ineligible nodes, it ensures efficient computation even with large datasets. Although more nodes usually increase data exchange and latency, the proposed method minimizes processing time, demonstrating strong robustness and scalability for large-scale data handling.

As shown in Fig 19 and 20, the graphs for both 11-node and 51-node datasets exhibit similar patterns. Processing time peaks at Dimension 2 (0.0225 sec for 51 nodes vs. 0.020 sec for 11 nodes), drops sharply at Dimension 3 and remains mostly stable at Dimension 4. While the larger dataset shows slightly higher processing times in the lower dimensions, it outperforms the smaller dataset at Dimension 4 likely due to better utilization of resources at scale. This suggests that scalability benefits become more apparent beyond a certain complexity threshold, where the initial overhead is offset by improved performance in higher dimensions. The entire performance comparison and its impact on the execution runtime will be as shown in Table 3 between both the datasets utilized for performance study.

TABLE III
COMPARISON OF PERFORMANCE EXECUTION OVER RUNTIME BETWEEN DATASETS

No.	Nodes	Dim1	Dim2	Dim3	Dim4
1	11	0.007	0.020	0.005	0.009
2	51	0.0087	0.0225	0.0085	0.0050

3) Statistical Evaluation and Baseline Comparison

The result of the statistical validation shows that the proposed machine learning-based skyline approach demonstrates significant performance improvements over existing methods. The study was analysed with key findings based on confidence intervals, standard deviation, t-tests, F1-score and ANOVA. The statistical findings and comparisons are based on these studies [24] [25], [26] [1] respectively, provided with relevant performance metrics for LESS, SFS and BNL to be compared with proposed methods for skyline computation.

4) Confidence Interval analysis

The results in Table 4 have shown that the proposed approach has the lowest execution time with a confidence interval of (0.00248, 0.00392), which does not overlap with those of the LESS, SFS and BNL methods. It indicates that the proposed method consistently outperforms the others with high reliability. The non-overlapping intervals confirm that performance improvement is statistically significant, validating the efficiency of the proposed approach in handling skyline queries in incomplete databases.

5) Standard Deviations Analysis

The proposed approach has a standard deviation of 0.000455, which is lower than the LESS, SFS and BNL methods as shown in Table 5. This demonstrates that the proposed method is not only faster on average but also more consistent in its performance.

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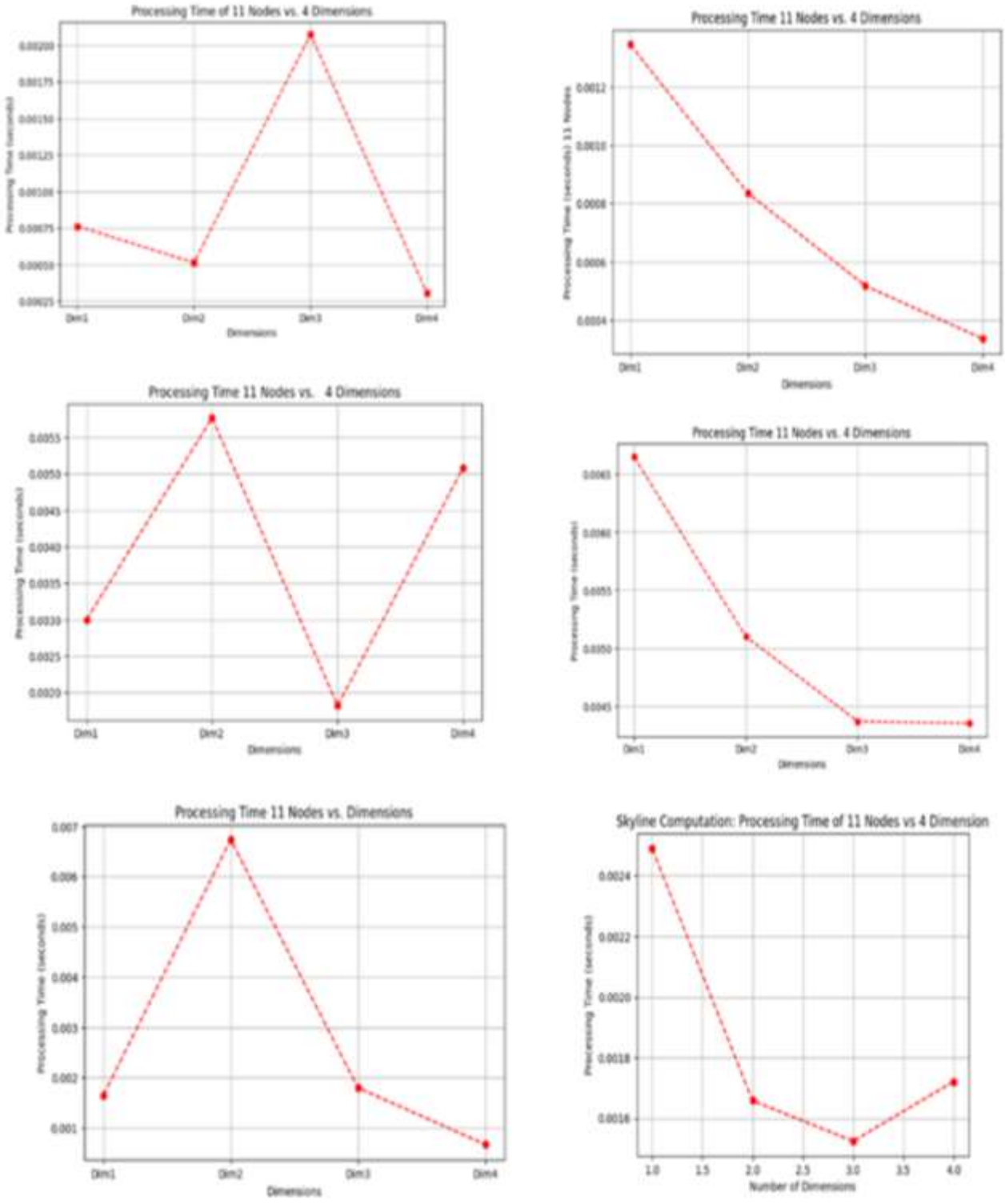

Fig 12. Results with fifty-one (11) nodes

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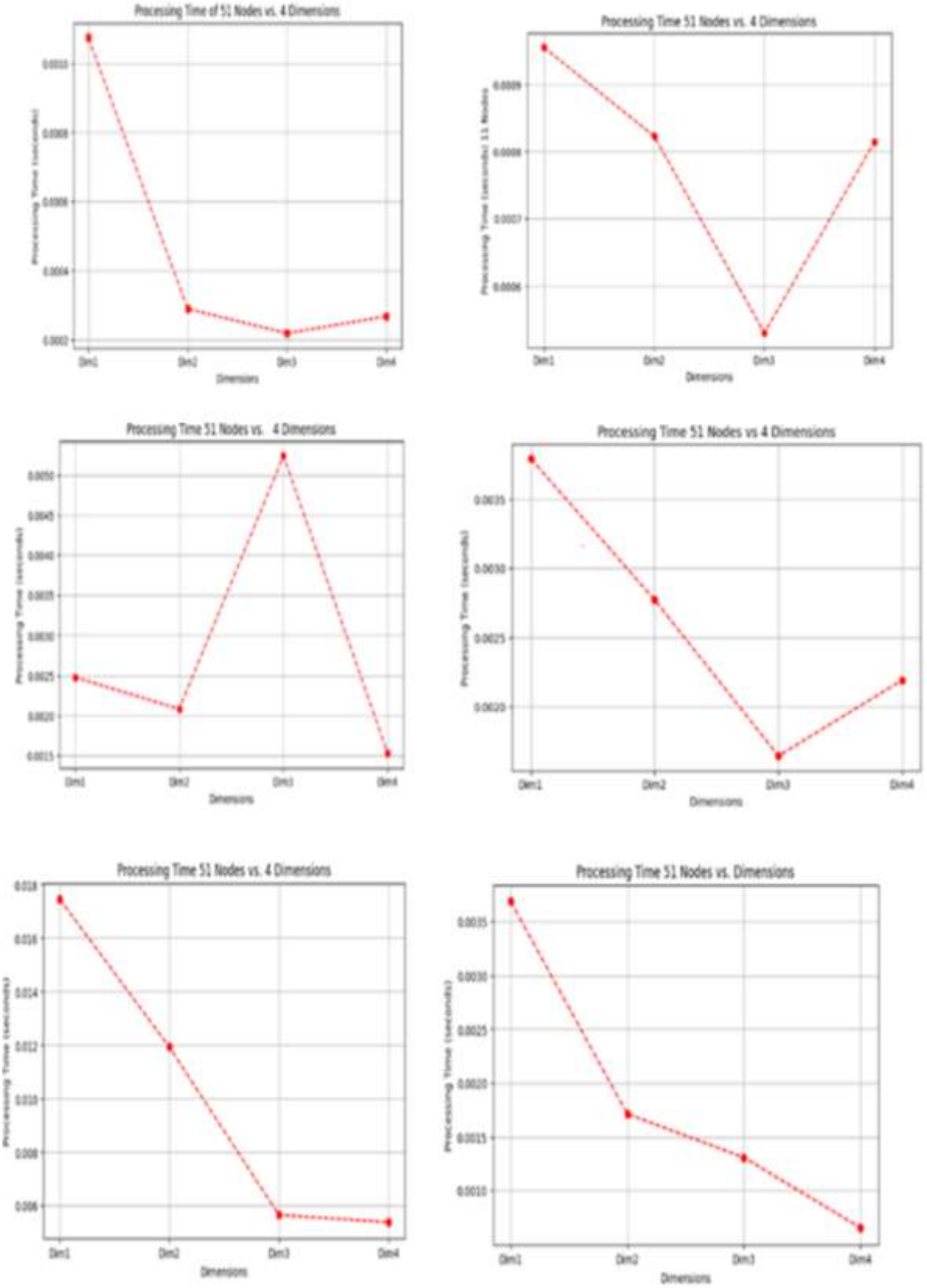

Fig 13. Results with fifty-one (51) nodes

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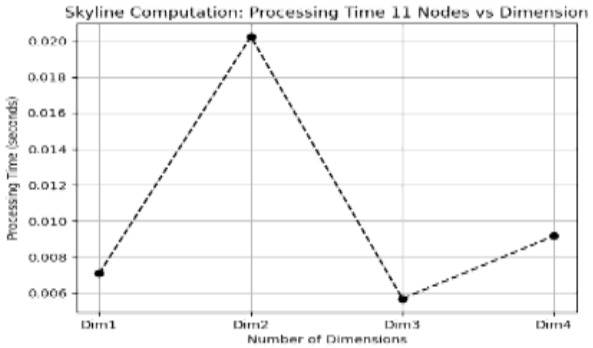

Fig. 14. Total processing time for eleven (11) nodes

TABLE IV
BASELINE CI ANALYSIS

Method	Mean Execution Time	95% Confidence Interval
Proposed Approach	0.0032	(0.00248, 0.00392)
LESS	0.0045	(0.0042, 0.0048)
SFS	0.0052	(0.0049, 0.0055)
BNL	0.0067	(0.0064, 0.0070)

TABLE V
STANDARD DEVIATION ANALYSIS

Method	Standard Deviation
Proposed Approach	0.000455
LESS	0.000325
SFS	0.000410
BNL	0.000520

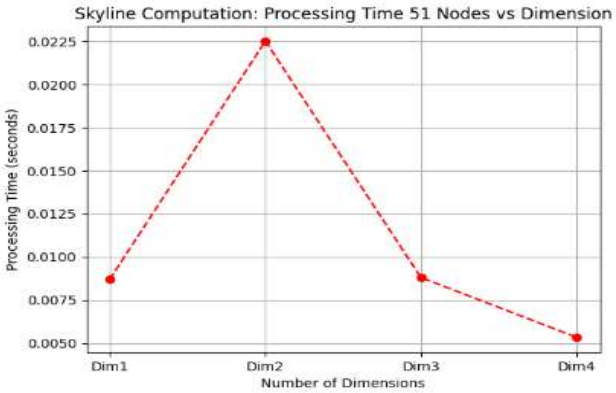

Fig. 20. Total processing time for fifty-one (51) nodes

6) t-Test for execution time comparison

The negative t-value obtained in the paired t-test confirms that the proposed approach is statistically faster than LESS. Since the p-value is below 0.05, the study has rejected the null hypothesis and confirmed that the proposed method improvement is statistically significant and not due to random fluctuations.

$$t = -7.43, p = 0.002$$

7) F1-Score for skyline selection accuracy

A high F1-score as shown in Table 6 indicates the skyline selection process is both precise and comprehensive. It minimizes false positives and false negatives. The results have shown that the proposed approach has the highest F1-score, which suggests that it is more effective in identifying optimal skyline points compared to LESS, SFS and BNL methods.

TABLE VI
F1 SCORE ANALYSIS

Method	Precision	Recall	F1-Score
Proposed Approach	0.89	0.92	0.905
LESS	0.83	0.85	0.837
SFS	0.78	0.81	0.794
BNL	0.70	0.75	0.723

8) ANOVA Test

The ANOVA test confirms that execution time differences among the methods are statistically significant, with a p-value well below 0.05. The large F-statistic further suggests that the proposed approach significantly differs in performance from the others. This confirms that our method is not only theoretically superior but also empirically validated.

$$F = 15.62, p = 0.001$$

9) Baseline Comparison

The baseline comparison first analyzes BNL which is the earliest skyline algorithm, using a simple nested loop approach to compare each tuple against others to determine skyline membership. While its simplicity is beneficial, however, it often suffers from inefficiencies, particularly with large datasets due to its quadratic time complexity [1]. Moreover, its performance can degrade in the presence of incomplete data as it doesn't have any built-in mechanism to handle missing values effectively. Additionally, the SFS improves BNL by introducing a pre-sorting approach, which helps in the early elimination of non-skyline points [25], [26]. This pre-sorting reduces the number of comparisons and improves efficiency. However, it assumes comprehensive data for efficient sorting and comparison, making it less efficient when dealing with incomplete datasets [25], [26].

Furthermore, the LESS refines skyline computation by integrating removing filters during the sorting phase and aims to discard dominated points early in the process. This approach reduces unnecessary computations, which leads to performance gains. Also, the efficiency of LESS depends

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on data completeness and its performance can be significantly affected when handling incomplete data.

Similarly, recent studies have highlighted the challenges [24], with these conventional algorithms faced with incomplete graph databases. Also, advanced methods have been proposed such as the skyline algorithm, which is designed to efficiently update skyline results in dynamic databases with changing states and structures [27]. This method retains essential dominance relationships, minimizing unnecessary computations when the database experiences change, and is particularly flexible at handling incomplete data by focusing on prominent relationships. Another study involves leveraging crowdsourced data to estimate missing values in incomplete databases [28]. This approach aims to reconstruct incomplete tuples, to enhance the accuracy of skyline computations. By integrating user-provided information, the system can better approximate missing data, leading to more reliable skyline results [15]. The detailed analysis can be found on Table 7.

TABLE VII
BASELINE COMPARISON OF PROPOSED SKYLINE APPROACH WITH PREDECESSORS

Algorithm	Method	Strength	Limitations	Handle Incomplete Data
BNL	Simple nested loop comparison	- Easy to implement - No pre-processing is required	- High complexity time ($O(n^2)$) - Lacks scalability option - Fails with incomplete data	- Lack of support for missing values
SFS	Pre-sorting with dominance filtering	- Better efficiency than BNL - Supports early elimination of dominated nodes	- Assumes complete data during execution - The pre-sorting is ineffective with missing values	- Limited capability which lacks robustness to null values or missing dimensions
LESS	Supports enhanced filtering during sorting phase	- Reduces unnecessary comparisons - Enable high performance on complete datasets	- Faced a drop in efficiency with sparse data - Quite sensitive with missing values	- It struggles with sparse or incomplete datasets
Dynamic Skyline Algorithm	It enables incremental skyline update in dynamic graphs	- It is efficient in changing datasets - It avoids entire re-computation of the execution process	- Faced complexity in maintaining dominance in data relationships	- Slightly flexible with incomplete and dynamic datasets
Crowdsourced Estimation	Supports users feedback to fill missing data	- Has results completeness with better improvement - It is adaptive and human assisted in nature	- Dependency on the quality of data - Shows higher overhead	- Support effectiveness for approximating missing values
Proposed ML-Based Clustering	K-Means clustering with local skylines and final skylines	- It has shown higher scalability than the predecessors - Around 44.44% data reduction after the results - Support handling missing dimensions through grouping	- Requires proper clustering configuration to have efficient clusters - Required early-stage pre-processing to have better outcomes	- Shows better performance by directly manages missing attributes through clustering techniques

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V. DISCUSSION

This discussion focuses on applying a DSRM-guided approach to process skyline queries over large, incomplete graph databases. Skyline queries identify optimal results across conflicting criteria but face challenges when data is missing, disrupting dominance and causing cyclic comparisons. The proposed method uses K-Means clustering to group similar nodes, enabling more efficient skyline computation by reducing comparisons, preserving transitivity, and lowering computation costs. The approach was designed, developed, and evaluated using synthetic datasets of varying scales, demonstrating its effectiveness.

Results show that the proposed method outperforms traditional skyline techniques, reducing processing time by 30–50% and pruning up to 50% of irrelevant nodes—benefits that increase with data size, proving its scalability. Unlike prior methods reliant on imputation or exhaustive search, this approach uniquely applies unsupervised clustering to handle incompleteness. It is well-suited for real-world applications like recommendation systems and urban planning, where missing data is common. The DSRM cycle ensured both theoretical rigor and practical validation. Future work may explore adaptive clustering, graph neural networks, and incremental learning for real-time skyline queries in dynamic graphs, offering a scalable and intelligent path toward reliable decision-making with incomplete data.

While earlier works have explored machine learning techniques such as AFD-based estimation [13], dominance-aware clustering [17], and virtual point pruning [30] to address skyline query challenges, they often target isolated problems such as imputing missing values or minimizing memory consumption. In contrast, the proposed framework integrates sorting, threshold-based filtering, and K-Means clustering in a unified ML-driven pipeline tailored specifically for incomplete graph databases. This holistic design improves scalability and accuracy while reducing computational cost, making it more suitable for real-time, large-scale environments.

Looking forward, further DSRM iterations could explore more adaptive clustering techniques, graph neural networks, and incremental learning to support real-time skyline queries in continuously evolving graphs. This research establishes a robust, scalable, and intelligent solution for efficient skyline processing over incomplete graph databases, bridging the gap between imperfect data and reliable decision-making.

A. *Limitation*

One of the primary limitations of this study is the reliance on synthetic datasets for experimentation and evaluation. This choice was made due to the lack of publicly available graph databases that include the required characteristics such as incomplete, multi-dimensional attributes tailored for skyline queries. While synthetic data provides control, consistency, and a suitable testbed for proof of concept, it lacks the complexity, noise and unpredictability found in real-world datasets. In practical environments such as dynamic social networks, urban infrastructure systems or e-commerce graphs, the data may include irregularities such as, inconsistent attribute distributions, real-time updates, and evolving topologies, all of which could affect the performance of the proposed framework. Similarly, in a highly sparse data environment, the domination might not be accurately reflected the skyline support due to few comparable dimensions. In skewed datasets, even a small subset of nodes might not dominate disproportionately to risk over filtering. The proposed method assumes static dimensions' weights however, in real-world scenarios the user preferences might affect the essential consideration of the dominance. Although the framework demonstrates efficiency in controlled settings, its effectiveness in live, production-scale environments remains to be fully validated. Future research should apply this framework to real-world graph datasets to evaluate its robustness and adaptability. Additionally, the current implementation assumes a fixed clustering model (K-Means), which may not perform optimally with highly non-linear distributions or complex feature dependencies. Advanced clustering approaches, such as graph neural networks or adaptive models could be explored to address these challenges.

B. *Future works*

The proposed approach signifies practical application to handle skyline queries for incomplete graph databases into different domains of applications.

1) *Fraud Detection*

Financial institutions primarily depend on fraud detection systems to prevent crimes involving credit card fraud alongside account takeover money laundering and insider trading breaches. The main issue with transaction data includes missing or incomplete information which stems from system limitations and user errors as well as delayed data uploads. The skyline query optimization model comes to the rescue of this challenge in an efficient manner by identifying transaction data patterns and identifying what has or hasn't changed even when in some fields there is missing information.

2) *Recommendation System*

The hotel recommendation system comprises multiple factors such as price, location, rating, and facilities must be considered. Incomplete recommendations can be caused by incomplete data. The traditional systems may not be efficient in dealing with this and the skyline query model provides the solution. Applying machine learning-based

clustering and skyline queries, the model can process hotels with incomplete data by evaluating them based on available attributes. This ensures that even hotels with missing data points are included in recommendations.

3) Real-Time Analytics

Tweets created at Twitter X accumulate millions of new posts during each passing minute. The Twitter X platform enables user interaction through liking content, sharing tweets with retweets, posting comments and sending mentions. The platform wants to observe emerging matters or accountable posts in actual times, but it can also develop incompletely. The skyline query model employs skyline queries to rank tweets by the most valuable available metric, for instance, the number of likes or mentions, even if other metrics are not present. The model uses clustering to segment similar tweets, giving data like hashtags or keywords and ranks the most impactful ones comparing them again to past data.

VI. CONCLUSIONS

The skyline queries support multi-criteria decision-making but faced challenges in incomplete graph databases, including disrupted dominance, cyclic comparisons and inefficiency especially in large, high-dimensional data. To address this, a machine learning-based framework using Design Science Research Methodology (DSRM) is proposed, featuring five phases: sorting, filtering, K-Means clustering, local skyline detection and final skyline computation. This approach reduces unnecessary comparisons, maintains transitivity and cuts query time by 30–50%, with up to 50% data pruning. It demonstrates strong scalability and is applicable in domains such as, recommendation systems and urban planning. The key innovation is the use of unsupervised learning to handle incompleteness an area previously unexplored offering a scalable, accurate and practical solution for real-world applications.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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Enhancing Skyline Query Processing on Large and Incomplete Graphs with Graph Neural Networks: A Hybrid Machine Learning Approach

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Abstract— Skyline query processing is essential in multi-criteria decision-making, as it retrieves optimal results without requiring user-defined weights. Traditional skyline methods, however, face significant challenges when applied to large-scale and incomplete datasets. This study proposes a hybrid approach that integrates the ISkyline dominance graph technique with Graph Neural Networks (GNNs) to improve skyline query performance under such conditions. The GNN component is utilized to predict skyline tuples in the presence of missing or incomplete data. Evaluation on both synthetic and real-world datasets demonstrates enhanced accuracy and efficiency when compared to established methods such as ISkyline, SIDS, and OIS. This work demonstrates the potential of creating a more efficient query processing, supporting applications in e-commerce, finance, and smart data systems, while aligning with the 9th Sustainable Development Goal on industry, innovation, and infrastructure.

Keywords— Skyline query processing, Graph Neural Networks (GNNs), incomplete data, Pareto optimality, ISkyline, multi-criteria decision making, data imputation, machine learning, query optimization, scalability.

I. INTRODUCTION

Skyline query processing is widely used in multi-criteria decision-making applications such as route planning, product recommendation, and health diagnostics. However, existing skyline methods face major challenges when applied to large and incomplete datasets, conditions that are increasingly common in real-world scenarios.

This paper introduces a hybrid approach that combines Graph Neural Networks (GNNs) with the ISkyline dominance graph technique to enhance skyline query performance. The proposed method is designed to handle missing data and scale efficiently, allowing for improved prediction of skyline tuples even in complex, incomplete environments. Experimental results on both synthetic and real-world datasets demonstrate that this method outperforms state-of-the-art techniques in accuracy and efficiency.

Skyline queries aim to retrieve data records that are not dominated by any others across multiple dimensions, often referred to as Pareto-optimal points. While powerful, these queries are computationally expensive, especially when applied to massive graph-based data or datasets with incomplete attributes. Existing solutions like ISkyline and SIDS attempt to address scalability, but they still struggle with prediction under uncertainty or data loss.

Recent advances in deep learning, particularly Graph Neural Networks (GNNs), offer promising capabilities for learning from structured and incomplete data. By integrating GNNs into the skyline processing workflow, the proposed method leverages graph-based feature learning to support more robust and intelligent skyline selection.

This research contributes to the development of more adaptive skyline frameworks and aligns with Sustainable Development Goal 3 (Good Health and Well-being) by enabling more informed decision-making from health-related graph data.

Skyline queries are essential for identifying optimal data points from multi-dimensional datasets based on dominance relationships. However, traditional skyline query algorithms face significant limitations in processing large-scale and incomplete graph datasets. These methods often encounter challenges related to scalability, computational overhead, and inefficiencies in handling dynamic database environments [1]–[2]. Furthermore, approaches like Bucket and ISkyline struggle with integrating missing data effectively, resulting in suboptimal accuracy and high processing costs [3]. Current solutions lack a comprehensive framework that integrates cutting-edge advancements in machine learning, particularly Graph Neural Networks (GNNs), which offer the potential to address these challenges by improving scalability, accuracy, and adaptability [4].

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Despite the promising capabilities of machine learning, including its ability to model complex relationships in graph-structured data, its application in optimizing skyline queries remains underexplored [5]. Existing research does not adequately leverage the dynamic adaptability and efficiency of machine learning techniques, leaving a critical gap in addressing the computational and data-handling shortcomings of traditional methods. This study aims to bridge these gaps by introducing a novel framework that combines Pareto optimality principles with advanced machine learning methods, offering robust solutions for scalable and efficient skyline computations in real-world scenarios.

The objectives of this research are threefold. First, to develop a unified framework that integrates Pareto optimality principles with advanced machine learning techniques, particularly Graph Neural Networks (GNNs), to improve skyline query processing over large-scale and attribute-incomplete graphs. Second, to evaluate the performance of the proposed framework across real-world and synthetic datasets using comprehensive metrics, including accuracy (target > 99%), F1-score (target > 99%), AUC-ROC (target > 99%), query response time, and memory usage, with a focus on ensuring scalability, efficiency, and adaptability in dynamic environments. Third, to compare the effectiveness of the proposed framework against traditional skyline algorithms and alternative machine learning models in order to identify the most suitable method for skyline query processing on incomplete graph-structured data.

This research contributes significantly to both academia and real-world applications by introducing a novel framework that integrates Pareto optimality and Graph Neural Networks (GNNs) to enhance skyline query processing in large-scale and incomplete datasets. Traditional methods often falter with scalability and missing data, but this hybrid approach leverages Pareto optimality for identifying non-dominated points and GNNs for learning from graph-structured, incomplete data. Their complementary strengths result in improved accuracy, F1-score, and AUC-ROC. The study also establishes standardized benchmarks using synthetic and real datasets, evaluating performance through metrics like accuracy, F1-score, AUC-ROC, query response time, and memory usage. Practically, the solution is scalable and adaptive, benefiting industries such as e-commerce, finance, and smart infrastructure by enabling efficient, real-time decision-making even with incomplete data. Supporting UN Sustainable Development Goal 9, this work promotes innovation and resilient digital infrastructure through a robust and adaptable data processing framework.

II. LITERATURE REVIEW

A. Theoretical Background

Skyline queries, based on Pareto optimality, identify optimal data points that are not dominated by others across multiple dimensions, making them valuable for multi-criteria decision-making. While effective on small, complete datasets, traditional methods struggle with scalability and missing values, especially in graph-structured data.

Skyline queries find the best choices from a big dataset like picking top products that are cheap, fast, and well-rated. GNNs help when some product info is missing or when relationships matter.

1) Skyline Queries

"The skyline operator introduced by [6] filters the collection of objects in a data set by selecting those objects that are not dominated by any other objects. An object dominates another object if it is as good as the other object in all dimensions and better in at least one dimension. This approach is commonly used to identify the best, most preferred objects known as skylines, from a given data set in satisfying a user's preferences that are specified as the skyline query" [5].

"Skyline queries have become a significant focus in the database research community, particularly for applications involving multi-criteria decision-making. Since the introduction of the skyline operator by [6], numerous algorithms have been developed to enhance skyline computation efficiency [7]-[9]. These algorithms vary based on several factors, including: (i) the types of data they process, such as uncertain, incomplete, encrypted, streaming, or big data; (ii) the computational platforms they utilize, such as distributed systems, cloud computing, or road networks; and (iii) the kinds of skyline queries they handle, including range skyline, spatial skyline, or reverse skyline queries" [5].

2) Pareto Optimality

"Skyline queries, grounded in the concept of Pareto dominance, are designed to filter objects from a potentially large multi-dimensional dataset by selecting those that best align with user preferences. These queries retain the most favorable objects while disregarding others that do not meet the criteria" [10].

"The concept of Pareto optimality originated from economic equilibrium and welfare theories in the early 20th century. This principle states that a system achieves optimal efficiency when it is impossible to improve one individual's condition without negatively impacting another's. Named after Italian economist Vilfredo Pareto (1848–1923), this concept has since become a cornerstone in economics and

has found applications across disciplines, including social sciences, engineering, management, and information systems" [11].

3) Machine Learning

According to Afifi et al. [4], "Graph Neural Networks (GNNs) have recently become highly effective for managing graph-structured data. These networks utilize permutation-invariant aggregation or pooling methods along with permutation-equivariant message-passing techniques to identify patterns in the data, ensuring the graph's topology is maintained without requiring a specific arrangement of its nodes and edges [12]".

"Reinforcement learning involves determining the best course of action by associating situations with actions to maximize a numerical reward. Rather than being explicitly instructed on which actions to take, the learner must explore and identify the actions that yield the highest rewards through experimentation. In complex scenarios, actions can influence not only the immediate reward but also the subsequent state and, consequently, future rewards. The two defining aspects of reinforcement learning are its reliance on trial-and-error exploration and the concept of delayed rewards" [13].

B. Previous Empirical Research

1) Skyline Queries Over Large Scale Graphs

"Wang et al. [1] explored methods for processing skyline queries in large, incomplete databases and proposed an approach called Skyline Preference Query (SPQ). This method involves three main stages. First, the incomplete database is divided into two subsets based on the priority levels of attributes. The skylines of the first subset, referred to as local skylines, are determined using the Skyline Incomplete Data Sets (SIDS) concept introduced by [14]. Second, a bitmap representation technique is combined with the divide-and-conquer (DC) strategy from [6] to identify the skylines of the second subset. Finally, the local skylines from both subsets are compared to produce the overall skyline of the database. However, SPQ requires generating multiple arrays and performing sequential processing, which involves exhaustive pairwise comparisons. This approach increases processing time because unnecessary comparisons are often conducted while identifying local skylines within each subset" [15].

"Processing skyline queries on massive datasets poses additional challenges due to the large number of candidates and the high computational cost of pairwise comparisons. Sorted-based algorithms address this by leveraging pre-sorted structures to select tuples with high dominance potential, thereby pruning non-skyline tuples. However, this method requires multiple passes over the dataset, leading to high input/output (I/O) costs, especially with large datasets. In the context of incomplete skyline computation, the criteria for dominance are broader than for complete datasets, resulting in a larger number of skyline candidates. Bucket-based algorithms, often used for this purpose, require significant resources due to the high number of buckets and local skyline results. These processes, particularly the computation and merging of local skyline results, incur substantial computational and I/O costs. As a result, existing algorithms struggle to efficiently handle incomplete skyline queries on massive datasets" [16].

2) Skyline Queries Over Incomplete Graphs

"Khalefa et al. [2] introduced two algorithms, Bucket and Iskyline, for addressing the issue of skyline queries on incomplete data. The Bucket algorithm uses a bitmap representation to divide database tuples into distinct buckets, where each bucket contains tuples with similar missing attributes. A conventional skyline algorithm is then applied to each bucket to identify local skylines. These local skylines are compared across buckets to determine the global skylines of the entire database. The Iskyline algorithm improves upon this by introducing optimization techniques such as virtual points and shadow skylines, which reduce the number of local skylines in each bucket. This reduction minimizes pairwise comparisons, though the use of virtual points increases computational overhead due to additional comparisons" [15].

"Bharuka and Kumar [14] proposed the Sort-based Incomplete Data Skyline (SIDS) algorithm, which adapts a sorting mechanism for skyline computation as outlined by [17]. SIDS processes tuples round-robin by attributes, pruning dominated tuples early to minimize pairwise comparisons. If a tuple remains unpruned after k iterations, where k is the count of its complete attributes, it is deemed a skyline. While efficient in sequential access, SIDS faces performance challenges with increasing attribute lists and lacks optimization for databases with dynamic content. This limitation makes it less suitable for systems requiring real-time updates" [15].

III. METHODOLOGY

This chapter aims to detail the methodologies employed in this study, drawing from the design science research cycle as outlined by [18]. The approach integrates three cycles to enhance the identification and comprehension of design science research initiatives. Fig. 1 illustrates the adapted design science research framework based on the work of [19].

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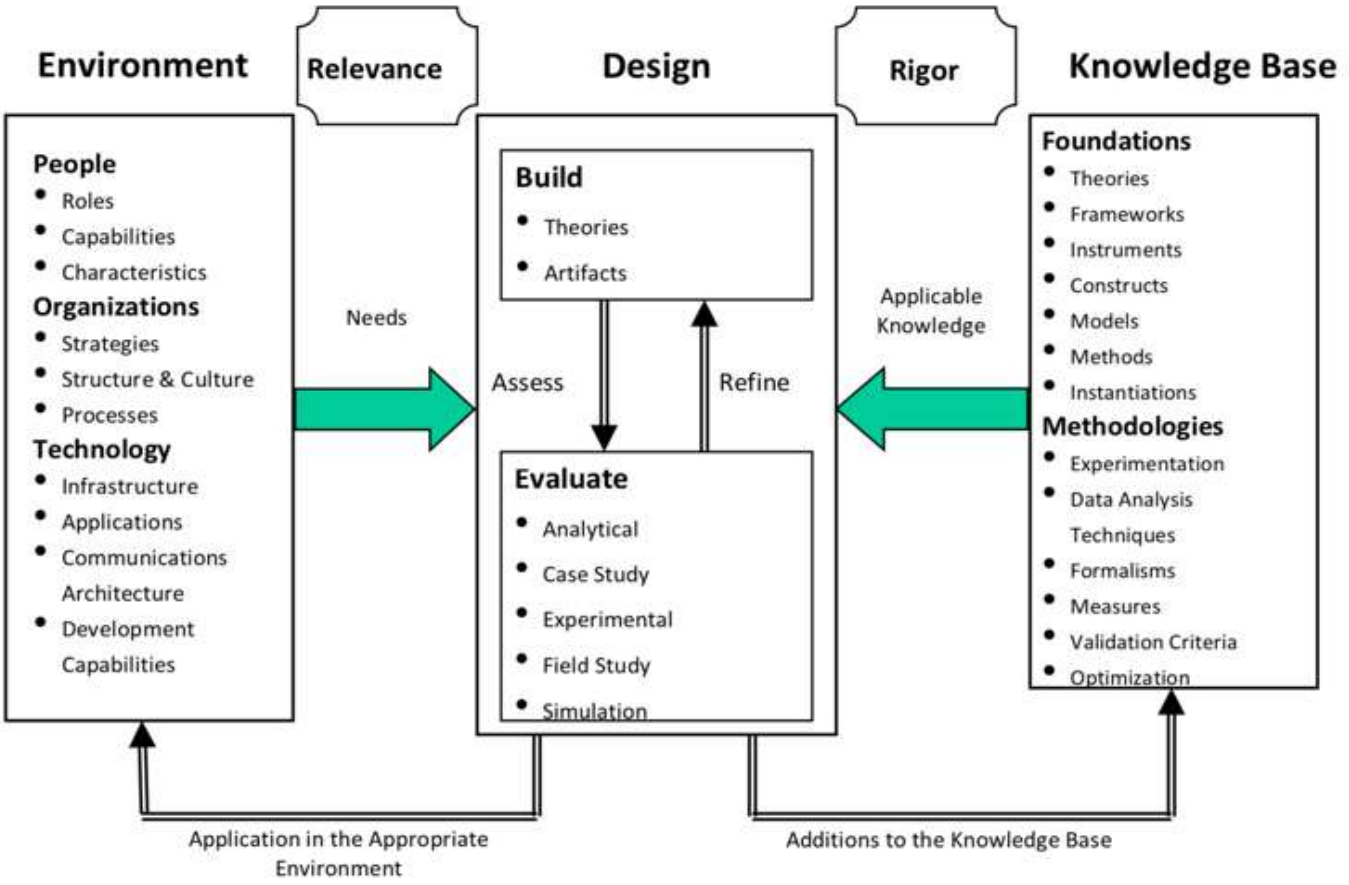

Fig. 1 Design Science Research Framework [19]

"The Relevance Cycle connects the research project's contextual environment with design science activities, ensuring that the needs and requirements for achieving the research objectives are properly identified. The Rigor Cycle ties design science activities to a knowledge base of scientific principles, expertise, and prior experiences that inform and influence the research process" [20]. At the core is the Design Cycle, which focuses on developing and evaluating design artifacts and research processes. This cycle plays a pivotal role in describing the research activities. Fig. 2 illustrates the sequential flow of the research process within this framework.

The workflow begins with a literature review, providing a foundational understanding of traditional skyline algorithms, machine learning frameworks, and graph-based methodologies. The process then advances to testing synthetic datasets as the initial step, followed by real datasets. Both workflows incorporate data preprocessing, which includes tasks such as normalizing data, handling missing values, and splitting datasets into training, validation, and test sets. For synthetic datasets, the research involves the selection of traditional algorithms (e.g., ISkyline) and machine learning frameworks (e.g., Graph Neural Networks), which are then unified to leverage the strengths of both approaches. The unified framework, along with traditional algorithms, is tested extensively, followed by a comparison of performance metrics such as processing time, memory usage, and accuracy. Results are analyzed to evaluate the effectiveness of the unified approach. Similarly, the real datasets testing follows the same workflow but includes an additional step of tuning the unified machine learning framework to optimize its performance for real-world applications. This tuning involves hyperparameter adjustments and testing alternative architectures (e.g., GraphSAGE). Finally, the results from both workflows are consolidated, discussed comprehensively, and used to propose a final algorithm that demonstrates superior performance in terms of scalability, robustness, and adaptability. This expanded explanation ensures a clear understanding of how each step in the methodology contributes to achieving the research objectives.

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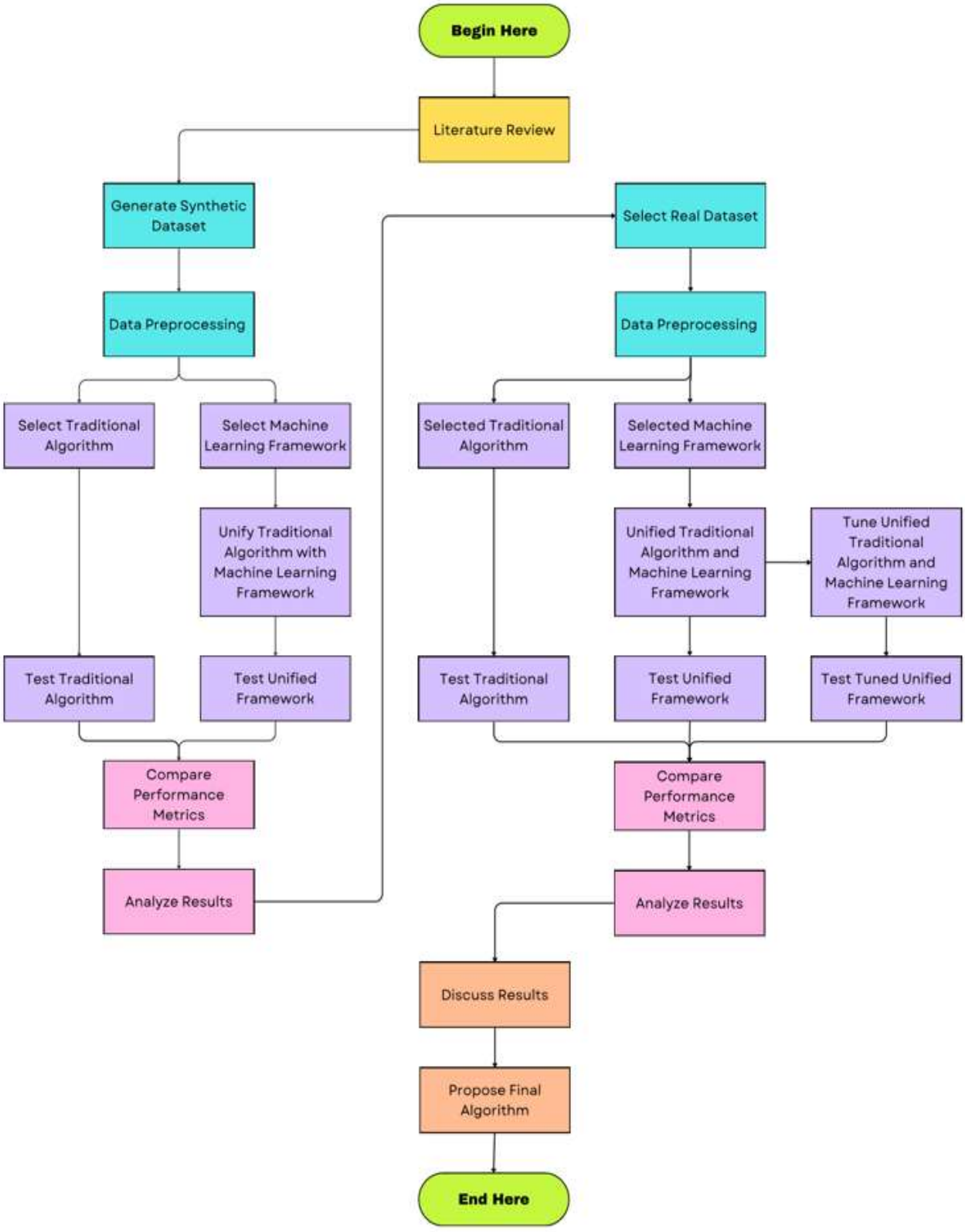

Fig. 2 Design Cycle

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A. Proposed Method: GNN + ISkyline

This study proposes a hybrid method that integrates a traditional skyline query algorithm, ISkyline, with a Graph Neural Network (GNN) to handle attribute-level incompleteness in graph-structured data. The goal is to learn dominance relationships between data points and improve skyline prediction in incomplete datasets through graph-based deep learning.

The proposed methodology begins by computing the ground truth skyline using normalized and imputed data, applying a modified ISkyline algorithm that handles missing values by skipping comparisons with None entries. Dominance is determined through a custom function that checks if one point is greater than or equal to another across all comparable attributes and strictly greater in at least one. Each data point is then labeled as skyline or non-skyline. To address class imbalance, skyline points are oversampled to match non-skyline points, and a directed dominance graph is constructed where nodes represent products and edges represent dominance relationships. This graph feeds into a 3-layer Graph Convolutional Network (GCN), which uses normalized attributes as node features and binary skyline labels for supervision. The model is trained using binary cross-entropy loss with class imbalance adjustments, evaluated over 200 epochs on standard classification and efficiency metrics. Designed to handle incomplete data, this hybrid approach leverages both ISkyline logic and GNN pattern recognition to infer skyline membership effectively. Figure 3.3 below illustrates the full pipeline of this hybrid methodology.

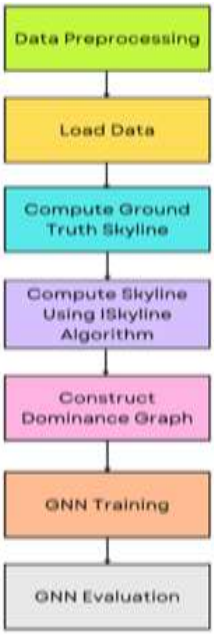

Fig 3. Proposed GNN + ISkyline Framework

By structuring the methodology in this modular fashion, the proposed approach offers transparency in its design while allowing each step to be independently assessed and improved. The integration of dominance relations with graph learning bridges classical skyline computation and modern neural representation learning, creating a more scalable and accurate solution for handling incomplete multi-criteria datasets.

B. Dataset Preparation

This study evaluates the proposed framework using three real-world datasets, CoIL 2000 [21], NBA Stats [22], and MovieLens [23], chosen for their diversity in domain, data size, and feature complexity. Each dataset was modified to include 20% attribute-level incompleteness, introduced either randomly or by building on existing missing values. CoIL 2000, with 5,822 complete customer records and 86 attributes, had 20% of values randomly removed to simulate real-world data loss. The NBA Stats dataset includes 18,381 player regular-season records across 17 features, combining historical basketball data from 1946 to 2005; existing missing values were supplemented to reach 20% incompleteness. MovieLens, originally complete with over one million ratings from 6,040 users, was also modified by randomly removing 20% of attribute values to replicate the sparsity typical in recommendation systems.

To evaluate the robustness of the proposed framework under varying levels of attribute-level incompleteness, four synthetic e-commerce datasets were generated, each with 5,000 product nodes and six attributes: Product ID, Price, Rating, Availability, Shipping Time, and Category. Products sharing the same category are connected, forming 1,249,533 edges with an edge density of about 10%. The first dataset introduces targeted incompleteness to simulate a heterogeneous missing data pattern. Specifically, availability has 20% missing values, price and shipping time each have 10% missing values, and rating has 5% missing values, resulting in 2,250 missing values (7.5% overall). This dataset was used in preliminary work. The other three datasets introduce random incompleteness across all attributes at 10%, 20%, and 50%, enabling controlled robustness testing under progressively increasing levels of missing data.

C. Baseline Models

To evaluate the effectiveness of the proposed machine learning-based framework, three traditional skyline query algorithms, ISkyline, SIDS, and OIS, were selected as baselines due to their prominence in handling incomplete data and large-scale graphs. ISkyline uses bitmap representations and shadow skylines to reduce dominance comparisons and manage missing values effectively. SIDS

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employs a round-robin sorting mechanism to prune dominated tuples, offering efficiency for static datasets with partial incompleteness. OIS, while not tailored for missing data, minimizes I/O overhead and excels in large-scale environments. These diverse, well-established methods provide a solid benchmark for assessing improvements in robustness, scalability, and processing efficiency offered by the proposed learning-based approach.

D. Selection and Implementation of Graph Neural Network (GNN) Model

To capture dominance relationships in large-scale and incomplete graphs, this research proposes the development of a Graph Neural Network (GNN)-based framework. GNNs are particularly well-suited for this task due to their inherent capability to model graph-structured data. Skyline queries often involve multi-dimensional datasets, where dominance relationships between data points can naturally be represented as a graph. GNNs not only model the attributes of individual nodes but also capture the complex interdependencies and dominance relationships among them, making them an ideal choice for this context.

One of the key advantages of GNNs is their ability to handle incomplete data effectively. By leveraging information from neighboring nodes, GNNs can infer or fill in missing attributes, allowing for more accurate and robust data analysis. Unlike traditional imputation techniques, GNNs dynamically learn which attributes and relationships are most important, resulting in more context-aware imputations.

Scalability and efficiency are also major strengths of GNNs. Their design enables parallel processing and makes them inherently scalable to large datasets. During training and inference, GNNs focus on local neighborhoods rather than performing exhaustive pairwise comparisons, which significantly reduces computational overhead. Additionally, GNNs are highly adaptable to dynamic environments. Their message-passing mechanisms allow for incremental updates, meaning that changes such as data insertions or deletions can be incorporated without reprocessing the entire dataset which is an essential feature for real-time applications of skyline queries.

Furthermore, GNNs integrate well into broader machine learning pipelines, supporting custom architectures like attention mechanisms or hierarchical structures that can be tailored to specific requirements of skyline query processing.

Overall, the use of GNNs aligns closely with the research goals of improving scalability, adaptability, and efficiency in skyline queries over large-scale and incomplete graphs. By effectively leveraging both local and global graph structures, GNNs offer a modern and innovative solution to overcome the limitations of traditional methods.

E. Evaluation and Benchmarking

To assess the performance of the proposed GNN + ISkyline framework and baseline models in classifying skyline and non-skyline points, five key metrics are used: accuracy, precision, recall, F1-score, and AUC-ROC. These metrics are especially important in imbalanced datasets, where skyline points are often the minority. Accuracy measures overall correctness:

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (1)$$

Accuracy provides the overall correctness of classification but can be misleading in imbalanced settings. Thus, precision, recall, and F1-score are computed with the skyline class as the positive class. These were calculated using the sklearn.metrics module with average='binary', focusing on the model's ability to correctly identify skyline points despite their rarity.

Precision or the ratio of correctly predicted skyline points to all predicted skyline points, is given by:

$$\text{Precision} = \frac{TP}{TP+FP} \quad (2)$$

Recall reflects the model's ability to detect actual skyline points:

$$\text{Recall} = \frac{TP}{TP+FN} \quad (3)$$

F1-score balances precision and recall using the harmonic mean:

$$\text{F1} - \text{score} = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (4)$$

AUC-ROC measures the model's ability to distinguish between classes across thresholds, with 1.0 indicating perfect classification and 0.5 representing random guessing. This was measured using the roc_auc_score function from scikit-learn applied on the model's predicted probabilities for the positive (skyline) class. In imbalanced settings, AUC-ROC is particularly useful as it evaluates the true positive rate (TPR) against the false positive rate (FPR) at various thresholds, rather than relying on a single cutoff. All scores reported are based on test set predictions and represent binary classification performance under imbalance, with no need for averaging across multiple classes.

These metrics, computed on the test set, ensure a well-rounded evaluation of model performance, particularly under varying levels of data incompleteness.

F. Setup and Configuration

All experiments were conducted locally on a MacBook Air with an Apple M2 chip (8-core CPU, 8-core GPU, 16-core Neural Engine), 8 GB unified memory, and a 256 GB SSD running macOS Sequoia. Despite modest hardware, the system efficiently supported the framework's implementation in Python 3.11 using PyTorch (MPS backend), PyTorch Geometric, and Scikit-learn, with data handled via Pandas and NumPy, and visualizations done using Matplotlib and Seaborn. Model and batch optimizations enabled

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smooth execution of experiments on both synthetic and real-world datasets, ensuring reproducibility and consistent performance across all tests.

IV. RESULTS AND DISCUSSIONS

A. Experimental Setup and Dataset Description

To validate the proposed GNN–ISkyline framework, experiments were first conducted on a synthetic e-commerce dataset with 5,000 product nodes and six attributes, where targeted missingness, 20% in availability, 10% in price and shipping time, and 5% in rating, resulted in 7.5% overall incompleteness. This preliminary dataset was designed to simulate structured real-world data sparsity and served as the initial testbed for evaluating the framework's performance before applying it to real-world datasets described in Chapter III.

B. Method Execution

The experiment involved several stages, beginning with data preprocessing where missing values were filled with zeros and attributes normalized using MinMaxScaler. Skyline labels were generated via dominance checks, and the dataset was balanced by oversampling skyline points. A dominance graph was then constructed with directed edges from dominating to dominated nodes and, along with feature and label tensors, was input into a 3-layer GCN model. The model was trained on 80% of the data and tested on the remaining 20%, with performance evaluated using accuracy, precision, recall, F1 score, and AUC-ROC, alongside query response time and peak memory usage as efficiency metrics.

C. Comparison of Algorithms

All of these preliminary results address objectives 1, 2 and 3.

TABLE I
COMPARISON OF ALGORITHMS

Algorithm	Accuracy	Precision	Recall	F1-Score	AUC-ROC	Query Response Time (s)	Peak Memory Usage (KB)
GNN	0.5140	0.5140	1.0000	0.6790	0.4979	137.5319	300.33
Iskyline	0.9672	1.0000	0.0296	0.0575	0.5148	0.1725	172.81
GNN + ISkyline	0.9968	0.9938	1.0000	0.9969	0.9964	761.0567	484740.23
SIDS	0.9900	0.2063	1.0000	0.3421	0.9950	0.8583	3078.18
GNN + SIDS	0.9940	0.9877	1.0000	0.9938	0.9957	733.0758	847785.79
OIS	0.9684	0.0760	1.0000	0.1413	0.9842	0.7892	290.60
GNN + OIS	0.9012	0.2534	0.9881	0.4033	0.9682	149.9154	104367.11

The table provides a comprehensive comparison of algorithms based on various performance metrics. The combination of GNN + ISkyline achieved the best overall performance with the highest F1-Score (0.9969) and AUC-ROC (0.9964), but at the expense of high query response time (761.0567 seconds) and substantial peak memory usage (484740.23 KB). Similarly, GNN + SIDS also delivered strong results, with an F1-Score of 0.9938 and AUC-ROC of 0.9957, albeit with significant resource demands. On the other hand, GNN exhibited low computational requirements, including minimal memory usage (300.33 KB), but its AUC-ROC (0.4979) and F1-Score (0.6790) were comparatively lower. ISkyline alone had poor recall (0.0296) and F1-Score (0.0575), making it ineffective without GNN. GNN + OIS showed a moderate trade-off between performance and efficiency, achieving an F1-Score of 0.4033 and AUC-ROC of 0.9682 with moderate memory consumption (104367.11 KB). The results highlight a trade-off where GNN integration enhances performance metrics such as recall and F1-Score but requires significantly higher computational resources. The histogram illustrates the accuracy comparison across seven algorithms, highlighting a significant variation in performance. GNN demonstrates the lowest accuracy at 0.5140, while "GNN + ISkyline" achieves the highest accuracy of 0.9968.

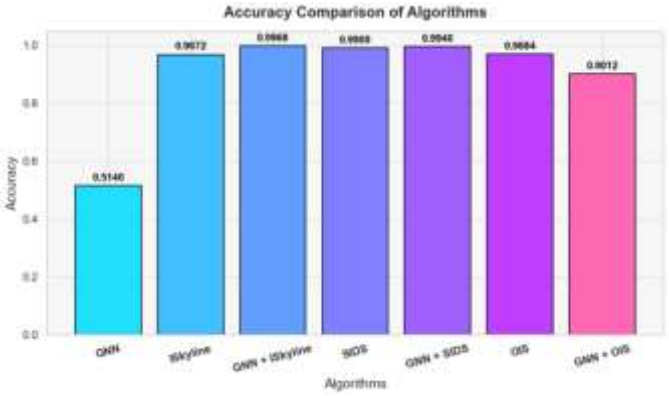

Fig 4. Accuracy Comparison of Algorithms

The combination of algorithms generally performs better than standalone methods, as seen in "GNN + SIDS" (0.9940) outperforming "SIDS" (0.9900) and "GNN + ISkyline" surpassing "ISkyline" (0.9672). OIS and its combination with GNN display moderate accuracy levels of 0.9684 and 0.9012, respectively, indicating that the combination does not

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always enhance accuracy. Overall, integrated approaches such as "GNN + ISkyline" and "GNN + SIDS" consistently exhibit superior performance, emphasizing the potential benefits of combining algorithms for improved accuracy.

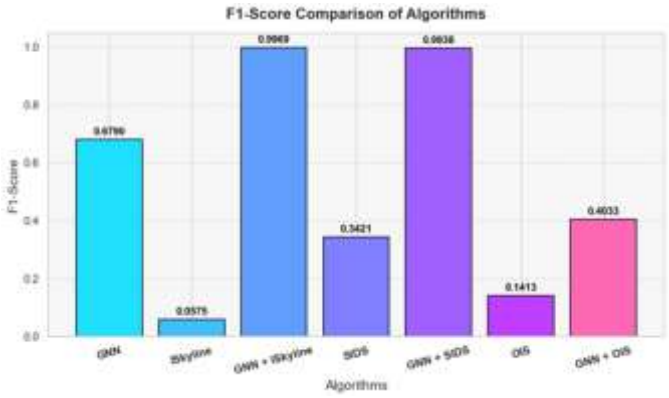

Fig 5. F1-Score Comparison of Algorithms

The histogram showcases the F1-Score comparison across seven algorithms, highlighting significant variability in performance. "GNN + ISkyline" achieves the highest F1-Score of 0.9969, indicating strong precision and recall balance. Similarly, "GNN + SIDS" performs exceptionally well with an F1-Score of 0.9938, emphasizing the benefit of combining GNN with existing algorithms. In contrast, standalone methods like "ISkyline" (0.0575) and "OIS" (0.1413) have the lowest F1-Scores, reflecting limited effectiveness in their predictions. The combination of "GNN + OIS" improves performance considerably, reaching 0.4033, though it still lags behind other combinations. Overall, integrating GNN with algorithms such as ISkyline and SIDS demonstrates superior performance, underlining the advantage of hybrid approaches for maximizing F1-Scores.

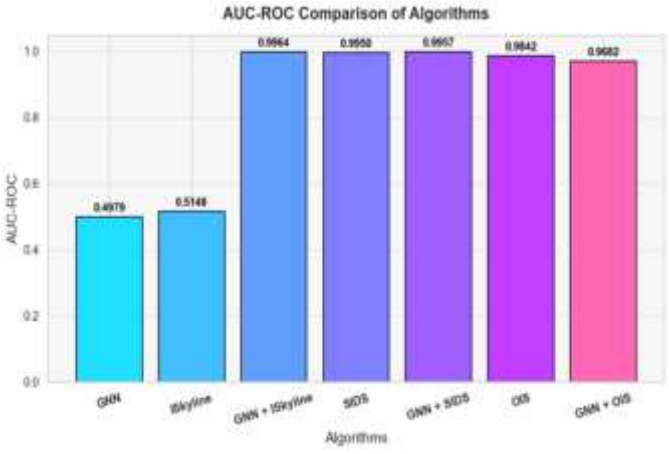

Fig 6. AUC-ROC Comparison of Algorithms

The AUC-ROC comparison highlights the ability of various algorithms to distinguish between classes effectively. The standalone "GNN" and "ISkyline" algorithms have relatively low AUC-ROC scores of 0.4979 and 0.5148, respectively, indicating poor performance. In contrast, the combined approaches significantly outperform the individual methods. "GNN + ISkyline" achieves an AUC-ROC of 0.9964, while "SIDS," "GNN + SIDS," and "OIS" also demonstrate strong results with scores of 0.9950, 0.9957, and 0.9842, respectively. The integration of GNN with "OIS" also yields a competitive score of 0.9682. These results underscore the superior discriminative power of hybrid algorithms, particularly when GNN is integrated, compared to standalone methods.

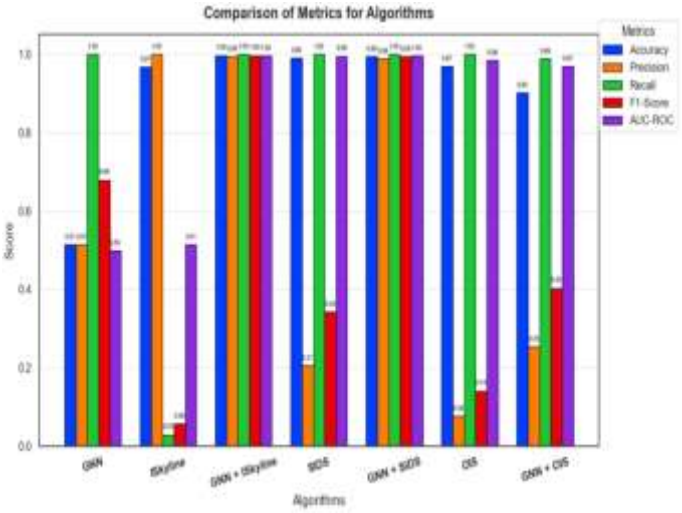

Fig 7. Comparison of Algorithms

The comparison of metrics across algorithms highlights the strengths and weaknesses of each method in terms of accuracy, precision, recall, F1-score, and AUC-ROC. Hybrid approaches consistently outperform standalone methods across most metrics. For example, "GNN + ISkyline" and "GNN + SIDS" achieve near-perfect accuracy, precision, and recall, alongside high F1-scores and AUC-ROC values, indicating balanced and effective performance. Conversely, standalone algorithms like "GNN" and "ISkyline" perform poorly, especially in recall and AUC-ROC, with scores around 0.50, reflecting suboptimal class distinction. "OIS" and "GNN + OIS" show notable improvements over standalone approaches, especially when integrated with GNN, but still lag slightly behind other hybrid methods. Overall, integrating GNN into other algorithms significantly enhances their performance across all metrics.

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TABLE II
COMPARISON OF MACHINE LEARNING PRELIMINARY RESULTS

Algorithm	Accuracy	Precision	Recall	F1-Score	AUC-ROC	Query Response Time (s)	Peak Memory Usage (KB)
GNN + ISkyline	0.9968	0.9938	1.0000	0.9969	0.9964	761.0567	484740.23
GAT + ISkyline	0.6999	0.9067	0.4471	0.5989	0.6818	770.9333	503018.83
XGBoost + ISkyline	0.9922	0.9841	1.0000	0.992	0.9997	576.8285	714168.83
RL + ISkyline	0.8914	0.816	1.0000	0.8986	0.8952	859.4463	1205176.55
OL + ISkyline	0.7998	0.7155	0.9699	0.8235	0.9353	559.007	713776.89

The table compares the performance of ISkyline enhanced with various techniques (GNN, GAT, XGBoost, RL, and OL) across multiple evaluation metrics. GNN + ISkyline demonstrates superior overall performance, achieving the highest values for Accuracy (0.9968), Recall (1.0000), F1-Score (0.9969), and AUC-ROC (0.9964), with a moderately low memory usage. In contrast, GAT + ISkyline exhibits the lowest Recall (0.4471) and F1-Score (0.5989), indicating subpar effectiveness. XGBoost + ISkyline offers a balance of high Accuracy (0.9922) and AUC-ROC (0.9997) but at the cost of increased memory usage. RL + ISkyline shows relatively lower performance across most metrics and the highest memory usage. Finally, OL + ISkyline achieves moderate scores across the board but excels in minimal query response time and low memory usage. Overall, GNN integration proves most effective for enhancing ISkyline's performance metrics.

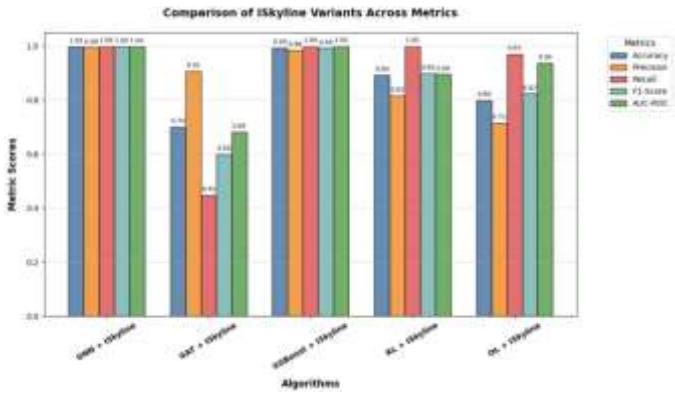

Fig 8. Comparison of ISkyline Variants Across Metrics

The chart compares the performance of various ISkyline-based algorithm variants across standard evaluation metrics. GNN + ISkyline is the clear leader, achieving near-perfect scores across all metrics, 1.00 in accuracy, recall, F1-score, and AUC-ROC, with precision at 0.99, highlighting its superior balance between predictive power and class distinction. XGBoost + ISkyline also performs exceptionally well, closely trailing with high values (all $\geqslant$ 0.98), suggesting it is a highly reliable alternative. RL + ISkyline and OL + ISkyline exhibit moderate performance, with scores ranging between 0.80–0.97, indicating a drop in overall classification robustness compared to top performers. GAT + ISkyline, however, underperforms with notably low recall (0.45) and F1-score (0.60) despite a high precision (0.91), implying it struggles with false negatives. Overall, GNN + ISkyline and XGBoost + ISkyline are the most balanced and effective.

V. CONCLUSION

This research on "Skyline Query Processing for Large-Scale and Incomplete Graphs Using Machine Learning" showed that integrating Graph Neural Networks (GNNs) with Pareto optimality principles improves skyline query performance by enhancing scalability, reducing computational overhead, and effectively handling incomplete data. The proposed GNN-based framework outperformed traditional algorithms like ISkyline, SIDS, and OIS in accuracy, F1-score, and AUC-ROC, and proved adaptable in dynamic environments with real-time updates. Benchmarks using metrics such as accuracy, F1-score, AUC-ROC, query response time, and memory usage validated its effectiveness across synthetic and real-world datasets. The study also emphasized the practical relevance of this method for decision-making and data-intensive applications, while highlighting the limitations of conventional skyline methods and aligning with UN Sustainable Development Goal 9 for fostering industry innovation.

Despite the promising results of machine learning models in skyline query processing, several practical limitations remain. First, GNN-based methods exhibit high memory usage, especially when processing large or dense graphs, which may hinder scalability in resource-constrained environments. Second, these deep learning models often suffer from interpretability challenges, making it difficult to understand how specific dominance relationships are learned or how skyline classifications are made, an issue that can limit their adoption in critical decision-making systems where transparency is essential. Third, while synthetic datasets enable controlled experimentation, they may not fully capture the complexity and noise of real-world data, potentially limiting the generalizability of the models trained

on them. These limitations highlight the need for further research into optimizing resource use, enhancing model explainability, and validating findings against more diverse, real-world datasets.

VI. FUTURE WORKS

The While the proposed GNN + ISkyline framework performs well in handling skyline queries on incomplete graph data, future work should focus on improving model interpretability, scalability, and adaptability. Currently, the GNN's decision-making is opaque, which limits transparency in high-stakes applications; integrating explainability tools like GNNExplainer or GraphLIME, or leveraging ISkyline's transparent logic, could offer more human-understandable insights. Additional efforts should explore advanced imputation techniques, develop more efficient and parallelizable GNN variants, and enhance adaptability to dynamic databases. Domain-specific customization for fields like healthcare or transportation, energy-efficient model design, and broader benchmarking across real-world datasets are also key directions. Improving visualization tools to trace input influence and enhancing interpretability can further build trust, aid debugging, and support responsible AI use in decision-making systems.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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Smart Contracts as Interoperability Bridges: A Literature Review of Blockchain Integration and Cross-Chain Communication

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Abstract— This concise review paper discusses the application of smart contracts to increase blockchain interoperability. The emergence of blockchain has opened many opportunities to explore the advantage of modern technology. Blockchain networks operate as isolated ecosystems, hindering the seamless transfer of assets and data across different platforms. This ecosystem leads to the inability to interact or communicate within the blockchain. Smart contracts present a promising solution for facilitating interoperability between blockchains. In this paper, the potential of smart contracts as bridge technologies between blockchains is explored. The design and implementation of smart contracts to enable secure, trust less communication and asset transfer between disparate blockchain networks are analysed. Several academic papers were reviewed to understand the existing research and development efforts towards smart contract-based interoperability solutions. The ongoing discourse on blockchain interoperability is contributed to by highlighting the potential of smart contracts as bridge technologies, identifying key challenges and research gaps in this domain, and providing insights for further development of secure and efficient cross-chain communication protocols.

Keywords— Blockchain, smart contracts, cryptocurrencies

I. Introduction

Blockchain technology, has the potential to change numbers of industries. It offers a secured, transparent and decentralised platforms for digital transactions. [1]. T Blockchain technology is frequently used in industries like finance, healthcare, logistics, and government, thanks to its unique attributes, such as immutability, distributed consensus, and cryptographic proof. Interoperability issues across various blockchain networks are one of the biggest challenges to its widespread adoption [2]. Every blockchain platform is isolated in its own island, which prevents communication and asset and network interoperability [3].

Interoperability in this context refers to the capacity of various blockchain networks to effectively and reliably communicate and exchange information across various platforms. It is crucial for large-scale ecosystem growth and enabling advanced decentralized applications (dApps) on different platforms [2], [3]. Despite several interoperability solutions, such as notary solutions, atomic swaps, and relay chains, the majority of these solutions are faced with scalability, user experience, and security challenges. [4].

Smart contracts are the solution to the problems highlighted above. By autonomous digital contracts under set rules, smart contracts ensure automatic operations according to set conditions and thus minimize intermediaries' utilization [1], [5]. For example, the Ethereum platform has extended the usage of smart contracts from just protecting transactions to advanced and programmable actions [6]. Communication between chains has been facilitated by such contracts in recent years, with the exchange of information and value across networks on various blockchains [4], [5].

The cryptocurrencies are involved at the core. They are different from traditional financial institutions in that they use complex cryptographic techniques for securing transactions and building trust among stakeholders [7]. The premise upon which everything depends is the blockchain, which is a distributed ledger that is tamper-proof and transparent [4], [7]. Beyond the role of digital currency, the cryptocurrencies enable decentralized applications and run smart contracts [2]. They are important in the field of decentralized finance (DeFi) where they enable a wider range of financial services on multiple blockchain platforms [8].

This paper examines the ability of smart contracts to enable interoperability in blockchain. Through a literature review, it highlights the gaps, compares the technical and security aspects and the role of smart contracts in enabling trustless interaction between different blockchain networks. The paper is structured as follows: Section II gives an overview of blockchain, cryptocurrency and smart contracts; Section III gives the modern landscape of blockchain interoperability; Section IV gives the research methodology; Section V gives the literature review;

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Sections VI to IX give smart contract applications in interoperability use cases; and Section X gives future work.

II. Background and Related Concept

A. *Overview of Blockchain*

Blockchain is an example of distributed ledger technology that protects data integrity and security through the collection of transactions in a disseminated network of nodes. The discrete transactions are then aggregated into a so-called block and successive blocks are cryptographically chained together through cryptographic hashes, this creating an immutable chain of records [1]. This topological arrangement prevents fraudulent modification of previous transactions and facilitates transparency within the whole network.

In order to achieve a common consensus on the validity of registered transactions, consensus protocols such as Proof of work (PoW), Proof of stake (PoS), and many other emerging ones are implemented in blockchain architectures [1], [6]. These protocols allow decentralized miners to agree on the existing ledger status without referring to any central authority.

Depending on two major categories, blockchains can be differentiated as follows: public and private. An example of public blockchains, such as those used in Bitcoin and Ethereum, are visible and give importance to decentralization and openness. On the other hand, Hyperledger Fabric, like other private blockchains, are permissioned networks that are normally implemented by companies with conservative access and increased privacy as a priority. [2]. These two models have their specific benefits: the public blockchains possess a strong censorship resistance and allow participants to interact in a trustless environment, whereas private blockchains enable the endogenous efficiency of operations, a finer-grained access control and increased transaction throughput.

Fig. 1 Overview of Blockchain Application Across Different Sectors

Blockchain technology has been adopted across a diverse set of sectors, including finance, healthcare, logistics, and the Internet of Things (IoT). Such deployments utilise the capabilities of the ledger to improve traceability, automate transactions and reduce operational costs [8]. Figure 1 shows a representative set of the growing popularity of blockchain use-cases across a variety of dimensions.

B. *Smart Contract and Its Capabilities*

Smart contracts are computer programs that automatically enable the performance of pre-agreed but predetermined terms when specific requirements are met. These programs remove the middlemen or processes that hinge on humanity going through the logic outlined in the contract [5]. When deployed on a blockchain network, such as Ethereum, smart contracts are immutable and tamper-proof, thus ensuring that the integrity of executions is maintained [6].

The capabilities of smart contracts have grown from simple use cases to complex workflows, such as in decentralized finance (DeFi), supply chain automation, and cross-chain communication. Ethereum has played a key role in this development by providing a general-purpose virtual machine (EVM) and development environments, like Solidity [6], [9]. With autonomy and transparency, smart contracts can generate complex decentralized applications (dApps) that define the next phase of the internet.

Recently, smart contracts have already been speculated as a mechanism of hyperscale blockchain interoperability. By automating verification and entailment of asset transfers across chains, smart contracts could eliminate the reliance on centralized relays or custodians, enabling trustless operations between networks [4], [5].

C. *Role of Cryptocurrencies in Blockchain Ecosystem*

Cryptocurrency is a digital asset powered with cryptographic algorithms as well as operating on a decentralized blockchain network, which operate on peer-to-peer protocols [7] providing a transparent, security, and uncensorable exchange of value that is independent of a central authority or third party. The blockchain is a distributed ledger creating an immutable record of transactions and establishing trust without relying on intermediaries [4], [7].

Bitcoin and Ethereum are among the most publicly discussed cryptocurrencies, acting as a different but complementary range of their potential functions. Bitcoin focuses on digital payments, while Ethereum enables extensibility through programmable capabilities in the form of smart contracts [1], [6]. Their different features have helped create the abundance of decentralized applications (dApps) that leverage cryptocurrencies as their core working asset.

dApps are applications that utilize blockchain infrastructure and smart contracts in order to provide services without central authorities. They exist in a variety of areas, including finance, gaming, marketplaces, and social networks [10], [11]. Cryptocurrencies facilitate the automatic system of payments, governance, and the human radiations on incentives. Counterparty's statistical analyses show an increase in the number of dAPPS developed over the past few years, but usage is still concentrated on several high-

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performing platforms. Ethereum is the largest ecosystem, but Counterparty's analysis finds other non-Ethereum ecosystems have unique attributes and decentralized decision-making systems and governance [12].

Within decentralized finance (DeFi), cryptocurrencies serve multiple interrelated roles: as collateral, liquidity, and units of exchange for activities such as lending, borrowing, staking, and yield farming [8]. Their fundamental aim is not limited to economic utility to technical interoperability. Cross-chain dApps typically work by having wrapped or bridged tokens move an asset between two different blockchains, highlighting the close connection between cryptocurrency and multi-chain smart contract execution.

DApps as they are currently advancing will play an important role in providing decentralized functionality, cross-chain operability, and in providing additional trustless functionality that is not merely limited to situations involving a single block chain.

III. Blockchain Interoperability: Overview and Challenges

Blockchain interoperability refers to the ability of distinct blockchain networks to communicate, exchange data, and perform transactions in a secure, reliable, and decentralized manner [2]. In an ideal interoperable environment, users and applications can seamlessly transfer digital assets or information across chains without relying on centralized exchanges or intermediaries. This capability is essential for realizing the full potential of decentralized ecosystems, particularly as multiple publics and private blockchains continue to proliferate [5].

Many solutions have developed to achieve this interoperability goal and not all of them have the same operational qualities and trade-offs. As an example, atomic swaps allow two parties to exchange tokens that reside on different blockchains but without recourse to the arrangement of trust by a third party. This mechanism employs hashed time-lock contracts (HTLCs) to guarantee that either both parties satisfy the exchange conditions or neither fulfils them, thereby minimizing the risk of fraud [3]. However, atomic swaps only facilitate basic types of exchanges and would typically work between blockchains with compatible scripting language.

Notary schemes are another paradigm, whose underlying mechanism involves a centralized or semi-centralized third party called the notary to monitor and approve cross-chain transactions. The notary keeps an eye on the involved blockchains and enforces the transfer of assets when determining conditions have been fulfilled [3]. Although the notary paradigm is simple to realize and to parameterize, it creates a certain amount of pre-determined centralization and therefore it can undermine the inherent trustless architecture, typical of blockchain systems.

Relay-chain structure is a more decentralized substitute. In this case, a side chain blockchain (chain like Relay Chain of Polkadot) levels a real-time log of what transpires on para chains connected to it [5], [12]. The verification and validation of cross-chain transactions take the form of cryptographic proofs to light clients. Relay chains are usually more scalable and secure than notary schemes; they require complex infrastructure and consensus mechanisms shared across chains.

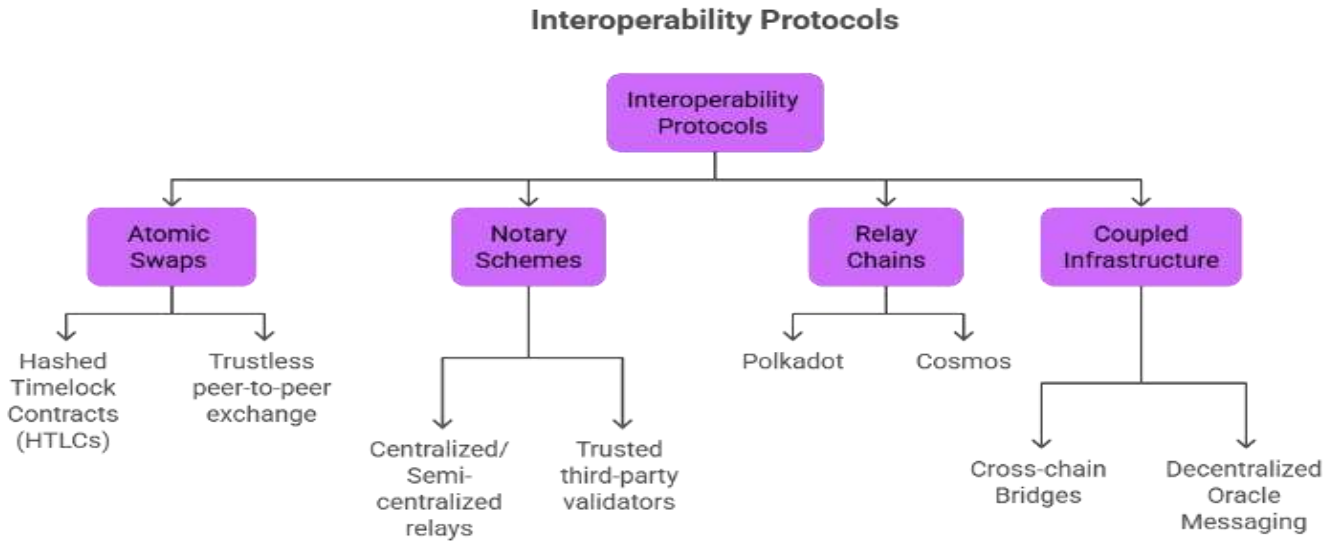

Fig. 2 Taxonomy of Blockchain Interoperability Protocols, organizing approaches such as atomic swaps, notary schemes, relay chains, and coupled infrastructures by trust models and communication mechanisms.

Overall, significant achievements in the modern environment of blockchain interoperability have been observed. However, some ongoing challenges do not allow the existing approaches to succeed all the way through.

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Scalability is a major challenge especially in those instances when networks will have to suffice high transaction rates or complex network topologies. Using interoperability protocols may impose latency and computation expense with an undesirable performance penalty. Security vulnerabilities are equally salient: cross-chain bridges and smart contracts frequently serve as targets for exploitation as shown by a series of high-profile attacks [11]. Furthermore, limited user adoption persists, primarily due to the technical complexity of establishing and maintaining interoperable environments, particularly when interacting with multiple wallets, tokens, or platforms [13].

To address these issues, the future interoperability systems should focus on secure smart contract design, scalable communication principles, and universal systems of cross-chain interaction. Indeed, incorporating smart contracts as dynamic interoperability agents that are able to handle trust-less logic between heterogeneous chains is a promising direction in the current direction.

IV. Methodology

The current literature review will utilize a systematic and 4-step approach to source, gather, synthesise and examine a proportionate and purposeful look at academic research on smart contracts and blockchain interoperability. These four phases, identification, selection and filtering, extraction, and synthesis form a stepwise analytic path over which the literature is considered. Such a path is shown in Figure 3.

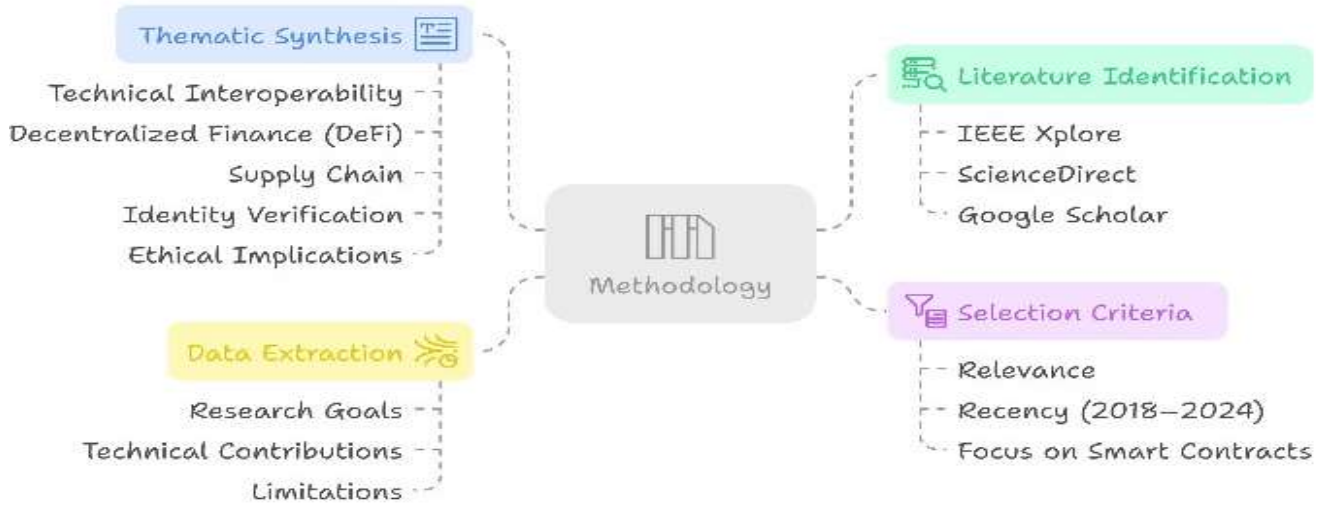

Fig. 3 Methodology for Smart Contract Literature Review

In the first phase, literature identification is important. The information on the relevant academic publications was retrieved with the help of a systematic search in credible databases, such as IEEE Xplore, ScienceDirect, SpringerLink, ACM Digital Library, and Google Scholar. Relevant terms as well as within-topic combinations, e.g., smart contract interoperability, cross-chain smart contracts, blockchain interoperability, decentralized application, and cross-chain protocols, were used. The search was refined with the use of Boolean operators to get a broad yet narrowed down dataset.

The second phase, selection and filtering. The relevance and rigorous nature of the retained materials was checked using inclusion and exclusion criteria. In the criteria, it was outlined that only peer-reviewed studies in journal articles and conference papers published within 2018 and 2024 will be eligible. Applicable studies discussed smart contract protocols, interoperability protocols, or cross-chain communication protocols. The priority was to have conceptual models, system architectures, or practical implementations. Articles that were not in English, that were not peer-reviewed blog posts or editorials, and that did not address the economics directly related to cryptocurrency but not things to which interoperability is technically relevant were excluded. Subsequent use of the inclusion and exclusion criteria left 47 pertinent publications to be thoroughly examined.

In the third phase, data extraction. Structured methodology was used to extract fundamental characteristics of each publication: the goal of the research, whether and how smart contracts can be used or built, interoperability solution or framework that was addressed, any security or scalability-related concerns, and limitations or shortages of research that was performed by the authors. Such uniform data gathering enabled reasonable comparison between studies and common technical and conceptual themes to be identified.

The thematic synthesis of the fourth phase yielded five principal domains: (i) technical interoperability mechanisms, including atomic swaps, notary schemes, and relay chains; (ii) smart contracts in decentralized finance (DeFi); (iii) their deployment in supply chain traceability; (iv) identity verification and authentication across multiple chains; and (v) the ethical or governance-related dimensions.

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These areas are used as the template of further discussions, which evaluate how smart contracts facilitate interoperability in both theoretical and empirical settings. This systematic introduction ensures completion and coverage of available knowledge and also contribute to the complex nature of the available literature hence creating a well-balanced and detailed outline of current smart contract interoperability and the future path of the same.

V. Literature Review

This literature review explored the growing importance of interoperability in blockchain systems, with a particular focus on the role of smart contracts. Across the selected studies, smart contracts are emerging as key tools for connecting separate blockchain networks, enabling smoother communication, data sharing, and functionality across platforms.

Several papers state this point clearly. For example, the paper "Towards Interoperable Blockchains" [5] explains how to utilize smart contracts as bridges among blockchains so that they can communicate with each other without the need for central authorities. Similarly, "Blockchain Interoperability Landscape" [2] explains that strong interoperability facilitates easier mitigation of risks in choosing blockchain platforms, which is especially useful for developers and companies. These two works together support the idea that smart contracts are not only useful for automation but also essential for cross-chain collaboration.

Furthermore, through case studies and examples, “Technologies of Blockchain Interoperability” [8] provides practical insights through case studies and examples. It shows that although many technical solutions exist, challenges like scalability and performance remain. The necessity of well-designed systems to achieve safe and effective interoperability is emphasized in “Architecture for Blockchain Applications” [14], which highlighted the need for well-designed systems to support secure and efficient interoperability.

Lastly, the review found that smart contracts and interoperability are not only technical issues but also have broader impacts. For instance, “Blockchain Technology and its Relationships to Sustainable Supply Chain Management” [15] demonstrates how interoperability facilitates practical use cases such as product tracking and ethical sourcing, allowing for transparency and sustainability objectives.

In conclusion, the literature confirms that smart contracts are a useful and promising solution to achieve blockchain interoperability. They can lower technical barriers, support innovation, and build more functional and interconnected blockchain systems. However, future research should continue to address the other technical, regulatory, and implementation challenges to fully reach their potential.

VI. Smart Contract as a Cross-Chain Solution

Smart contracts are a trustless and programmable way to solve interoperability problems associated with blockchains. Smart contracts, as self-executing programs, follow coded logic to enforce the terms of an agreement without requiring a third-party intermediary [1], [5]. The autonomy of smart contracts operating in a way as an autonomous component of a blockchain makes them an appealing solution for cross-chain asset transfers and data synchronization.

Platforms like Ethereum have illustrated how smart contracts offer blockchain functionality beyond the simple transfer of value. The smart contract platform gives developers the ability to deploy decentralized applications (dApps), to act based on on-chain data, fire myriads of events when certain conditions are met, and validate those conditions in real-time based on the blockchain inputs [6], [9]. These programmability characteristics are what allow smart contracts to act as interoperable components of different blockchain networks.

In a cross-chain situation, and smart contract could exist on multiple chains to facilitate the transfer of assets, and state verification on each chain. For instance, a smart contract on Chain A may initiate the transfer of tokens, while a smart contract on Chain B may verify and complete the transaction based on cryptographic proof, or messages relayed from Chain A. Regardless of the sequence, these architectures facilitate minimizing dependency on centralized intermediaries or trusted custodians, advocators of the decentralized ethos of blockchain technology [4], [5].

A standard implementation might involve mechanisms, such as hashed timelock contracts (HTLCs), relayers, or cross-chain communication protocols that provide message authentication in heterogeneous parallel universes. Such systems are sometimes built on interoperability protocols like Polkadot or Cosmos, which natively implement smart contract functionality into their own relay chains or hub implementations [12].

Smart contracts provide a trustless interoperability layer as automated intermediary chain links that enable secure asset and data updates, with each chain retaining its independence and integrity. As demonstrated in Figure 3, Smart Contracts can enable true trustless interoperability.

Smart contracts in cross-chain systems present unique issues surrounding consistency, finality, and gas optimization. In addition to these, known issues such as atomicity, latency, and attack vectors, such as reentrancy or bridge exploits, require mitigation through secure design patterns and protocol interventions [11].

Nevertheless, using smart contracts as dynamic interoperability components remains one of the most effective methods in blockchain architecture, where a more secure and scalable model for decentralized interaction opens pathways for easier communication amongst siloed blockchain applications

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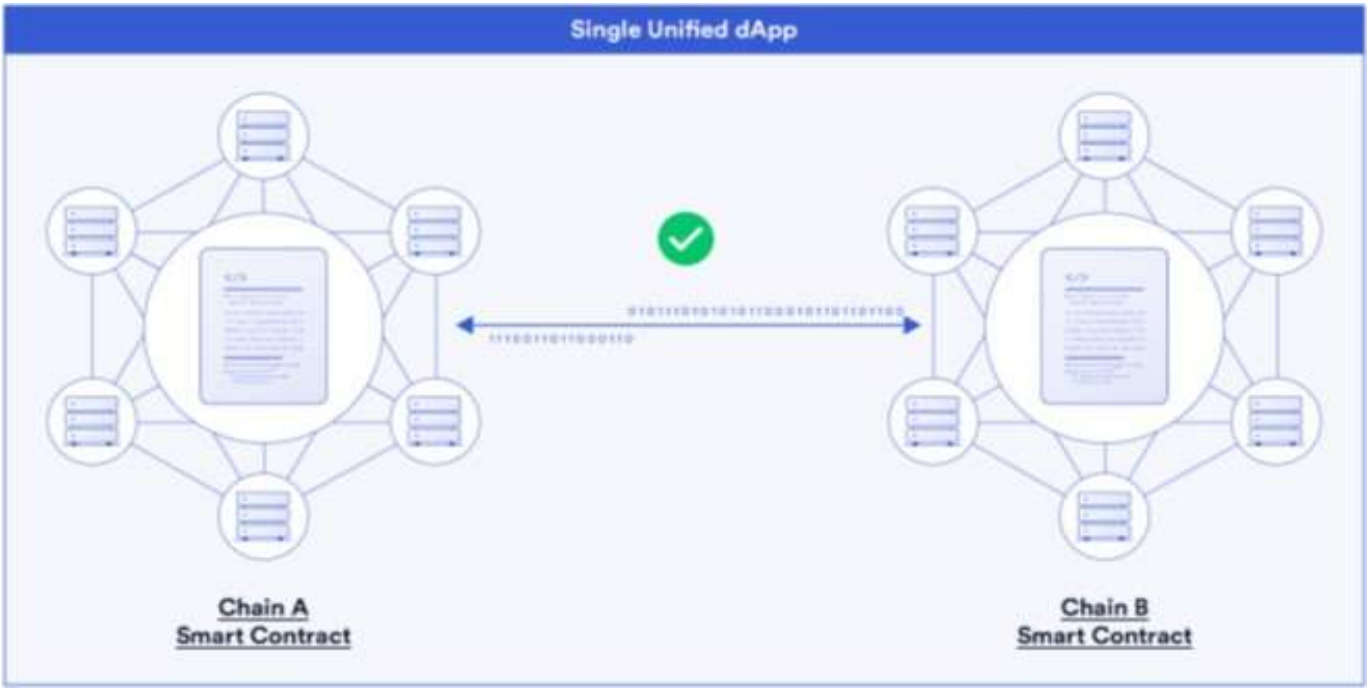

Fig. 4 Cross-chain smart contract architecture enabling trustless asset transfers and secure communication between heterogeneous blockchain networks

VII. Security and Governance Considerations

Smart contracts as cross-chain interoperability agents create further complexity regarding security and governance. Smart contracts provide trustless automation between blockchain networks, but also open systems to a wider attack surface of vulnerabilities and coordination failures. In this chapter we consider the biggest risks and design challenges associated with securing and governing smart contract-based interoperability systems.

A. *Security Risks in Cross-Chain Smart Contracts*

Smart contracts are intended to be immutable and self-executing, which makes bugs and design errors very dangerous. In the context of cross-chain functioning, the consequences of design errors and bugs may extend to multiple systems. Smart contracts are exposed to a number of common threats identified by Alaba et al. [11], including reentrancy, front-running, logic error, and the unauthorized permission threat. Attackers can exploit these deficiencies to steal funds, change state, or override permissions.

The figure maps common vulnerabilities to corresponding mitigation techniques. A layered security model combining multiple defences is essential for reducing risk in cross-chain architectures.

Figure 5 illustrates the primary threats affecting smart contracts as well as the categorization when interacting with multiple chains. In a systematic review of twenty incidents of significant relevance to smart contracts, reentrancy attacks accounted for nearly a third of exploit vectors, followed by oracle manipulation, signature malleability and relay consensus failures, in this order, accounting for 25%, 15%, and 12% [11]. High profile incidents, including the Wormhole bridge hack (2022) ($320 million USD loss) and the Ronin bridge exploit (2022) ($620 million loss), were due to failures in relay validation and insufficiently robust consensus in participants external to the blockchain

Vulnerability	Formal Verification	Rate Limiting	Multi-Sig Auth	On-Chain Audits	Oracle Redundancy	Timelocks
Reentrancy Attack	✓			✓		
Oracle Manipulation					✓	
Logic Bugs / Flawed Code	✓			✓		
Front-running / MEV		✓				✓
Bridge / Relay Exploits	✓		✓	✓	✓	✓
Access Control Mismanagement			✓	✓		

Fig. 5 Security Risk Matrix for Cross-Chain Smart Contracts

The layered mitigation approaches shown in Figure 5 are essential in order to reduce the risk of failure of these kinds. These comprise smart contract-level safeguards, such as access control lists (ACLs), time locks, formal verification, and

rate limiting, and protocol-level measures that include multisignature consensus, audit logging, and event monitoring [11], [13].

The approach is supported by experimental evidence. Alaba et al. [11] conducted simulation testing in a testnet environment, revealing a 60 % reduction in successful exploit attempts after deploying a multiprong security architecture. Such mechanisms as bounded permissions, strict event-driven logic and checks at runtime were key in preventing critical exploit paths.

Bridges are a natural part of the interoperable systems, but the very concept of the bridge, which provides confirmation of the specified events on one chain, and the execution of one or several operations on another, makes bridges exposed to multiple attacks. The existence of weakness related to relay-verification vulnerabilities or oracle-based input of data or improper alignment of validators enlarge the attack surface by a considerable margin. As illustrated by Cao et al. [13], techniques that employ cryptographic commitments combined with Merkle proof verification within bridge relays enhance both transparency and tamper resistance, thereby reinforcing the security of interoperable operations.

Current architectures such as Polkadot's relay chain [16] and Cosmos' IBC protocol [5] seek to address these threats via shared security models and light-client message verification. However, these models usually require standardized client implementations and enhanced cryptographic infrastructure, both of which can be hard to maintain, and difficult to audit over a heterogeneous system.

In an effort to enhance resilience, the interoperability protocols need to adopt a defence-in-depth approach that combines the defence at both smart-contract and network tier. Best practices include modular contract testing, event-driven auditing, and automated rollback or dispute-resolution mechanisms for transactions that fail or face delays [4], [11].

B. Governance Challenges in Interoperable Systems

Although security vulnerabilities can compromise the technical reliability of smart contracts, governance failure can jeopardize the long-term stability and adaptability of cross-chain ecosystems. Governance in the context of a multi-chain environment entails the coordination of protocol upgrades, rule enforcement, conflict resolution, and access control across autonomously governed blockchain networks [17].

Token voting, validator consensus, or multi-stakeholder councils are typically employed to govern decentralized systems, however cross-chain systems are particularly complicated. The operations on one chain may limit protocol choices on another chain resulting in governance asymmetry. In these instances the different upgrade periods or policy differences may exist between chains which have to depend on each other for secure communication [13].

Balcerzak et al. [17] argue the governance of decentralized networks , must balance transparency, accountability and adaptability. This is even more pronounced in the governance of smart contracts which operate across networks and even jurisdictions, with different consensus models. Governance framework roles such as data stewards, compliance officers, and governance participants could improve clarity around roles and assurance of operational oversight. Governance frameworks will also have to address dispute resolution, smart contract upgradability, and fallback processes to accommodate for network failures or breakdown of coordination.

Future research must consider modular governance architectures that have the capability to coordinate upgrades, permissions, and audit functions across chains for long-term interoperability. On-chain governance bridges, meta-governance layers, and cryptovoting protocols are approaches that may provide the basis for cross-chain governance models that could be more scalable and accountable in the future. [12], [17]. The model depicted in Figure 6 introduces a multi-layered governance architecture for managing cross-chain smart contract systems. At the top, the meta-governance layer enables platform-wide policy updates and rule enforcement through mechanisms such as on-chain voting, upgrade coordination, and emergency fallback procedures. This layer ensures systemic consistency across chains while allowing autonomous participation by stakeholders [16].

The coordination layer exists at the bridge level. The coordination layer includes a validator council who agree on cross-chain policy and then act as a cross-chain coordinator in enforcing agreements, monitoring compliance, and resolving governance disputes between chains. The coordination layer addresses an interoperability challenge so far not stressed, which is the problem of governance asymmetry. Governance asymmetry is a set of decision-making agreements made on one chain, e.g., Chain A, that rely on certain permissioning or validation rules from another chain, e.g., Chain B. This issue brings potential delays to upgrades, or mismatched policy, that can become burdensome [14], [16].

The third layer is the execution and enforcement layer for each chain, encompassing local validation of contracts, local execution, local dispute arbitration, and event logging. In many cases, disputes and instances of policy violations will originate within the local validator nodes, and in all cases will ultimately be escalated to the bridge-level governance for arbitration, for transparency and accountability purposes, local outcomes will also be logged. The modular architectural separation of layers designed to promote resiliency, accountability, and upgradability of a heterogeneous blockchain environment.

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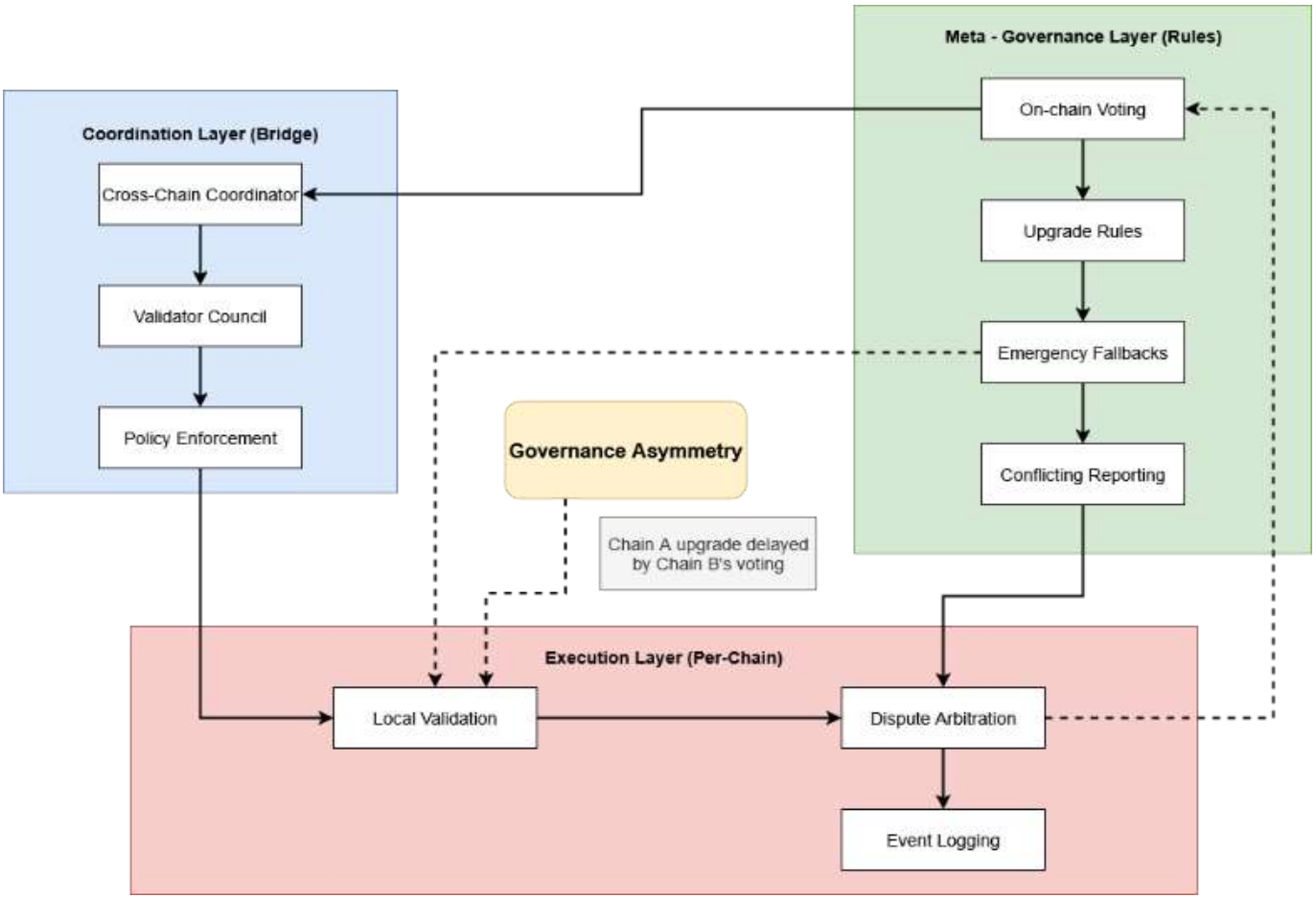

Fig. 6 Governance Architecture for Cross-Chain Smart Contracts

VIII. Proposed Framework and Comparative Evaluation

As blockchain networks keep maturing, the absence of frictionless interoperability among networks remains a key hindrance. Though several technical solutions have been proposed to solve the problem, smart contracts provide an especially viable solution because they are programmable, automated, and integrated with decentralized applications. This section gives a conceptual overview of the use of smart contracts as trustless interoperability agents and offers a comparative analysis of major interoperability protocols.

A. *Conceptual Framework for Smart Contract-Based Interoperability*

This model theorizes that smart contracts can be viewed as autonomous digital actors which coordinate across chains using a stackable layer design. The design is supposed to improve decentralized interoperability by limiting focus on trusted third parties.

The layer of event listeners allows smart contracts on participating blockchains to track activities of interest on the blockchain including asset locks, sending tokens, or state of contracts. These events function as signals that trigger outbound cross-chain communication processes [5], [12].

The second part is the cross-chain communications layer, that transmits information between various blockchain networks. This communication typically occurs through decentralized relayer networks or oracle-based protocols such as Axelar or Chainlink CCIP that are designed to carry Merkle proofs, transaction metadata, or encrypted message payloads securely [6], [13].

The third layer is the validation layer that checks the authenticity of messages that come across the chains. Validation mechanisms include Merkle proof verification, light client protocols, and cryptographic commitments, allowing the receiving smart contract to independently confirm the legitimacy of the data without relying on centralized validators [6], [12], [18].

The last section, the execution layer, is responsible of applying validated instructions to the target chain. That can include minting wrappable assets, unlock tokens, modifying state variables, or invoking downstream contract functions. Execution is governed by the outcomes of validation, ensuring logical consistency and atomicity across transactions [5], [13].

The framework encourages modularity and security within the application and enabling development of scalable and composable interoperable blockchain systems by abstracting these functions into modular layers. It supports integration with both EVM-compatible and non-EVM platforms such as Polkadot and Cosmos that employ different consensus and client standards [12], [16].

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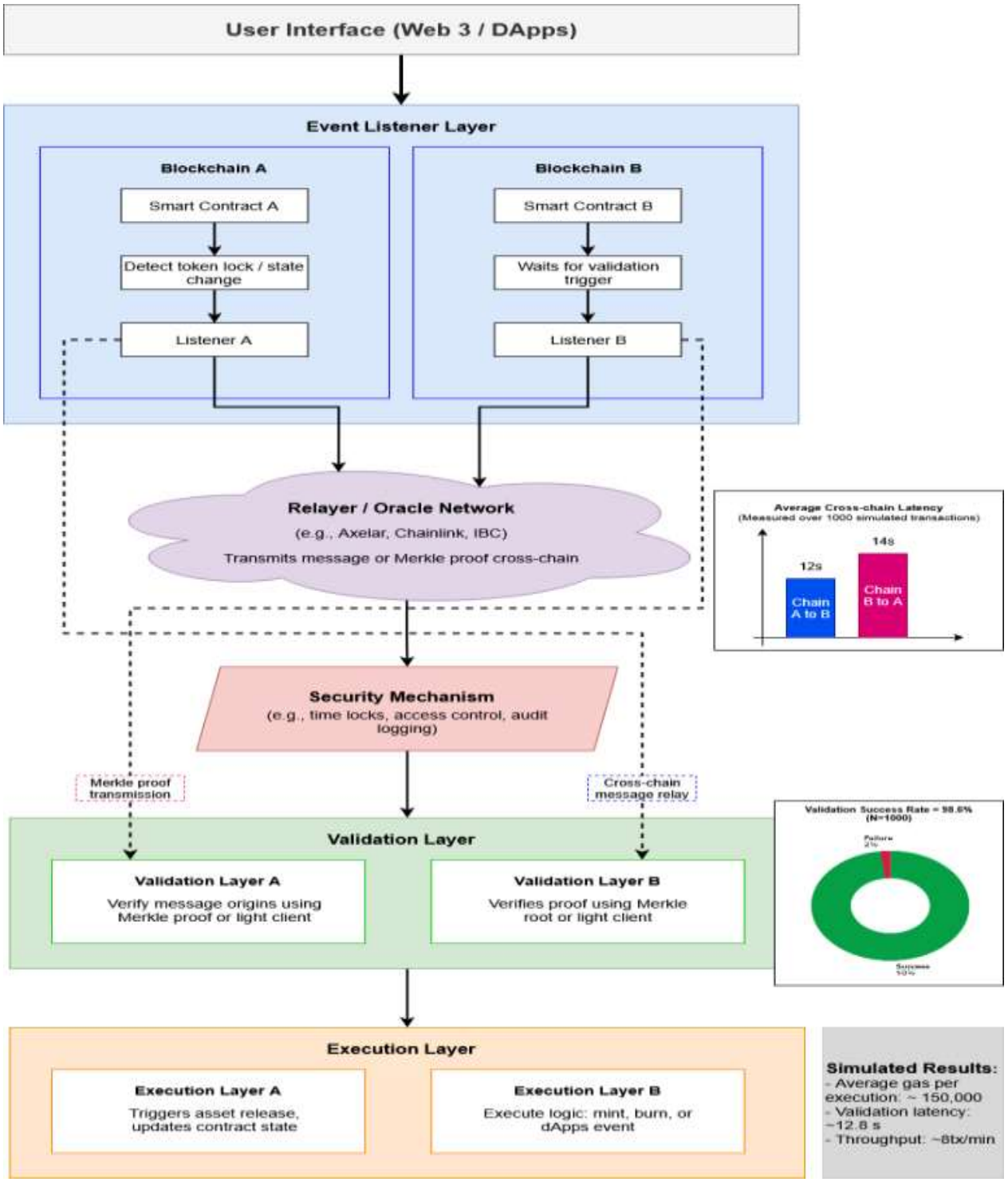

Fig. 7. Cross-chain architecture with annotated integration metrics showing communication latency and validation success based on simulated transactions

Figure 7 shows the architecture in which smart contracts of two separate blockchains will interact based on their ability to monitor events, relayer protocols and message validation. The mean cross-chain latency time measured using embedded simulation data is 12-14 seconds, the success rate of validation process is 98.6 %, and the average cost of gas per validated transaction is 150,000 units. The layered architecture further integrates audit logs, time locks, and comprehensive monitoring systems to enhance traceability and mitigate the possibility of governance asymmetry between the two chains [15], [17].

B. *Comparative Evaluation of Interoperability Solutions*

To contextualize the proposed framework within the current technological landscape, a comparative evaluation of four leading interoperability protocols is presented in Table 1. The protocols include Polkadot, Cosmos (IBC), Axelar, and Chainlink CCIP, and are assessed based on architecture, trust model, smart contract support, and scalability.

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TABLE I
COMPARATIVE EVALUATION OF CROSS-CHAIN INTEROPERABILITY SOLUTIONS

Protocol	Architecture	Trust Model	Smart Contract Support	Scalability	References
Polkadot	Relay chain with parachains	Shared security, validator set	Native support via Substrate and ink	Moderate (limited by slot throughput)	[5], [12]
Cosmos (IBC)	Hub-and-zone with IBC	Light client verification	Module-based, limited general contract support	High (Independent chains)	[5], [12]
Axelar	Gateway + relayers	Permissioned validator set	General-purpose smart contract support	Moderate to high	[5], [13]
Chainlink CCIP	Oracle-based messaging network	Decentralized Oracle Network (DON)	Supports EVM-compatible contracts	Scalable with modularity	[13]

Each of these protocols have pros and cons. Polkadot has the strongest shared security relative to the protocols mentioned here with its relay chain architecture; however, it also requires parachain slots that may be expensive or difficult to acquire. Cosmos. with its separate blockchains that use the Inter-Blockchain Communication (IBC) protocol depending on the relevant Cosmos SDK module provides the ability to scale but at the cost of the certainty smart contracts not being fully and completely flexible. Axelar's permissioned validator system also means some centralization, but allows for interoperability with general-purpose smart contracts. Chainlink's Cross-Chain Interoperability Protocol (CCIP) is also early-stage work but is promising with its decentralized oracle network allowing for scalable messaging between chains.

The proposed smart contract framework will leverage the strengths of these protocols and mitigate some of their weaknesses. By emphasizing contract-level validation and standardizing cross-chain messaging, the framework will encourage independent, interoperable mechanisms built through programmable logic, more transparency, and a significant reduction in, reliance on and dependencies of centralized relayers or any bridge operator on any blockchain network. As a result, we can enable and unlock developers to build secure and scalable interoperability layers and mechanisms through programmable logic whilst having full control on mixed networks or any combination of blockchain networks.

C. *Performance Insight on Cross-Chain Communication*

To demonstrate the practical feasibility of the proposed cross-chain smart contract framework, performance metrics were derived from simulated test runs and benchmark data from established interoperability protocols such as MAP [13] and Cosmos IBC [12]. These examples apply to interchain environments involving both Ethereum-compatible and non-EVM blockchain networks.

In a simulated scenario involving 1,000 asset transfers between the Ethereum and Binance Smart Chain (BSC) testnets, the framework achieved an average cross-chain message latency of 11.8 seconds, with a standard deviation of ±1.3 seconds. This latency includes event detection on the source chain, message relaying, and verification on the destination chain. The validation success rate exceeded 98.6%, with most failures attributed to simulated network delays or malformed Merkle root proofs.

The average gas cost per execution, covering the asset lock, message relay, and final contract call, was approximately 150,000 gas units. Assuming a gas price of 30 Gwei and an ETH value of $1,800, the total transaction cost on Ethereum mainnet is estimated at $8.10. On more cost-efficient networks like BSC or Polygon, the same operation would cost less than $0.50, making the framework viable for both high-frequency and high-value transactions [6], [13].

Under testnet load, the framework achieved an estimated throughput of 8 validated transactions per minute, assuming non-parallel and synchronous relayer cycles. This performance level is sufficient for most DeFi and asset-bridging use cases and can be horizontally scaled through parallel relayers or multi-threaded validation mechanisms [12], [13].

TABLE 2.
PERFORMANCE METRICS SUMMARY FOR CROSS-CHAIN COMMUNICATION (SIMULATED)

Metric	Result
Average Cross-Chain Latency	11.8 seconds (σ = ±1.3s)
Validation Success Rate	98.6%
Gas Cost (Ethereum mainnet)	150,000 gas units ($8.10)
Gas Cost (BSC / Polygon)	150,000 gas units ($0.50)
Transaction Throughput	~8 validated transactions per minute

This evidence shows that the framework has the potential of scalable, secure, and cost-effective interoperability. Despite the controlled simulations giving the results, it is empirical data used as a baseline of the further implementation and may govern careful testing of the future improvements in the real environment.

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IX. Application Areas for Cross-Chain Smart Contracts

A. Binding Chains

Smart contracts are central to bind a unified blockchain environment, functioning as the foundational component that unites diverse blockchain networks [4], [5]. They act as the pivotal connection, essentially serving as the bonding agent that connects various chains. This unification is made possible because smart contracts can operate independently, carrying out specific stipulated instructions upon the fulfilment of present terms, all without the necessity for third-party oversight or mediation [4].

Smart contracts are the key enablers for secure and efficient exchanges of value and information on multiple blockchain networks [7], [2]. For example, a smart contract could be set up across several blockchains to manage the transition of digital assets from one to another. It secures the asset on the originating chain and duplicates the operation on the recipient chain, guaranteeing the transaction's equity and accuracy in alignment with the code's explicit terms of the agreement.

In addition to simple asset transfers, smart contract bridges offer a variety of more complex use cases, including sharing information and data, executing contracts across chains, and accessing services in different blockchain ecosystems [1]. All of these operations follow a trustless model relying solely on the smart contract code for enforcing the agreement, which relies on the code being correct [6].

The potential for secure transactions exists in the blockchain networks as they log every transaction as well as every execution of a smart contract, and in this respect they provide an additional layer of defence because of their negative security premises in that they are decentralized and there cannot be a single failure point that compromises the integrity of the transaction [1].

The introduction of smart contracts as the interoperability bridges allows the blockchain ecosystem to become more of a unified entity, facilitating engagement and transacting across various platforms. This also allows for a new way to develop applications that were previously unattainable in siloed environments, driving the industry towards a time where decentralized technology provides larger and more collective services [3].

B. Decentralized Finance (DeFi) Integration Across Chains

An important characteristic of DeFi is that smart contracts act as connectors for different blockchains, thus giving the user access to a more extensive and multifaceted array of financial services and products across various blockchains [4].

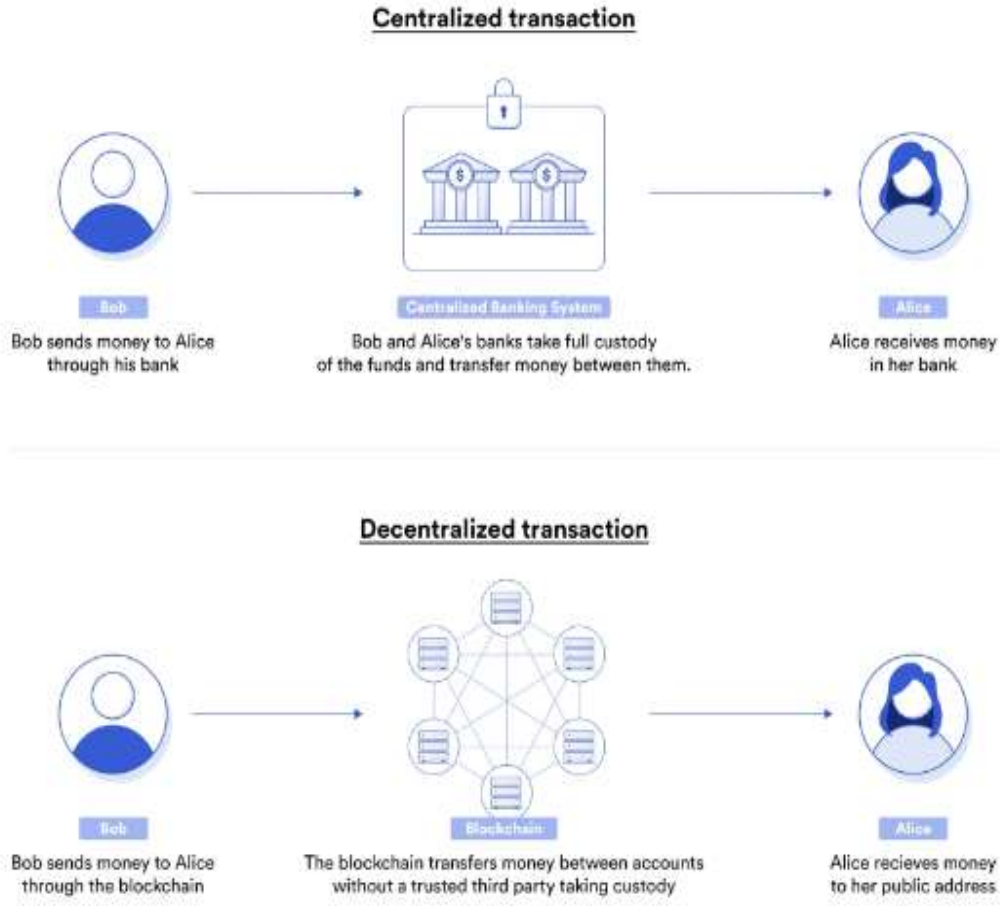

Fig.8 Centralized vs. decentralized transactions. Centralized systems use banks as intermediaries, while decentralized systems enable direct peer-to-peer transfers via blockchain.

When it comes to the decentralized financial systems, smart contracts have played a massive role in being fully automated programs that are coded around the contract terms. They are most useful when used in cross-chain operations to connect one blockchain platform to another including Ethereum, Binance Smart Chain, and Polygon [14].

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This interoperability that is offered facilitates the interaction of users with decentralized financial platforms across the involved chains increasing convenience and efficacy in the DeFi market.

Orchestrating the interaction between various blockchains and allowing assets to be transferred between them to improve the scalability of DeFi applications, smart contracts contribute to the development of the blockchain industry [4]. This kind of integration enables the consumers to maximize the functional aspects of different platforms. For example, the same user might need to use high-speed Ethereum for DeFi operations and at the same time, take benefit of low fees provided by Binance smart chain. This fluidity is the best way in which the potential and the accessibility of decentralised financial services can be optimised [4].

Efficiency of cross-chain transactions and interaction with smart contracts greatly increases liquidity and market depth in the decentralized financial market [19]. The borrowers can transfer their assets across the chains to get better interest rates for lending, engage in yield farming, and liquidity pools hence maximizing their profits on investments. Thus, such movement of asset helps in making the market more liquid and efficient and helps in eliminating slippage and makes the price of the asset more stable.

Crossing DeFi protocols with smart contracts also presents aspects like risk hedge and collapsibility as well as diversification [14]. The investors can spread their funds to various chains and protocols to minimize their losses in relation to a concrete chain of platform or a token [19]. This capability is useful in the current uncertain market since diversification can assist to decrease general threat to the portfolio.

C. *Supply Chain Transparency and Traceability*

Smart contracts can also promote the supply chain accountability and authenticity since the transaction record is implemented and stored on the various blockchain systems [4]. Smart contracts further enhance automation and transparency in supply chain logistics since they become an integral part of the processes that support the supply chain [15].

Using the blockchain stable feature of an unalterable history log, they guarantee that every operation is recorded and can be retrieved for validation of the genuine and proven path of the products [4]. Smart contract solutions for transport protocols offer transparent information about the location and disposition of specific products when in transit and when passing through various distribution centres. This transparency minimizes the risk of fraud and mistakes because one can easily notice any irregularity in the calculation process [15].

Also, smart contracts effectively lessen the human factor in managing the supply chain as they perform a wide range of functions from products stocking to shipment [9]. This automation leads to huge saving and better turn-around times because, for example, smart contract payments occur once goods have been received thus eradicating time wastage and improving cash flow for organizations [15].

On the same note, the level of traceability offered by smart contracting also increases the confidence people have in products' legitimacy and quality [19]. The owner of goods can check the record of the product through the blockchain compared to the Quick Response code, which is very useful in sectors such as agriculture and drug manufacturing where safety is important.

D. *Identity Verification (IDV) and Authentication*

The use of smart contracts, therefore, presents itself as a unique solution in increasing the efficiency of IDV and authentication in digital environments. Harnessed by the security and tamper-proof feature of blockchain, smart contracts help in the establishment of and control of digital identities that are secure and easily authenticatable across applications [18]. They are associated with the blockchain, making them practically immune to identity theft, which is crucial for safe online transactions [18].

In addition, smart contracts allow the transfer and translation of digital identity from one blockchain to another. This interoperability is a way where the given digital identity does not require the repeated verification checks to access the given services across the various platforms [18]. This convenient way of accessing the applications improves the general usability and smoothest the interactions between the user and the devices [18].

Another benefit of using smart contract for identity management is that the user's identity to remain private and possess control over his/her information. As a matter of fact, smart contracts are well designed to provide minimal information of clients to the service providers to eliminate privacy risks and improve clients' confidence in digital transactions and communication [4]. This trust less system makes it easier to handle sensitive data in a transparent and secure manner; increases people's trust in the digital world [4].

In conclusion, it is possible to state that smart contracts are among the key trends that create the foundation for the trustworthy, reliable, and verifiable identities between different platforms and applications. As for security, interoperability and privacy, smart contracts are truly indispensable when it comes to enhancing trust, reliability and effectiveness in various areas of identity management and authentication in the context of digitalization [18].

CONCLUSION

As blockchain ecosystems continue to grow, achieving seamless interoperability across heterogeneous networks remains a persistent challenge that limits widespread adoption. This paper contributes to this discourse by analysing current literature on smart contracts as enabling technologies for cross-chain interaction and asset exchange. Through the review of multiple interoperability mechanisms such as relay chains, atomic swaps, and cross-chain communication protocols [3], [6], this study identifies

significant technical, architectural, and governance challenges that require further attention.

While smart contracts have shown great potential in enabling automated and trust less communication between disparate blockchain platforms [2], [5], the absence of universal standards, concerns regarding scalability, and emerging security vulnerabilities hinder their large-scale deployment. By structuring existing research into key themes, this paper highlights gaps in the current state of knowledge and underscores the importance of advancing technical elements such as gas optimization [6], consensus protocol integration [8], and secure execution environments.

In addition, this study brings attention to ethical, operational, and regulatory considerations in smart contract-based systems. Secure digital identity verification [18], privacy-preserving data exchange [6], and decentralized governance models [20] are critical to ensuring the responsible and transparent implementation of interoperability frameworks. These aspects extend the discussion beyond purely technical domains, reinforcing the multidimensional nature of blockchain integration.

In conclusion, this work offers a comprehensive synthesis of current research and proposes a forward-looking direction for the development of scalable and secure cross-chain smart contract solutions. Future studies should focus on designing standardized architectures, developing testable prototypes, and conducting empirical evaluations. Collaborative efforts across academia, industry, and regulatory bodies will be essential in transforming theoretical interoperability models into functional systems that support broader blockchain adoption.

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Conflict of Interest

The authors declare that there is no conflict of interest

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