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The Future of Food Security: The Role of Blockchain Technology in Global Aquaculture

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Abstract— The aquaculture sector faces challenges in maintaining a transparent and traceable supply chain, leading to issues like fraud and compromised food safety for consumers worldwide. Studies reveal that nearly 20% of the global seafood industry engages in mislabelling practices, which significantly undermines consumer trust. From harvesting to sale, blockchain technology offers a safe, immutable database that records each stage of the supply chain. Reliability is ensured by users verifying the data. IoT devices and QR codes gather real-time data on product origin, quality, and handling to improve safety and trust making it available to authorities and consumers. The importance of implementing a robust sustainability and traceability system and becomes evident with the European Commission's decision to temporarily suspend fish imports from Thailand due to the prevalence of illegal fishing practices. This blockchain-based strategy offers an integrated solution to current supply chain problems by enhancing regulatory compliance, minimising fraud, and fostering sustainable behaviours. By documenting each stage in an immutable ledger, this study explores blockchain's potential to transform the aquaculture supply chain, creating a system where product history is fully transparent for consumers and regulators. Most case studies and research, focus primarily on developed regions. This underscores the need for further exploration of blockchain implementation in small-scale and underdeveloped aquaculture settings. Ultimately, this solution fosters a safer, more responsible seafood industry that promotes sustainable practices and benefits society overall.

Keywords— aquaculture, blockchain technology, traceability, food safety, sustainability

I. INTRODUCTION

The agriculture and aquaculture sectors are responsible for food security at a global level, but these sectors are facing major challenges when it comes to transparency, sustainability and operational efficiency. The industry's growing inability to cope with consumer demand for sustainably sourced and safe food is further compounded by issues such as fraud, poor data management, and environmental degradation in conventional supply chains that are already stalling and expanding. The use of valuable digital technologies (e.g. blockchain, IoT, AI) can be the efficiency solution of these problems through the increasing supply chain traceability and guaranteeing food safety, validated by several survey data and case study evidence [1].

This rapidly growing area of food production has its own challenges but has a lot of things in common, including illegal, unreported and unregulated (IUU) fishing, an absence of transparency about how these foods are produced and low levels of consumer confidence. In 2014, more than half of all seafood was grown on farms; and with continued growth and improvement of the industry, aquaculture is destined to play a role in meeting the high turnover of seafood hunter's seafood consumption trends globally. But this boom has also brought issues of sustainability and supply chain waste into sharper focus. Blockchain based security with IoT devices, AI based analytics and big data ecosystems in aquaculture presents a strong underpinning for ensuring data integrity, enhanced monitoring and sustainable practices [2], [3]. In the recent past, there has been a lot of buzz about blockchain as it provides a trustless and distributed ledger system which is immutable. You have that technology, where you can instantly collect and verify data up and down the supply chain. The IoT takes key metrics around fish health, water quality, feeding schedule etc. and records this information in a way that is immutably secure, on something like a blockchain, so everyone knows what, when where, and why (and can, ideally, trust it as homegrown) and to where it should be going [4]. This leads to improved traceability that guarantees compliance (with regards to environment friendliness), reduces fraud, and increases consumer confidence [5].

Moreover, the results of this research correspond directly to a number of United Nations Sustainable Development Goals (SDGs). Together, by enabling the agriculture and aquaculture sectors to amplify

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transparency, sustainability and operational efficiency is the way we help drive towards SDG 2: Zero Hunger, SDG 12: Responsible Consumption and Production and SDG 14: Life Below Water. Increasing traceability and preventing fraudulent activity improve food security and reduce environmental impacts such as pollution for example from overfishing. These technological advancements may significantly contribute to the construction of a more equitable and sustainable food system that offered advantages to both producers and consumers by promoting sustainable practices and equipping consumers with reliable information [6].

Figure 1 is an overview of aquaculture blockchain-enabled seafood traceability, which shows all the key steps in the traceability of aquaculture supply chains. It starts with egg laying, and then fish are cultivated in controlled environments. The fish is then checked for quality and packed while ensuring adherence to health and safety guidelines. Conditions, including temperature and handling, are tracked as the seafood is shipped to distribution centers or retailers. Products are stored and then made available for sale to end users. The icons at each stage represent how data is securely recorded and verified on the blockchain, creating a transparent, traceable, and accountable system. Such a system provides consumers and other stakeholders with verified and transparent information about their seafood, from harvesting to plate, engendering trust and helping to support more sustainable businesses.

Fig. 1 Blockchain traceability system in the aquaculture supply chain

Since 2003, China has been at the forefront of providing blockchain technology and other digital innovations as the world's largest aquaculture producer [7]. So, in this transition, so many new innovations of IoT and AI Technologies are being used to modernize aquaculture practices as fish farming have many common problems: However, challenges for the industry remain high in terms of implementation costs, the need for standardized protocols, and a need for a more cohesive strategy in how we approach sustainability concerns [8]. Case studies around the world, like blockchain-based shrimp and tuna tracking programs, serve as growing evidence of this transformation — and of the use of the technology with sustainability by design and securing. This paper aims to review the applications of blockchain technology within the aquaculture industry, highlighting its potential with other advanced technologies such as the Internet of Things, Artificial Intelligence, and others. This paper aims to review the applications of blockchain technology within the aquaculture industry, highlighting its potential with other advanced technologies such as the Internet of Things, Artificial Intelligence, and others. It delves into how the potential of blockchain technology can improve traceability, promote sustainability and improve operational efficiencies, across the aquaculture supply chain. A framework is proposed for cannabis adoption in aquaculture, noting challenges and opportunities associated with this pathway and providing case studies that exemplify the impact of cannabis on aquaculture systems.

This paper is organized as follows; Section I gives a brief overview of how blockchain technology, combined with other digital tools like IoT and AI, is transforming aquaculture industry. Section II provides literature reviews for this work. Section III covers the methodology used for this study. Section IV represents the results and discussion of this study which provides a detailed explanation of the benefits and potential applications of blockchain technology in aquaculture industry. Lastly, Section V provides the summarization and conclusion of this study.

II. LITERATURE REVIEWS

Table 1 represents a literature review, summarizing key studies and insights on the role of blockchain technology in enhancing food security within the global aquaculture sector.

TABLE I
LITERATURE REVIEW

Article	Key Findings/Argument	Supporting Evidence/ Sample Characteristics/ Method	Strengths/ Limitations
[9]	This research discusses how blockchain boosts safety, quality, traceability, and transparency in seafood supply chains.	The research explores blockchain in aquaculture, highlighting transparency, sustainability, and tackling IUU fishing practices.	This research explores blockchain in aquaculture, focusing on sustainability, transparency, adoption barriers, and stakeholders resistance.
[10]	This study finds blockchain reduces illegal fishing, improves traceability, and supports sustainable consumer demands globally.	The literature review, using PRISMA, identified 37 blockchain records (2018-2021) with text-mined terminologies detailed in tables.	The study highlights research gaps, blockchain use in fisheries, and aquaculture but notes potential obsolescence.
[11]	The paper highlights advanced technologies in aquaculture, promoting sustainability, while outdated laws hinder innovation adoption.	This paper emphasizes aquaculture, "Industry 4.0" data insights, and innovations boosting fish production efficiency.	This paper highlights aquaculture's current state, tech potential, and strategies, yet lacks global applicability.
[12]	The study highlights Blockchain Technology's potential in improving aquaculture traceability and ensuring supply chain transparency.	The study suggests Blockchain Technology addresses data gaps, ensuring traceability and emphasizing stakeholder collaboration for standards.	This study excels in sustainability and safety insights but faces adoption challenges from costs and distrust.
[13]	The study highlights blockchain's potential for aquaculture traceability, emphasizing transparency and differing company needs.	The authors developed a tailored blockchain solution for L Aquatic Products Co., Ltd. After analysing their processes.	The study highlights blockchain's aquaculture potential but is limited by narrow focus and outdated literature scope.
[14]	Blockchain enhances aquaculture supply chain transparency, automates compliance, boosts efficiency, and fosters consumer trust.	This study highlights a multilayer system for supply chain tracking, improving food safety, and blockchain cost-effectiveness.	The study highlights IoT-driven environmental compliance but faces challenges in underdeveloped nations due to costs and readiness.
[15]	This paper proposes a decentralized blockchain system for fishery traceability, emphasizing precise stakeholder data input.	The researchers use sequence diagrams, smart contracts, and security analysis to enhance fishery traceability and resilience.	The blockchain solution boosts fishery traceability with IoT and engagement but needs accurate data and further testing.
[16]	This study finds blockchain improves fisheries traceability, ensuring transparency, with Ethereum smart contracts enhancing monitoring.	The study demonstrates Ethereum-based blockchain and smart contracts for fish supply chain traceability, ensuring transparency and compliance.	This study proposes a blockchain approach for aquaculture, enhancing transparency and trust but facing scalability and cost challenges.
[17]	The study highlights blockchain's role in improving traceability, security, and trust in marine aquaculture via IoT, AI, and Big Data.	Blockchain applications like FishCoin and ShrimpChain enhance seafood traceability, while IoT and AI optimize quality and operations.	This blockchain-IoT framework enhances aquaculture transparency but faces adoption, cost, and data reliability challenges.
[18]	Blockchain is expected to enhance fishery traceability, simplify processes with smart contracts, and promote sustainable practices.	This research emphasizes IoT sensors for supply chain transparency and YOLOv8's role in environmental monitoring, requiring integrated data collection for model optimization.	This research effectively employs Blockchain, IoT, and YOLOv8 for fisheries management but faces technological and adoption challenges.
[19]	Integrating blockchain, IoT, and machine leaning enhances fish supply chains, addressing challenges with a layered framework for authenticity and data sharing.	The researchers reviewed Blockchain in fish supply chains and developed a framework emphasizing machine learning for quality and safety.	This paper highlights blockchain, IoT, and ML integration for fish supply chains but notes implementation and research gaps.
[20]	This study showcases blockchain's role in aquaculture, enhancing transparency, communication, and sustainability through compliance tracking.	This study examines blockchain adoption in aquaculture, integrating interviews and analytics to compare its efficiency with traditional methods.	This study highlights blockchain's economic and scalable benefits for aquaculture but notes resistance, compatibility, and long-term viability concerns.

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[21]	The research shows blockchain enhances product transparency, boosting customer engagement and informed seafood purchasing decisions.	Surveyed consumer attitudes show blockchain improves seafood traceability, origins access, and sustainability awareness.	This research showcases blockchain's role in sustainable seafood initiatives but notes sample bias and short-term focus.
[22]	The study shows blockchain reduces aquaculture's environmental impact by enhancing compliance, preventing overfishing, and ensuring responsible sourcing.	The case study analyses blockchain's role in aquaculture sustainability using catch reports and compliance records insights.	This study showcases blockchain's role in aquaculture sustainability but highlights challenges like data accuracy and adoption resistance.
[23]	The research suggests blockchain enhances stakeholder collaboration in aquaculture, improving information flow and sustainability practices.	The research uses focus groups to explore blockchain's role in aquaculture collaboration and reviews successful case studies.	The research emphasizes blockchain's role in stakeholder collaboration for sustainability but notes challenges like resistance and data subjectivity.
[24]	The study finds a blockchain platform boosts fish product traceability, transparency, trust, and data integrity across the value chain.	The study emphasizes fish value chain integration, highlights Ethereum smart contracts, and supports blockchain traceability with ISO 22005.	Despite challenges like technology, data management, and interface needs, the study proposes blockchain to enhance fisheries traceability.
[25]	The paper identifies blockchain implementation challenges in fisheries and recommends building trust, infrastructure, and financial incentives.	The paper employs a three-phase framework with expert input: identifying barriers, refining them, and analysing causal links.	This paper excels in enhancing data reliability but has limited generalizability due to context-specific expert biases.
[26]	The study highlights data reliability and challenges in poor regions, advocating blockchain, IoT, and AI for food traceability.	This study reviews food traceability literature, exploring blockchain-IoT benefits, data gaps, and technical needs for implementation.	The study deeply analyses food traceability but lacks real-world examples, focusing on developed areas and requiring further research.

A. Research Gaps

Literature review on blockchain technology aquaculture brings considerable understanding of various benefits associated with this technology, which includes increased traceability, sustainability, and efficiency of operations. However, a number of these gaps are persisting and provide a constraint to a comprehensive understanding of its application and scalability.

One of the gaps found the geographic scope. Most of the research focused on developed regions, and there are only a few studies related to blockchain adoption in developing countries. The small-scale aquaculture practiced throughout these regions poses other set of challenges due to the lack of technological and financial infrastructure. This would give further insight into how blockchain could be fitted to those contexts to have truly inclusive solutions serving the larger aquaculture industry.

Despite the theoretical benefits that blockchain could impart, very few quantitative case studies have measured the real-world impact of the technology. Specific data such as fraud-reduction rates, operational cost savings, or improved sustainability metrics is rarely provided. Without these empirical data, a stakeholder would have a very difficult time justifying the necessary investment to adopt blockchain.

Issues that are always talked about involve a high cost of implementation as well as resistance by stakeholders. In any case, there is no detailed analysis regarding the two issues. For example, the stakeholders in conventional supply chains are either unfamiliar or distrustful of digital technologies. Addressing these challenges effectively through education, incentives, and simplified blockchain solutions are important for wider diffusion, especially in underdeveloped regions.

B. Recommendations for Future Research

Thus, future research should focus on filling these gaps. The emphasis on future research should be based on studies in developing regions and in small-scale aquaculture systems, since many of them have special economic and infrastructural problems which are not well reflected in the literature review. In this respect, research should be done on blockchain solutions tailored to suit them, affordable and feasible, with broader inclusion and equity in aquaculture advancement.

Potential benefits due to blockchain would have to be emphatically determined through empirical research. Future research should hence focus on the collection and analysis of data that would realistically measure indicators of performance related to fraud reduction, cost savings, and improvements in sustainability metrics. These insights would provide stakeholders with the justification needed to adopt blockchain technologies.

Research on looking into overcoming high costs of implementation and stakeholder resistance, especially those that are not familiar with digital technologies needs to be done. The research may look into training the stakeholders or giving them financial motives, while at the same time developing simplified blockchain solutions which will easily be adopted and integrated within supply chains. Building trust among these stakeholders shall be paramount for wide acceptance.

III. METHODOLOGY

The methodology used for this paper focuses on a comprehensive analysis of blockchain technology in addressing food security challenges within the global aquaculture sector. A thorough literature review, supported by a systematic collection of data from reliable academic databases and industry publications, served as the basis for the paper.

The data from these sources are published from 2019 onwards to guarantee that the most updated information is obtained to pinpoint recent developments in blockchain, IoT, and AI applications in aquaculture. The focus is on very recent studies to ensure that the latest developments and case studies are covered. However, foundational works published before 2019 are also referenced when applicable, as they provide theoretical foundation and historical context for the evolution of technology.

The number of papers used as a reference is at least 15 papers. The literature review studied focuses on identifying blockchain's application in aquaculture, including supply chain transparency and traceability, fraud prevention, and reducing inefficiencies in food distribution. By identifying challenges and chances to formulate a solution in implementing blockchain technology in the aquaculture industry, recommendations are made thoroughly to fulfill this criterion.

There were still some possible biases and limitations to note in the paper themselves, despite the system analysis. Most of these are regionally or contextually based case studies that could inhibit, to some degree, the generalizability of findings across aquaculture contexts worldwide. This study considered the geographical and contextual nature of each paper under review for area trends that could be applied to larger regions. However, it acknowledges that the unique challenges and infrastructural constraints in small-scale settings or underdeveloped regions of aquaculture require further exploration and tailored solutions.

Methodologically, reliance on secondary data brings potential limitations in the accuracy and completeness of the original studies. This analysis, therefore, prioritizes papers with robust methodologies, such as empirical research and systematic reviews, while highlighting gaps in areas where the data is sparse or inconsistent.

The study aims to address these considerations by providing research relevant to a wide range of aquaculture stakeholders, while also identifying areas where further research is needed to enhance regional applications.

IV. RESULTS AND DISCUSSION

A. Key Benefits of Blockchain Technology

As blockchain technology promises efficiency, transparency, and traceability globally, its application in food security has grown recently. This is because consumers will be able to learn where their food comes from thanks to this technology. The use of blockchain has huge potential to improve food security, particularly at a time when aquaculture is expected to remain the primary source of protein. It has the potential to change the way aquaculture meets global food demands by resolving issues with traceability, sustainability, and efficiency.

One of the major benefits of blockchain technology in aquaculture is increased traceability of the products throughout the value chain. Stakeholders can track the origins of fish products from wherever they came to their plates thanks to blockchain's decentralized and unchangeable record. This is very important in ensuring the safety of food since sources of contamination can be identified quickly, thus helping increase consumer confidence in what they consume. [27]. For example, blockchain technology can be used to guarantee that fish and seafood are sourced responsibly and that their origins are transparent in areas where aquaculture plays a major role in local economies [28] will help to ease consumer concerns about overfishing and environmental degradation [29]. In recent years, blockchain technology has picked up tremendous momentum in its application to food security because of the promise it holds for efficiency, transparency, and traceability across the world. This is because, with the technology, consumers would finally be able to trace where their foods come from. According to the study made by T. Asha Vijay and M. S. Raju, research indicates that approximately 20% of the global seafood industry is involved in mislabelling practices [30]. Food security could possibly be greatly enhanced through the integration of blockchain, at least at a time when aquaculture was expected to remain the leading source of protein. It has the potential to change how aquaculture contributes to global food security by trying to solve the problems of efficiency, sustainability, and traceability [31], [32]. This ability lowers financial costs related to food recalls and waste while also boosting consumer confidence [33]. It is evident that apart from lesser-known industries like trade finance and convertible bonds, blockchain technology can also enhance more common activities such as stock trading and international payments. Today, blockchain is gaining significant attention from countries, and the environment is well-suited for its growth and adoption [34]. Aquaculture producers can improve their sustainability practices and lessen their ecological imprint by using blockchain to track ratios of feed conversion and health factors, which will help ensure global ability to adjust to climatic shifts and fluctuations in the market [39], [40].

Furthermore, there is a possibility that blockchain technology will enhance the efficiency of logistics and reduce administrative obstacles in aquaculture. Durach et al. add that blockchain could help in enhancing the processes of delivery by making the process transparent, where all stakeholders will have real-time information on shipments, which would encourage mutual trust and accountability [41]. Through a source of truth that is tamper-proof, blockchain will simplify all documentation processes and improve communication amongst stakeholders from farmers to merchants [42]. Consumer will benefit from premium seafood at competitive pricing as a result of the resulting efficiencies, which will reduce costs and enhance service delivery [43].

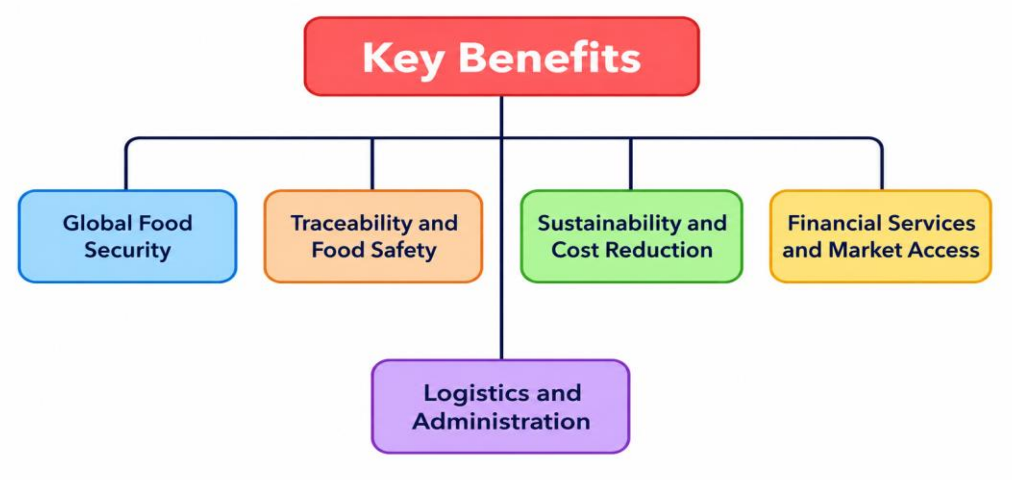

Fig. 2 Key Benefits of Blockchain Technology

food security [35]. For instance, due to the significant scale if illegal, unreported, and unregulated fishing activities, the European Commission issued a yellow card to Thailand a few years ago, temporarily halting all fish imports from the country. Implementing an end-to-end supply chain system for seafood tracking and tracing, enabled by AI and blockchain technology, holds the potential to modernize the industry and boost export opportunities [36].

Apart from improving production, there might also be other beneficial ways where blockchain technology can be used to facilitate financial services and market accessibility. Farmers who document their catching processes well and the good qualities of the seafood grown with excellent service would win consumers' trust for much higher prices [37]. This is particularly true in underdeveloped countries where small-scale aquaculture plays a significant role in local food systems and revenues [38]. Furthermore, blockchain can facilitate aquaculture farmers' access to insurance and financial solutions that meet their demands, improving their

Figure 2 summarizes some of the key benefits that can be achieved by using the blockchain technology in aquaculture, including improved global food security, enhanced traceability and food safety, increased sustainability and cost reduction, provided better financial services and market access, and optimised logistics and administration.

B. Implementation Challenges and Recommendations

Although blockchain technology has the potential to improve global food security and sustainability in global aquaculture, its application in underdeveloped countries and in traditional supply chains face significant obstacles.

One of major challenges is technological barriers. This is because the complexity of blockchain technology and the lack of understanding among stakeholders are significant hurdles. Many supply chains lack the necessary infrastructure and technical expertise to implement blockchain effectively, which is particularly pronounced in underdeveloped regions [44], [45], [46]. Despite its potential, the technology used is still in its early stages, and there is a need for further research and development to address this barrier [47], [48]. Enhancing data management by investigating methods to improve data asymmetry and management within blockchain systems to ensure seamless integration across the supply chain can help solving this [49], [50]. Future research should prioritize developing standardized data structures to enable blockchain implementation in aquaculture supply chains. This approach will help resolve data asymmetry issues and support real-time interventions aimed at achieving the Sustainable Development Goals (SDGs) [49], [51]. Future implementations could involve using smart contracts to automate and manage transactions within the aquaculture supply chain. This would enhance efficiency, reliability, and security while eliminating the need for intermediaries [52], [53].

Additionally, unfavourable institutional environments and the lack of supportive policies and standards hinder the adoption of blockchain technology. This challenge is particularly significant in developing countries, where regulatory frameworks do not accommodate such technological advancements [45], [46], [48]. Working with policymakers to establish regulations that support the adoption of blockchain in aquaculture, while addressing critical concerns such as data privacy and security, can help resolve this issue [48], [51]. Other suggestion is by working towards creating standardized protocols and guidelines for blockchain implementation to ensure consistency and interoperability across different regions and sectors [54], [55]. To successfully implement blockchain technology in global aquaculture, it is crucial to involve all stakeholders actively. This involves engaging aquaculture companies, retailers, and consumers to ensure they understand the benefits and are motivated to support the implementation of blockchain systems [12], [42].

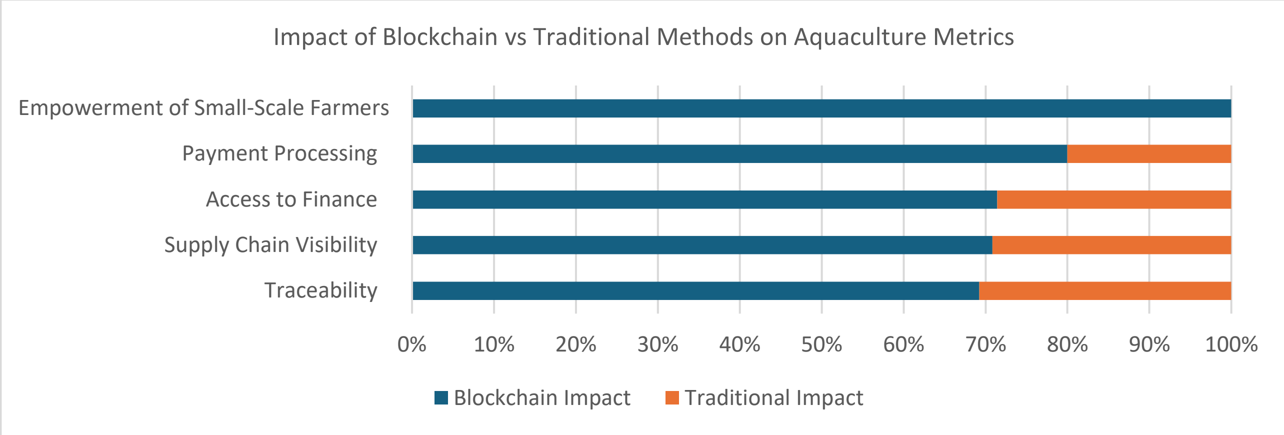

Fig. 3 Impact of Blockchain vs Traditional Methods on Aquaculture Metrics

Furthermore, countries with limited financial resources face challenges due to the high costs and resource demands associated with implementing blockchain technology, including setup and maintenance [45]. The implementation of a sustainable supply chain using blockchain technology is further complicated by the absence of well-defined business models and best practices for adopting this system [56]. To address this, conduct detailed cost-benefit analyses to assess the financial implications of blockchain adoption and uncover potential cost-saving opportunities. Seek and secure funding from governmental and non-governmental organizations to support blockchain projects in aquaculture, emphasizing long-term sustainability and scalability [51], [53]. Explore strategies to optimize resource allocation in blockchain projects, ensuring that investments are focused on areas with the greatest potential to enhance food security and promote sustainability [49], [57].

Blockchain technology can only be effective in aquaculture finance if it is integrated with existing digital systems. Achieving this requires a significant move toward digitalization within the industry, which may become a critical prerequisite for the successful operation of blockchain [58]. According to [20], IUU fishing accounts for 20 percent of the global catch, with this figure reaching up to 50 percent in certain regions. The sector often relies on bonded labour, destructive fishing practices, and fraudulent methods to generate income, all while harming local fisheries, coastal states, and marine ecosystems.

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Recognized as a major global issue, IUU fishing is estimated to involve one-fifth of all wild-caught fish, translating to economic losses of $10 billion to $23.5 billion annually. Creating a detailed implementation roadmap that encompasses concept development, compliance, and optimization is crucial for addressing this issue effectively [42]. Designing pilot projects and prototypes can help evaluate the feasibility and efficiency of blockchain technology in aquaculture. These initiatives provide valuable insights into the practical challenges and advantages of implementing blockchain, paving the way for further refinements and optimizations [42]. Offer education and training programs to help stakeholders understand the benefits and workings of blockchain technology, promoting a culture of innovation and adaptability [48], [53].

C. Comparison between Blockchain Technology with Alternative Technologies

Blockchain technology is gaining widespread recognition for its ability to enhance transparency, traceability, and trust within supply chains, particularly in the aquaculture and agri-food sectors. Its core features, such as immutability, auditability, and provenance, work together to promote transparency and minimize the risk of fraudulent practices [48], [57], [59]. The decentralized nature of blockchain ensures that no single authority can modify the data, making it a reliable and robust solution for maintaining trustworthy records [55]. In aquaculture, blockchain technology can strengthen the relationship between producers, retailers, and consumers by ensuring transparency, credibility, and fairness in transactions [12].

Several alternative technologies are available for use in aquaculture. One of the most common is traditional databases, which are often employed for record-keeping in supply chains. However, these databases lack the inherent trustworthiness of blockchain, as they are vulnerable to tampering and rely on a central authority for data management and verification [58]. Figure 3 illustrating the impact of blockchain technology with traditional methods on different aquaculture metrics, like the empowerment of small-scale farmers, payment processing, access to finance, supply chain visibility, and traceability. While these alternatives can be effective in digitalized environments, they do not inherently offer the same level of transparency and traceability as blockchain. Additionally, while digitalizing supply chains can significantly enhance efficiency and data management, it does not inherently ensure data integrity or prevent fraud—two critical advantages provided by blockchain technology [58]. IoT devices play a vital role in aquaculture by enhancing data collection and monitoring, offering real-time insights into environmental conditions and fish health. However, IoT alone cannot address data integrity and trust issues. Blockchain complements IoT by securely recording data in an immutable ledger, ensuring reliability and transparency [60]. AI can significantly optimize aquaculture operations by forecasting trends and automating various processes. However, while it enhances efficiency, AI alone does not address the critical issues of data transparency and traceability, which are essential for building consumer trust and ensuring regulatory compliance [60].

Blockchain technology is ideally suited to addressing the challenges of transparency, traceability, and trust within aquaculture and agri-food supply chains. Its design guarantees secure, immutable records of transactions, making it superior to traditional databases and other technologies that lack these built-in features. While digitalization and IoT enhance data collection and operational efficiency, blockchain stands out by uniquely ensuring data integrity and credibility—critical for building consumer trust and achieving sustainability objectives [49], [57], [51].

In conclusion, while other technologies provide certain advantages, blockchain's distinctive features of immutability and decentralized trust make it an excellent choice for improving transparency and traceability in global aquaculture and food supply chains.

V. CONCLUSION

The food security of the world is dependent on the farming and aquaculture industry as two of its main pillars. Yet, they struggle to deliver transparency, sustainability, and operational efficiency. In this paper, we investigated the use of disruptive digital technologies in aquaculture, like blockchains, IoT, and AI, which could pave the way for transformation in aquaculture practice. All of this was possible over mainstream technologies with ease and should be enough to universally improve supply chains crippled with differentiation, piracy, management or environment driven issues.

Blockchain provides a decentralized and tamper-proof ledger system that can greatly enhance traceability and transparency in the aquaculture supply chain [15]. Blockchain offers security in the supply chain through the validation and verification of data when combined with Internet of Things (IoT) devices that monitor conditions like fish health, water quality and feeding schedules [61]. This integrated approach has direct implications for combatting illegal, unreported and unregulated (IUU) fishing, enhancing consumer confidence, and addressing the increasing demand for sustainably produced and safe seafood.

Global case studies, including blockchain-supported shrimp and tuna tracking initiatives, demonstrate how these technologies can help remedy problems of environmental degradation and supply chain opacity [62]. An example can be found in countries such as China — a world leader in the aquaculture sector — which offers you insights into how blockchain and IoT are revolutionizing operations and creating new standards in sustainability and in providing innovative practices. Among China's measures are the establishment of blockchain-based systems for end-to-end traceability in shrimp, tuna, and other seafood [25]. Such systems help verify product information by generating unalterable records at all points in the supply chain. The use of IoT-enabled devices like water quality sensors and a feeding monitor generates real-time data about aquaculture operations and keeping the water environment in check to ensure maximum efficiency and minimal waste [63], [64], [65]. However, most of these systems are still witching optimization, as they have not yet finished several aquaculture cycles to reach full operational maturity. While difficult, China's leadership in the uptake of digital aquaculture technology shows that these innovations can be scaled — a model from which other countries wishing to modernise their aquaculture sector can learn. Great way to phrase it: China's pro-active fisheries supply chain engagement is helping not just with the transparency and efficiency in the aquaculture supply chain, but also the consumers trust in sustainably sourced seafood [66]. But with the world's hunger for seafood ever on the rise, China's ambitions are a blueprint for how to use advanced technologies to help solve systemic problems across an industry. China's holistic approach to the digital transformation of aquaculture, focusing on collaboration and standardized protocols, will ultimately transform the industry for the better.

There are still significant obstacles ahead, though. Another barrier identified is high implementation costs, lack of standardized protocols, and fragmented strategies around food systems that make widespread adoption difficult [67]. Moreover, there are still challenges in both harmonizing interests among stakeholders and adapting technologies to different industrial and regional activities. However, the strides we've made thus far point to a bright future.

To solve these challenges now and in the future we need to take action on multiple fronts. To achieve this, standardized protocols and interoperable systems for data exchange and integration can be developed, promoted, and adopted along the aquaculture value chain. It is essential to invest in research and development to decrease the high prices to implement and make these technologies more simpler to use. Encouraging cooperation and dissemination of information among various stakeholders (governments, industry players, and academia) is key to the successful implementation and scaling of these technologies.

Adoption of these innovations will be critical in bringing the aquaculture industry towards greater sustainability, efficiency, and transparency. This has direct links to several United Nations Sustainable Development Goals (SDGs) — SDG 2: Zero Hunger; SDG 12: Responsible Consumption and Production; and SDG 14: Life Below Water. Digitizing the aquaculture industry will secure the food source for the future and protect the ocean whilst securing sustainable food sources for generations to come [6].

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Conflict of Interest

The authors declare that there is no conflict of interest

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