Volume 5 July 2025 Number 2

halalsphere

International Islamic University Malaysia

https://journals.iium.edu.my/

E-ISSN: 2773-6040

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Published by

IIUM Press

IIUM Press
International Islamic University Malaysia
Jalan Gombak, 53100 Kuala Lumpur, Malaysia
Phone: (+603) 6421 5014, Fax: (+603) 6421 6298

E ISSN 2773 6040

HALALSPHERE
E-ISSN: 2773 6040

HALALSPHERE
Volume 5, Issue 2, July 2025
https://doi.org/10.31436/hs.v5i2

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HALALSPHERE
International Islamic University Malaysia - INHART

Detection of *Rusa spp.* DNA in ready-to-eat food (RTF) using singleplex of Polymerase Chain Reaction

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Received:18/11/2024
Accepted: 30/6/2025
Published:31/7/2025

Keywords:
Deer, COI 1 gene, Polymerase Chain Reaction (PCR), CerV gene

Abstract

Deer meat is more expensive than meat from domesticated animals, making it a possible target for adulteration. As a result, a practical approach for detecting deer DNA was developed by employing a Polymerase Chain Reaction (PCR) assay to target a region of the mitochondrial Cytochrome Oxidase Subunit I (COI) gene in locally ready-to-eat food (RTE) products. A specificity trial was performed on eight deer-based RTF to include *Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa,* and *Rendang Tok Rusa* food matrices (to include the four commercially processed RTE food products) and deer DNA was detected from four commercial RTE products (*Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa* and *Rendang Tok Rusa*) with the CerV primers at 0.0001 ng/µL detection limit, showing that both the primers and the assays were effective at detecting DNA targets in thermally treated matrices. This assay addresses critical gaps in halal certification and food fraud prevention, offering a reliable tool for regulatory enforcement and consumer protection in Malaysia's growing RTE market. The CerV gene detection limit was 0.0001 ng of CRM, consistent with the Certified Reference Material (CRM) used in this investigation (Red Deer). As a result of the present investigation, it is clear that PCR targeting the CerV COI 1 gene is appropriate for identifying deer DNA in RTE food samples.

1. Introduction

Consumers' eating habits and lifestyles have changed in this modern era of globalisation. Fast, ready-to-eat and frozen food are in high demand from consumers in this millennium because they are convenient. The significant changes in the processed food industry in recent years have improved knowledge of food composition and its effects on consumer health (Siro *et al.*, 2008). The food industry's continual development, which includes processing methods such as marinating, canning, or cooking, as well as the production of ready-to-eat meals, helps prevent food items from being destroyed, driving the increase in processed meat production. Consumers worldwide are now more aware of the ingredients in the food they consume, largely due to innovations in the meat production industry, which has led to increased demand for clear and accurate information labels on food products (Sentandreu & Sentandreu, 2014).

Modern methods of meat processing, such as marination, canning, and mechanical tenderisation, can mask the morphological and organoleptic properties of meat, making visual verification impossible (Flores-Munguia *et al.*, 2000). For example, a 2023 audit and report by the Malaysian Department of Islamic Development (JAKIM) stated that 15% of the 'halal-certified' meat products had species that were not reported, indicating an urgent need for DNA-based verification (JAKIM, 2023). Deer meat is sold in Malaysia for 3–5 times the price of beef and can, therefore, be highly susceptible to adulteration with cheaper meats, such as pork or buffalo. This puts consumers at risk of noncompliance regarding religious rules and health issues. All of this has led to an increase in food fraud. In situations of processed meat food fraud, the risks to customers might range from using lower-quality components to intentionally mislabeling goods. While regulatory bodies, food producers, and consumers expect high-quality control, it is critical that consumers demand greater quality control measures to avoid such fraudulent practices and protect themselves. Additionally, there is an insufficient analysis of meat authenticity, resulting in the incidence of illicit meat and unknown species in food (Bottato *et al.*, 2014).

A range of meat products, including meats, minced meats, dried meats, and pet foods, were found to have between 20% and 70% of their labels misread (Cawthorn *et al.*, 2013; Okuma & Hellberg, 2015; Quinto *et al.*, 2015). Food fraud occasionally occurs in processed meat, which has a significant impact on public health and the Malaysian economy. Customers who have meat allergies may be put in danger if there are hidden ingredients in their food. For instance, a study by Masiri *et al.* (2016) found that undeclared pork residues in beef products increased the risk of pathogen infection. Due to the impact on consumer confidence, this issue has made it difficult for the beef industry to access new

markets (Zhao *et al*., 2014).

Additionally, improper meat product labelling results in the illegal sale of endangered, protected species like deer and thwarts efforts to conserve these animal species. Therefore, commercial food products must not raise health concerns for consumers to comply with national and international food rules (Ballin, 2010). Food manufacturers are prohibited from making claims about the composition, quality, origin, or processing of food products that are intentionally false or deceptive, as food products must also be legitimate. On the other hand, food adulteration has become an international issue. According to studies, meat products are frequently tampered with (Premanandh *et al*., 2013; Fajardo *et al*., 2010).

In general, DNA identification techniques have changed and revolutionised methods used for the conservation of deer populations around the world. This knowledge is valuable when formulating management approaches to protect threatened or endangered species. One of the famous techniques in molecular biology is named PCR (polymerase chain reaction), which involves the amplification of a target DNA sequence.

Now, beyond the forensic context, PCR methods for identifying deer DNA are fundamental to deer conservation efforts. These methods help researchers understand how deer populations change, where deer genetic diversity is located, and how well conservation strategies are effective. This makes PCR very accurate for identifying deer species within populations, which provides researchers with information about where deer populations are, how many there are, and how variable their genetic makeup is. In addition, these methods may be useful for identifying hybridisation between deer species and detecting threats to the genetic integrity of these species.

This method enables researchers to explore and analyse genetic diversity and structure within deer populations. The amplification process through PCR is essential for accurately identifying deer DNA. A notable variant of this technique is qPCR, or quantitative polymerase chain reaction, which offers several advantages over conventional light microscopy methods for identifying deer DNA. PCR has sensitivity, rapidity and a good chance for future automation (McLennan *et al*., 2021). Researchers can use PCR to get high specificity for the amplification of only the DNA of the species they want to study. Importantly, PCR provides a method for quantifying deer DNA, which enables the monitoring of gene flow in deer as well as changes in the genetics of deer populations. qPCR has such high sensitivity that it can detect small amounts of deer DNA.

This method enables the simultaneous amplification of multiple DNA targets, making it a suitable approach for identifying deer species. In Gaur's (2016) study, PCR amplification of eight deer-species microsatellite loci was utilised to identify different deer DNA samples. There are loci associated with deer, which help differentiate between deer species. Appropriate deer-specific primers for PCR are critical to obtaining reliably identified deer DNA. Applying CR assays from species that have been validated provides essential support for DNA samples identified as deer in a forensic capacity for poaching. Furthermore, these validated PCR methodologies can significantly contribute to conservation initiatives by facilitating the monitoring of deer populations.

The development of methods for identifying species from unidentified sources has advanced significantly due to the government of Malaysia's enforcement of biosecurity and food regulations (Armstrong & Ball, 2005; Fajardo *et al*., 2010; Bottero & Dalmasso, 2011; Ali *et al*., 2014). Such methods include quantitative PCR (qPCR), Real-Time PCR, multiplex PCR, and restriction fragment length polymorphism (RFLP) based on PCR. In order to identify animal species from various types of matrices, such as faeces, feathers, hair, saliva, skin, and urine, molecular approaches have been confirmed and well-established (Dalén *et al*., 2004; Waits, 2009).

Molecular techniques have been developed rely on the use of a common target region in mitochondrial DNA (Cytochrome Oxidase Subunit 1) with unique primers, resulting in amplicons of varying sizes in the Cervidae family (Dalén *et al*., 2004), which the primers are designed and positing well and easily discernible on agarose gels (Bottero & Dalmasso, 2011). Because mitochondrial DNA gene sequence data sets were publicly available for the target animal species (Janke *et a*l., 2002; Hassanin *et al*., 2012; Meiri *et al*., 2013; Martins *et al*., 2017), this study focused on using markers within the mitochondrial Cytochrome Oxidase Subunit I (COI). Furthermore, a specialised DNA amplification using a particular genetic marker target can assist in unambiguous identification and animal species classification based on mitochondrial cytochrome oxidase subunit I (COI). This marker has been widely adopted for DNA barcoding initiatives, where it is used for rapid and conclusive species identification. Moreover, analyses of COI I sequences can provide information on the evolutionary relationship and biodiversity of animal populations.

COI I sequences were used to accurately identify and authenticate the presence of the Rusa species in the RTF food items in this study. This method provided a reliable and effective means of ensuring that labelled products will be good and genuine. Therefore, singleplex PCR that can generate, dissociate and validate the genetic markers of the mitochondrial Cytochrome Oxidase Subunit I, as well as the commercially available CerV oligonucleotide primers, were used to detect and amplify the genetic markers of mitochondrial Cytochrome Oxidase Subunit I and Rusa spp in the Rusa labelled Ready-To-Eat (RTF) foods in Malaysia. Although PCR-based methods are available for detecting deer DNA (Druml *et al*., 2014), it is worth noting that most assays are limited to examining fresh or frozen meat. This research significantly advances the understanding of a single-plex PCR for the food matrix of processed ready-to-eat (RTE) foods, a food matrix recognised as problematic due to thermal treatment leading to DNA fragmentation (Martins *et al*., 2017).

2. Materials and methods

2.1 Sampling

Four samples that were marketed as being made from *Rusa spp*. (*Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa,* and *Rendang Tok Rusa*) and one RTF made without deer meat (*Daging Lembu masak Cili Padi*) was tested. Following the manufacturer's instructions, 10 g of RTF samples were extracted using the Epicentre MasterPure™ DNA purification kit. During the RTF extraction process, blank and chicken flesh were also included, with these two indicators functioning as extraction and blank controls in the extraction method.

2.2 Extraction and amplification of the CerV gene

Genomic DNA was extracted in triplicate from 10 g homogenised samples of each RTE product (*Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa, Rendang Tok Rusa,* and control *Daging Lembu masak Cili Padi*) using the Epicentre MasterPure™ DNA Purification Kit (Catalogue No. MCD85201) following the manufacturer's protocol. Blank controls (n = 3) and chicken DNA spikes (n = 3, 50 ng/µL) were included to assess extraction efficiency. DNA concentration was quantified via NanoDrop™ 2000 spectrophotometer (Thermo Fisher), and purity was confirmed (A260/A280 ratio ≥1.8). Following that, the isolated DNA was submitted to PCR amplification. CerV primers (F-5'TCT TTA TGG GCT AAC AGC-3') and (R-5'-CTT GTT CCG TTG ATC AAT T-3') were used to amplify genomic DNA targeting deer mtDNA. A volume of 1 µL of 100 ng DNA, 12.5 µL of universal PCR master mix (MyTaqTM Red Mix), 8.5 µL of sterile distilled water, and 1 µL of 25 pM each of the forward and reverse primers were used in the test (Apical Scientific SDN BHD). Amplification was carried out in a Thermal Cycler BioTone (Analytical Jena, GmbH) using a temperature program that included an initial denaturation at 95°C for 1 minute, followed by 40 cycles of denaturation at 95°C for 30 seconds, annealing at 56°C for 30 seconds, and extension at 72°C for 1 minute. The amplified fragments were seen with a UV transilluminator after electrophoresis in 1.5 per cent (w/v) agarose 1X TBE (0.1 M Tris, 0.1 M Boric acid, 0.2 mM EDTA) at 120 V for 60 minutes (Alpha Imager TM2200).

2.3 Sensitivity studies of CerV oligonucleotide primers set

The detection limit of CerV oligonucleotide primers was investigated using Red Deer genomic DNA as Certified Reference Material (CRM). The PCR test conditions were identical to those described in PCR amplification using various oligonucleotide primers and concentrations of genomic DNA ranging from 0.0001 to 100 ng.

2.4 Reproducibility studies using the CerV gene in ready-to-eat foods (RTF) deer-based products

In the repeatability investigation, five varieties of RTF were used: *Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa, Rendang Tok Rusa,* and *Daging Lembu masak Cili Padi*. The Epicentre MasterPure™ DNA purification kit was used to extract all samples, and the extraction process workflow was followed according to the manufacturer's instructions. The concentration of genomic DNA recovered was then diluted to 50 ng. Following this, PCR analysis targeting the CerV genes was performed as described earlier.

2.5 Specificity studies of CerV oligonucleotide primers set

CerV specificity experiments have been undertaken using several types of animal DNA to ensure that the virus exclusively detects deer DNA. Five (5) distinct types of animal DNA were employed in the specificity investigations, including sheep, porcine, cattle, buffalo, chicken, and red deer. The PCR analyses were carried out on the five distinct animal DNA samples using the CerV gene, as described in the earlier subheading.

3. Results and discussion

For the specificity study on an agarose gel, the amplicon generated by PCR analysis revealed a band of 116 base pairs (Figure 1). Except for the Red Deer, which revealed a positive band, none of the other animal DNA genomics (goat, chicken, wheat, soya, porcine, lamb, duck, sheep, horse, beef, buffalo, mutton) were positive for the CerV gene. The CerV primer was shown to be specific for *Rusa spp*. DNA.

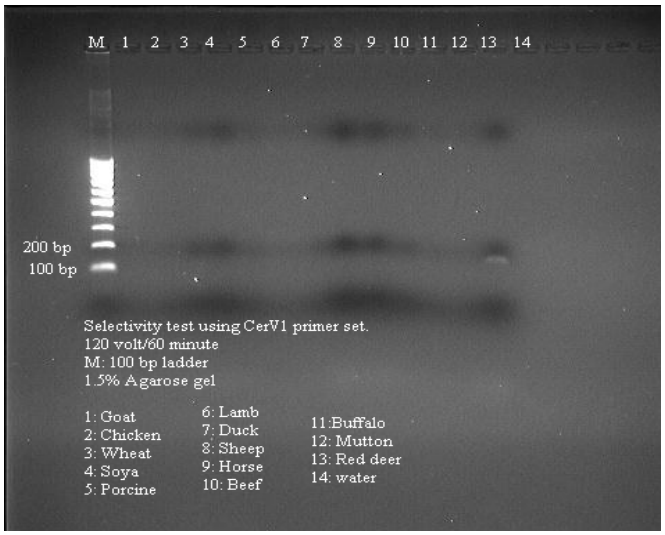

Figure 1: Specificity studies on *Rusa spp*. from genomic DNA of Red Deer. Lane M: 100 kb ladder; Lane 1: Goat DNA; Lane 2: Chicken DNA; Lane 3: Wheat DNA; Lane 4: Soya DNA; Lane 5: Porcine DNA; Lane 6: Lamb DNA; Lane 7: Duck DNA; Lane 8: Sheep DNA; Lane 9: Horse DNA; Lane 10: Beef DNA; Lane 11: Buffalo DNA; Lane 12: Mutton DNA; Lane 13: Red Deer DNA; Lane 14: Water.

The sensitivity of single-plex PCR was estimated using the target species' serially diluted DNAs (from 100 ng to 0.00001 ng per reaction). Detection limits were tested using Certified Reference Material of Red Deer DNA purchased from the manufacturer. For sensitivity, PCR analysis was used to determine the detection limit of the CerV gene using varied quantities of DNA from certified reference material, Red Deer. The lowest amounts of genomic DNA identified using the PCR test for the CerV gene were as low as 0.00001 ng/ µL (Figure 2). The high sensitivity of this assay led to the accurate and reliable detection and differentiation of meat from target deer species.

Rusa spp. DNA was detected among the four ready-to-eat foods (RTFs), which claimed to consist of deer meat (*Kerutup Rusa, Kari Tulang Rusa, Kurma Rusa, Rendang Tok Rusa*), though band eight (8) shows a smearing effect, which might be due to high DNA content (Figure 3). The following findings were obtained using a consistent forward primer/reverse primer concentration ratio (25 pmol: 25 pmol). During the experiments, no cross-reactivity with other animal species was observed. The CerV primers in this experiment could detect the genus *Rusa* genes in the RTF products. Similar findings were also reported by Khatun *et al.* (2021), who detected buffalo and chicken DNA in beef-labelled products and found buffalo DNA in cheese samples, despite the cheese being declared as bovine cheese.

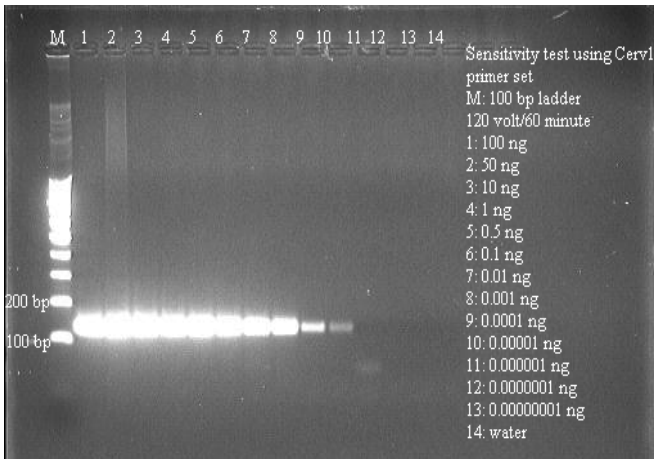

Figure 2: Detection limit of CerV gene from genomic DNA of DNA of Red Deer). Lane M: 100 kb ladder; Lane 1: 100 ng; Lane 2: 50 ng; Lane 3: 10 ng; Lane 4: 1 ng; Lane 5: 0.5 ng; Lane 6: 0.1 ng; Lane 7: 0.01 ng; Lane 8: 0.001 ng; Lane 9: 0.0001 ng; and Lane 10: 0.00001 ng; Lane 11: 0.000001 ng; Lane 12: 0.0000001 ng; Lane 13: 0.00000001 ng; Lane 14: Water.

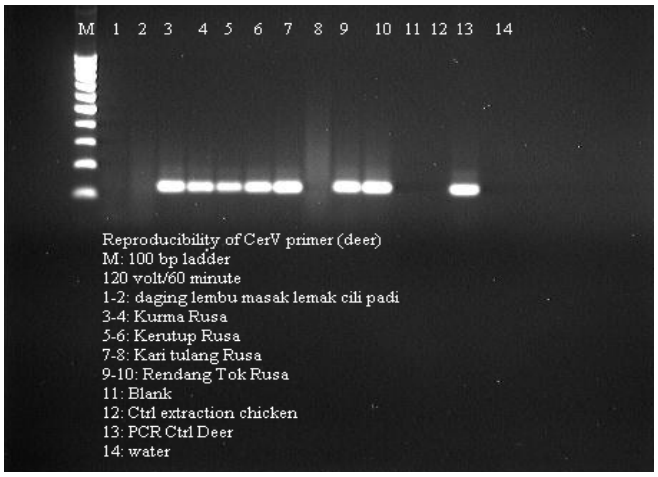

Figure 3: Detection of CerV gene in various types of ready-to-eat foods (RTFs) samples. Lane M: 100 kb ladder; Lane 1-2: *Daging Lembu masak Lemak Cili Padi*; Lane 3-4: *Kurma Rusa*, Lane 5-6: *Kerutup Rusa*; Lane 7-8: *Kari Tulang Rusa*; Lane 9-10: *Rendang Tok Rusa*; Lane 11: Blank; Lane 12: Control Extraction Chicken; Lane 13: PCR Control Deer; Lane 14: Water.

Therefore, DNA-based approaches play a crucial role in meat authenticity and may be used to detect deer meat adulteration in RTF products. Furthermore, by direct identification of *Cervus* spp. targeting particular primers in meat products, meat producers and restaurant owners could authenticate and sell their products with high confidence to the consumers (Druml *et al*., 2014; Kaltenbrunner *et al*., 2018). This current study shows that PCR analysis using CerV primer is a quick, easy, and reliable technique for detecting *Rusa spp*. DNA in food products.

As mentioned in the specificity study, the CerV primer amplified only DNA from *Rusa spp*. The PCR analysis, shown in agarose gel electrophoresis, yielded a band of 116 base pairs for the Red Deer DNA sample, confirming a positive result. In contrast, the other animal DNA genomic samples (goat, chicken, wheat, soya, porcine, lamb, duck, sheep, horse, beef, buffalo, and mutton) are negative. The results are highly specific, indicating that the assay has the capacity to clearly distinguish between deer DNA and that of any other related species. This may prove efficient in determining Rusa spp. in different food samples.

The CerV assay established a LOD (limit of detection) at 0.00001 ng/µL (Figure 2), exceeding sensitivity from previous deer-specific assays (Kaltenbrunner *et al*., 2018: LOD 0.001 ng/µL). This ultra-low LOD should provide assurance within manufactured processed foods, in which reliability can vary due to DNA degradation processes, which can reduce template availability by 90–95% (Gharst *et al*., 2013). Additionally, no cross-reactivity was observed when tested against porcine DNA (Lane 5), which is an important consideration when producing products sold in halal markets (countries with a Muslim majority).

As noted, the assay produced near-perfect sensitivity. However, a smear was noted with *Rendang Tok Rusa* (Figure 3), which could be caused by PCR inhibitors within the spices, such as turmeric, or excessive DNA loading. Future studies may want to consider utilising inhibitor-resistant polymerases or DNA clean-up techniques prior to PCR (Quinto *et al*., 2015). This high sensitivity concurs with findings suggesting that the PCR assay is capable of detecting the presence of deer DNA in very small amounts, making it useful in detecting *Rusa spp*. in ready-to-eat processed food products. This confirmed our belief that the CerV detection limit for the study was valid, as demonstrated by the CRM used, which had a detection limit of 0.0001 ng. The sensitivity and specificity of the assay to quantify deer DNA in a range of food commodities, including at such low amounts, provide confidence in detecting *Rusa spp*. in ready-to-eat products.

The reproducibility study in the current research reveals a significant function of a self-designed primer in accurately amplifying the CerV gene. This way, the authors also guaranteed that the primers provided reproducible and species-specific amplification of *Rusa spp*. DNA in any ready-to-eat food samples they would want to test. These obtained values indicate similar conditions to those of other analysed samples, suggesting that the used primers are valid and can detect deer DNA without interference from other animal species (Dalén *et al*., 2004). Additionally, the reproducibility study ensures that quantitative diagnoses can be made beyond the research setting through applications such as food analysis and forensic science, thereby refuting any argument that may be made against the specific and sensitive design of the primer. The possibility of obtaining a good agreement between the two methods reasserts the value of developed PCR assays for successfully identifying and estimating deer DNA in processed food textures (Grattarola *et al*., 2014). Together, these studies provide relatively robust experimental evidence that supports the notion that reproducibility is a critical step in the development of PCR assays, whether for food safety, forensics, or genetic conservation.

The developed assay showed that cytochrome subunit 1 (COI 1) can be used to identify deer species based on their DNA. Several studies have used COI to identify deer species and are also able to distinguish between different subspecies of deer, such as the Sika deer (*Cervus nippon*) and the Japanese deer (*Cervus nipplon centralis*) (Galimberti *et al*., 2012). Fonseca and Friend (2015) also used COI sequencing in their study to

identify the species of deer found in Portuguese markets and distinguish between different subspecies of red deer.

In conclusion, the single-plex PCR assay designed in this study effectively detects deer DNA from a range of food matrices. The results of this study also support the generalisation that COI can be used to identify deer in various types of food samples and can be useful in deer conservation and management. The developed PCR assay was equally efficient and precise in terms of recovery rate, especially for samples that had been subjected to thermal treatment, such as ready-to-eat food items. The outcomes of the study include the development of a deer-specific PCR assay optimisation that has an LOD of 0.0001 ng/µL. Additionally, the study validates the proposed assay and its suitability for identifying and measuring deer DNA in RTE foods.

The study concludes that the newly developed single-plex PCR assay for detecting deer DNA in different food matrices is effective, efficient, sensitive and specific. The assay proved valid, as the limit of detection (LOD) was 0.0001 ng/µL, and effectively identified deer DNA in ready-to-eat food products offered to traders that had been thermally treated. The study suggests that the candidate gene COI may be useful for identifying deer species, which has a positive impact on food chain traceability, providing reassurance to consumers and supporting wildlife management for the deer species. Furthermore, the validated PCR methodologies also aid in combating food misbranding and adulteration, particularly in forensic applications related to the issue of poaching (Grattarola *et al.*, 2014).

These PCR assays are useful in detecting deer DNA in ready-to-eat foods, which provides information about the composition of such foods. Therefore, validated PCR methods are beneficial because they maintain the purity of food articles concerning these components, thereby avoiding food misrepresentation or adulteration. This is crucial for ensuring the stability of the food supply and maintaining consumers' trust, as well as developing measures to protect the food system. The literature analysed prompted crucial views on the viewpoints of PCR-based techniques for identifying deer DNA. Cervini *et al.* (2006) observe that microsatellites are essential in cattle genetics and can also be used for deer species.

The validation of PCR methodologies for identifying deer DNA represents a crucial field of study with substantial ramifications for both forensic investigations and conservation efforts (Gharst *et al.*, 2013; Cervini *et al.*, 2006). It provides food safety professionals with a reliable method for identifying potential instances of contamination, thereby helping them meet FDA regulations. Furthermore, the contribution of this method can increase traceability across the food supply chains, making it easier to respond to contamination cases. The combined application of this approach with existing food safety measures may help improve consumer confidence and reduce economic losses related to foodborne illnesses. However, renewed research efforts toward optimising the sing-lex PCR technique with regard to sensitivity and specificity will enhance its application enormously in the complex food matrix. Adopting single-plex PCR methods not only enhanced the understanding of food sources and increased food consumers' confidence, but also enhanced the systems used in identifying the level of pathogens in different food crops.

The assay presented in this study is based on a single gene, and the process was designed to minimise interference from other animal species. The assay's accuracy, working range and robustness were then identified in this study. The findings are consistent with those of several authors, including Kaltenbrunner *et al.* (2018), who have developed a real-time PCR assay to identify and quantify sika deer in meat products with efficiency and reliability, meeting the established parameters for accuracy. To this end, employing these molecular techniques enables regulatory bodies to identify contamination and pinpoint its origin through genetic fingerprinting, leading to the implementation of the aforementioned approaches. Moreover, due to the enhanced sensitisation to food pathogens, there is a need to understand the food labels used. Real-time PCR applications are best suited to address this issue, enabling consumers to verify the truth in claims regarding the species of meat involved or the presence of allergens in processed foodstuffs. Thus, the progress towards increased accountability may lead to increased stringency of rules and norms within the industry, a healthy focus on food safety, and proper encouragement of innovation.

4. Conclusion

Overall, the study demonstrates that the developed singleplex PCR assay is easy to use, efficient, sensitive, and specific for detecting *Rusa spp.* DNA in a variety of food matrices with a limit of detection (LOD) of 0.0001 ng/µL. This assay may serve as a valuable method for monitoring food fraud in food products containing deer meat. This PCR assay is helpful in verifying food authenticity, such as detecting mislabeling and adulteration. The assay can also help trace the origin of deer meat in food products, thereby maintaining transparency in the food supply chain. The developed PCR assay is a promising tool for regulatory agencies and food manufacturers to enforce labelling regulations and assure consumer trust due to its high sensitivity and specificity. In conclusion, the PCR assay offers a reliable method for detecting deer meat in a wide range of food products, thereby enhancing consumer trust and compliance within the food industry.

5. Acknowledgement

Special thanks to the deer breeder in Northern Malaysia for continuously supplying the deer meat sample.

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Evaluating PCR and ELISA for porcine detection in collagen-based products for halal authentication

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Received:8/7/2025
Accepted:24/7/2025
Published:31/7/2025

Keywords:
ELISA, PCR, Porcine, Halal authentication, Highly processed products, False negative

Abstract

Collagen is a widely used protein in various highly processed products across the food, cosmetic, pharmaceutical, and biomedical industries due to its versatility and unique properties. Its primary sources include pigs, cows, and marine animals, with industrial extraction typically performed from hides, bones, tendons, and skin. Given the importance of halal authentication, especially in Muslim-majority markets, a key challenge lies in reliably detecting porcine-derived collagen in highly processed products due to DNA degradation, protein denaturation, and matrix interference. These issues often result in detection failures and false negatives, underscoring the need for a comparative evaluation of available analytical methods. This study compares two analytical approaches for porcine detection: the DNA-based Polymerase Chain Reaction (PCR) and the protein-based Enzyme-Linked Immunosorbent Assay (ELISA). A total of nine collagen-based samples were analysed. PCR successfully detected porcine DNA in three samples, while ELISA detected porcine antigen in two samples, including one not detected by PCR. However, two porcine-labelled samples were missed, leading to a false negative rate of 66.7%. Four samples, specifically samples 5, 6, 8, and 9, resulted in an Overall Agreement Rate (OAR) of 44.4%. The combination of real-time PCR and ELISA offers complementary advantages. Real-time PCR is particularly effective for detecting low-level porcine DNA in undenatured type II collagen. At the same time, ELISA helps mitigate false negatives that may arise from DNA degradation or PCR inhibition caused by the presence of the collagen matrix. These findings suggest that integrating real-time PCR for detecting trace DNA in less processed matrices with ELISA for identifying degraded proteins in hydrolysed products enhances the overall reliability of porcine detection and strengthens halal authentication protocols across diverse product types.

1. Introduction

Detecting porcine contamination in processed collagen-based products is a significant challenge in halal authentication. As collagen undergoes extensive hydrolysis and thermal processing, its DNA may become highly fragmented and denatured, reducing the effectiveness of DNA-based detection methods like PCR (Othman *et al.*, 2023). Similarly, protein denaturation can limit the performance of immunoassays such as ELISA. This technical barrier poses a critical risk in halal compliance for processed foods, pharmaceuticals, and cosmetics (Nawwaruddin *et al.*, 2024). In Islam, halal (permissible) and *tayyib* (pure, wholesome) are essential principles derived from the *Qur'an,* which commands: "O people, eat from the earth what is *Halalan Tayyiban*" (*Qur'an* 2:168). *Halalan Tayyiban* not only denotes permissibility under *Shari'ah* law but also assures that the product is safe, clean, and beneficial for health (Hayat *et al.*, 2023). In Islamic jurisprudence, halal refers to that permitted under *Shari'ah* law, while *tayyib* implies that the product is lawful but also safe, clean, nutritious, and beneficial. According to Aghwan (2021), the *Halalan Tayyiban* concept encompasses products permissible under *Shari'ah* and free from elements harmful to health, reflecting the broader interpretation promoted by institutions such as the Halal Industry Development Corporation (HDC) Malaysia.

Food processing has become increasingly complex with the rapid advancement of science and technology. This complexity makes it more difficult to trace the origins of ingredients and increases the risk of unintentionally including non-halal substances (Jaswir & Guntarti, 2021). Highly processed foods (HPFs) have experienced rapid global growth, particularly in Asia, with the highest increase in sales from 2009 to 2019 observed in India, Pakistan, and Indonesia (Baker *et al.*, 2020). The HPFs, also known as ultra-processed foods, often consist of industrially reformulated mixtures containing ingredients from questionable or untraceable sources, such as additives, stabilisers, and emulsifiers (Shinozaki *et al.*, 2023). This complexity increases the difficulty in identifying specific components like collagen, which is frequently used in processed formulations and poses challenges for halal

authentication.

Collagen is widely used in food, cosmetic, and pharmaceutical products, but its sourcing from porcine materials presents a serious halal concern. While pig-derived collagen is cost-effective and structurally similar to human collagen, it is strictly prohibited in Islam. Ensuring collagen-based products are free from porcine derivatives is essential for halal compliance. While high-end analytical platforms such as Liquid Chromatography–Tandem Mass Spectrometry (LC-MS/MS) and Nuclear Magnetic Resonance (NMR) offer highly sensitive detection of animal-derived compounds, they are often costly and less accessible (Sani *et al.*, 2023). As such, molecular-based (e.g., PCR) and immunoassay-based (e.g., ELISA) techniques remain widely used for routine halal authentication due to their cost-effectiveness, specificity, and applicability to various matrices (Abdullah Sani *et al.*, 2021). However, the authentication process is complicated by the effects of hydrolysis, heating, and chemical treatment, which degrade DNA and denature proteins. DNA-based methods like PCR may fail due to fragmented or low-quality DNA (Muflihah *et al.*, 2023). Protein-based methods like ELISA can suffer from reduced antigenicity or matrix interference. These limitations highlight the need for a comparative evaluation of both methods to identify a more robust approach to detecting porcine residues in highly processed products. Identifying the animal origin of ingredients, such as collagen, is essential to ensure compliance with halal standards. Thus, Food authenticity is a critical issue that concerns consumers and industry stakeholders.

Polymerase Chain Reaction (PCR) is currently the most widely used DNA-based method for detecting species-specific genetic material in processed food products. Its sensitivity and specificity allow it to amplify even trace amounts of porcine DNA (Rosyid *et al.*, 2023). However, applying PCR to highly processed samples, such as collagen, may face challenges, including DNA degradation, low DNA yield, and inhibition caused by proteinaceous matrices (Chen *et al.*, 2025). These limitations may lead to false negatives or inconclusive results.

Protein-based detection methods, such as the Enzyme-Linked Immunosorbent Assay (ELISA), have been employed as complementary or alternative approaches to address these limitations. ELISA targets antigenic proteins and is highly specific and sensitive, even for heat-treated samples *(*Nhari *et al.*, 2019). Commercial ELISA kits, such as sandwich-type ELISAs, can detect porcine collagen proteins even after prolonged heating. Halal regulatory frameworks, such as the Malaysian Standard MS 1500:2019, the Manual Procedure for Malaysia Halal Certification (MPPHM) 2020, and the Malaysian Halal Management System (MHMS) 2020, emphasise the importance of ensuring products are free from non-halal ingredients, including porcine derivatives. In practice, both PCR and ELISA methods are widely used in halal testing laboratories and are recognised for their specificity and sensitivity in detecting animal-derived substances. However, the standards do not prescribe a definitive method for all matrices, which presents challenges when verifying highly processed products, such as collagen (Yörük, 2021). This gap underscores the importance of evaluating and optimising both methods for halal authentication.

While PCR is a widely used method for porcine detection due to its high sensitivity and specificity, its effectiveness significantly decreases in hydrolysed or extensively processed collagen due to DNA fragmentation and matrix inhibitors (Muflihah *et al.*, 2023). ELISA, which targets antigenic proteins, may offer complementary advantages in such cases (Liu *et al.*, 2024). However, a direct performance comparison between PCR and ELISA for porcine detection in highly processed collagen-based products remains limited, particularly in halal authentication.

This study aims to compare the efficacy of PCR and ELISA in detecting porcine content in highly processed collagen samples. Specifically, it assesses each method's ability to classify samples as porcine-positive or porcine-negative accurately and evaluates the false negative rate for both techniques. Real-time PCR offers advantages in low-level DNA detection, while ELISA may overcome false negatives caused by poor DNA extraction or PCR inhibition. Ultimately, the findings support the integration of both DNA- and protein-based methods to enhance the robustness and reliability of halal authentication in complex processed products.

2. Methodology

2.1 Materials and equipment

The materials used in this experiment consisted of nine highly processed collagen-based products, purchased from local retail stores in Malaysia—product categories included powdered supplements, jelly, gummies, cream masks, and liquid supplements. Information from product labels, including stated ingredients, collagen source, and halal certification status, was recorded to support sample classification and the interpretation of results. Also, chloroform, nuclease-free water, Milli-Q® water, and deionised distilled water were of analytical grade. A DNA Extraction Using In-House CTAB method, Porcine DNA RealTime PCR, Halkit II, and a commercial kit of ELISA Porcine Gelatine Detection Halkit were employed from Global Haltech Sdn. Bhd., Malaysia. Powdered porcine type I collagen (YO Proteins AB) and bovine type I collagen (Merck KGaA, Darmstadt, Germany) were purchased and employed as positive and negative controls, respectively.

The equipment utilised in this experiment included an analytical balance, vortex mixer, incubator, centrifuge, thermal cycler with Fluorescein Amidite (FAM) detection capability for real-time PCR (qPCR), and a microplate reader set to 450 nm for Enzyme-linked Immunosorbent Assay (ELISA) analysis.

2.2 Experimental design and data analysis

The experimental workflow is illustrated in Figure 1. Each of the nine collagen-based product samples underwent DNA- and protein-based analysis, following parallel workflows. A total of nine samples were purposively selected based on product diversity, including various forms (powder, cream, gummy, jelly, and liquid), different collagen sources (porcine, fish, marine, plant-based), and a mix of halal-certified and non-halal-certified products. This sample size was considered sufficient for an exploratory comparative study to observe trends in detection capability across different matrices and halal claims. In addition to the market samples, two reference materials were included: pure porcine collagen (positive control) and pure bovine collagen (negative control), both in powder form and obtained from certified suppliers. These were used as external validation controls in both qPCR and ELISA assays.

For DNA analysis, samples were subjected to CTAB-based

extraction followed by real-time PCR using a porcine-specific acetone and buffer extraction for ELISA-based detection of porcine antigens. Each test was performed in duplicate, and the results were compared to determine concordance and false-negative rates.

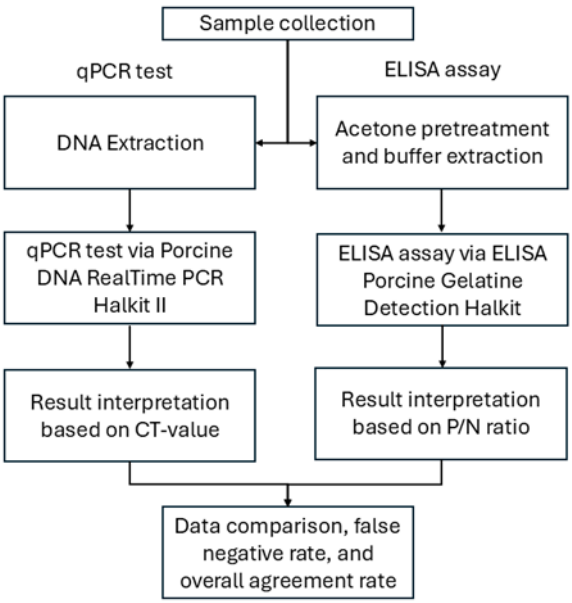

Figure 1: Overview of experimental workflow for porcine detection in highly processed collagen-based products.

Agreement between qPCR and ELISA results was assessed qualitatively based on matched positive/negative outcomes, and an overall agreement rate (%) was calculated across all nine samples.

2.3 DNA extraction

Before being subjected to the real-time PCR analysis, the samples must undergo the following extraction steps outlined in the Porcine DNA RealTime PCR Halkit II (Global Haltech Sdn. Bhd., 2021b)

2.3.1 Sample preparation and cell lysis

Samples were weighed for 1 g. Other than powder, solid samples were cut into smaller pieces and weighed to 1 g for each sample. A volume of 10 mL of Elution Buffer (EB) and 10 µL of Proteinase K were added to the sample. However, the liquid samples used 5 mL EB and 5 µL of Proteinase K. It was then vortexed to obtain a homogeneous solution. Next, the sample was incubated at 65°C for 1 hr in a shaking water bath to ensure thorough digestion. Then, it was centrifuged at 4000 x g for 20 mins. Then, 1000 µL of supernatant was transferred into a new 2 mL tube. Then, 1000 µL of chloroform was transferred, vortexed, and centrifuged for 15 min at 10,000 × g. The upper layer of the aqueous supernatant was subjected to DNA precipitation.

2.3.2 DNA precipitation

A volume of 1000 µL of the upper layer aqueous supernatant was transferred into a new 2 mL tube. A volume of 700 µL of Isopropanol (IPA) and 5µL of Glycogen were added and mixed by vortexing. The tubes were left at -20°C for an hour or more for precipitation. Lastly, the sample was centrifuged for 15 mins at 10,000 × g to precipitate the DNA. All the supernatant was probe. In parallel, the same samples were pretreated using then carefully discarded, without disturbing the pellet formed at the bottom of the tube. The pallet was subjected to DNA washing.

2.3.3 DNA washing

A volume of 700 µL of 75% ethanol was added to the pellet and mixed by vortexing. It was then centrifuged for 5 mins at 10000 x g. The supernatant was discarded without disturbing the pellet. This series of steps was performed twice. Afterwards, the tube with only the pellet was centrifuged again at 10000 x g for a minute. The remaining supernatant was carefully removed to eliminate residual waste. The tube was left at room temperature for 2 mins to dry the residual waste completely. The washed pellet was subjected to DNA elution.

2.3.4 DNA elution

100 µL of preheated Milli-Q water at 65°C was added directly to the DNA pellet and gently mixed to dissolve the pellet. The DNA sample was stored at -20°C before proceeding with the qPCR test.

2.3.5 Assessment of DNA purity

The purity of extracted DNA was assessed using the A260/A280 ratio, with average values ranging from 1.70 to 2.00, indicating acceptable purity for PCR amplification (Sani *et al.*, 2023).

2.4 Real-time polymerase chain reaction (qPCR)

Reagent preparation was done by spinning down all tubes in the Porcine DNA Real-Time PCR Halkit II (Global Haltech Sdn. Bhd., 2021b). For each DNA sample, a reaction mix was prepared using 10 µL of 2X qMastermix and 2 µL of 10X porcine-specific probe/primer mix provided in the kit, which targets a conserved region of the porcine mitochondrial genome. The remaining volume was completed with DNA template (≥ 50 ng) and nuclease-free PCR water, to a final reaction volume of 20 µL. Next, sample DNA templates were prepared for each of the samples. A volume of 10 µL containing at least 50 ng of DNA template was pipetted into each tube. For a negative control tube, 8 µL of nuclease-free PCR water was used. The final volume in each tube should be 20 µL. It was then spun down briefly to collect the reaction mix at the bottom of the tubes.

A TaqMan®-based probe was employed to target a conserved region of the porcine mitochondrial cytochrome b (cyt b) gene for species-specific identification due to its high copy number and interspecies variability. The primers and probe sequences were provided within the Porcine DNA Real-Time PCR Halkit II (Global Haltech Sdn. Bhd., Malaysia); however, the specific sequences are proprietary. Fluorescence detection was performed using the Fluorescein Amidite (FAM) channel.

A Real-time PCR (qPCR) test was performed according to the protocol outlined in Table 1. A standard curve was generated using serial dilutions of the positive control provided in the kit to validate assay efficiency and linearity. The qPCR machine determined the CT value. This calibration ensured consistent amplification performance and CT-value interpretation, as in Figure 2. Reaction efficiency was considered acceptable between 90% and 110%.

The results were presented and interpreted as described in Table 2. Each qPCR run included internal kit controls and was accompanied by a pure porcine collagen sample as an external positive control and a bovine collagen sample as an external negative control. These controls were used to verify method accuracy and the absence of cross-reactivity.

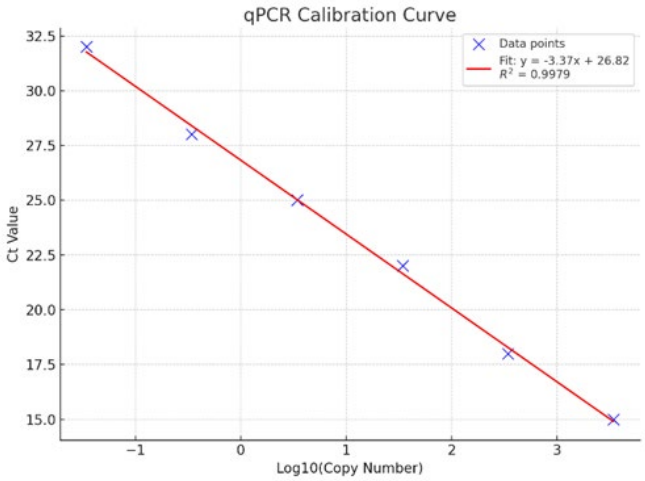

Figure 2: Calibration curve for porcine DNA real-time PCR Halkit II.

Table 1: Amplification protocol of real-time PCR

Cycle	Step	Time	Temperature
1	Initial Denaturation	2 mins	95°C
40	Denaturation	15 sec	95°C
	Annealing	1 min	60°C

2.5 Pretreatment of collagen samples for enzyme-linked immunosorbent assay (ELISA)

Before conducting the ELISA assay, all collagen samples underwent a pretreatment procedure. The sample was weighed at 1 g in the collection tube, washed with 2 mL of cold acetone (-20°C) and the acetone was discarded. An additional 2 mL of cold acetone was added, and the sample was then centrifuged directly at 300 × g for 5 mins. After discarding the remaining acetone, the sample was resuspended in 10 mL of buffer (50 mM Tris-HCl, pH 7.4, 50 mM NaCl, 2 mM Ethylenediaminetetraacetic Acid (EDTA), and 1% Sodium Dodecyl Sulfate (SDS), then cooled at -20°C for 30 mins. Afterwards, the solution was sonicated at 10000 rpm for 2 × 10 seconds and left to cool at -20°C for 5 mins. It was then centrifuged at 10,000 x g for 20 mins. The supernatant was transferred to a new tube and labelled. A volume of 2 mL of the liquid portion of this pretreated mixture was transferred and stored at -20°C for ELISA analysis.

2.6 Enzyme-linked immunosorbent assay (ELISA)

500 µL of the pretreated sample and 1 mL of 0.5 M NaCl were added to the collection tube. The tube was closed and vortexed vigorously for 30 seconds until the sample dissolved. The tubes were then centrifuged at 3710 rpm for 15 mins, and they were ready for the ELISA assay.

The assay procedure was performed using the ELISA Porcine Gelatine Detection Halkit (Global Haltech Sdn. Bhd., 2021a), a sandwich-type ELISA specific for porcine collagen peptides, with a modification of loading 100 µL of 0.5 M NaCl into the blank well. A 100 µL NaCl solution was added to the blank well instead of the sample buffer to serve as a matrix-matched control and maintain ionic strength consistency across all wells, minimising background signal variation during absorbance reading. The absorbance (OD) of the wells was read at 450 nm with a Thermo Fisher Scientific Multiskan SkyHigh Microplate Spectrophotometer (Waltham, Massachusetts, USA). The manufacturer-specified cut-off for positive detection was a P/N ratio ≥ 1.3, where P is the sample's optical density (OD) and N is the OD of the negative control. The kit's reported limit of detection (LOD) is 0.1% porcine gelatin (w/w) in a food matrix. According to the manufacturer's specifications, the kit exhibits no cross-reactivity with bovine, fish, or chicken collagen proteins. (Global Haltech Sdn. Bhd., 2021a). These performance criteria were used to interpret the ELISA results obtained in this study.

The results were interpreted using the porcine collagen P/N ratio, where P refers to the mean optical density (OD) of the test sample, and N refers to the mean OD of the negative control. This ratio standardises the absorbance values by comparing the test sample signal against the background or baseline signal. The formula is shown below:

$$Porcine\ collagen\ \frac{P}{N}\ ratio = \frac{Mean\ OD\ of\ test\ sample}{Mean\ OD\ of\ negative\ control}$$

Table 2: Result interpretation of real-time PCR

Case	CT-value			Interpretation
	Sample	Positive Control	Negative control	
1	CT < 38	CT < 38	No CT or CT > 38	A porcine-specific gene was detected in the sample.
2	No CT or CT > 38	CT < 38	No CT or CT > 38	A porcine-specific gene was not detected in the sample.
3	No CT or CT < 38 or CT > 38	No CT or CT > 38	No CT or CT > 38	Invalid, rerun PCR.
4	No CT or CT < 38 or CT > 38	CT < 38	CT < 38	Invalid, rerun PCR.

A P/N ratio of 1.3 or greater indicates positive detection of porcine collagen, while a value of less than 1.3 indicates a negative result, as summarised in Table 3.

Table 3: Result interpretation of ELISA

Case	Porcine contamination	P/N value
1	Positive	≥ 1.3
2	Negative	< 1.3

ELISA analysis included external validation with pure porcine collagen as a positive control and pure bovine collagen as a negative control. Both were processed using the same pretreatment steps as the test samples.

2.7 Statistical analysis

The results for duplicate samples of the qPCR and ELISA were calculated as a mean ± standard deviation (SD). One-way analysis of variance (ANOVA) with Tukey's test was performed to determine the significant difference between the means at a 95% confidence level ($p < 0.05$) using XLSTAT 2025 statistical software (Lumivero, USA).

2.8 Determination of false negative rate

The qualitative data obtained from the qPCR and ELISA methods were gathered, plotted, and compared, and the False Negative Rate (FNR) of each method was calculated with the following formula:

$$False\ Negative\ Rate\ (FNR) = \frac{FN}{(TP + FN)}$$

Where FN is a false negative for porcine labelling, and TP is a true positive for porcine labelling.

2.9 Overall agreement rate (OAR)

An overall agreement rate (OAR) was determined to measure the general concordance between the two methods. The OAR is the proportion of samples for which both methods, qPCR and ELISA, give the same positive or negative result. The formula to calculate OAR is as follows:

$$Overall\ Agreement\ Rate\ (OAR), \% = \frac{Number\ of\ samples\ with\ matching\ qPCR\ and\ ELISA\ results}{Total\ number\ of\ samples}\ x\ 100$$

3. Results and discussion

3.1 Porcine detection by real-time polymerase chain reaction

Polymerase Chain Reaction (PCR) is an oligonucleotide-based method (DNA approach) widely used to detect the authenticity of food components, particularly in complex matrices such as highly processed products. The sensitivity of the real-time PCR method using porcine collagen was previously validated at 0.001% (Global Haltech Sdn. Bhd., 2021b). This study interpreted samples as porcine-positive when their cycle threshold (CT) values were below 38 for both test duplicates and the spiked positive control (Global Haltech Sdn. Bhd., 2021b). A lower CT value indicates a higher concentration of target porcine DNA, and vice versa. This result was in line with the Malaysian Standard MS 2627: 2017 Detection of porcine DNA - Test method - Food and food product, which states that a CT-value of 32 to 40 indicates the positive presence of porcine DNA (Department of Standards Malaysia, 2017).

Out of nine highly processed collagen samples tested, real-time PCR detected porcine DNA in three samples, namely samples 2, 3, and 4, corresponding to fish peptide, undenatured type II porcine peptide, and marine collagens, respectively, as shown in Table 4. The CT-values of these samples were not significantly different ($p < 0.05$), indicating a similar level of porcine DNA presence. These samples included one porcine-labelled sample and two unexpectedly positive samples despite being labelled as fish- and marine-based products. This result highlighted both the method's sensitivity and the challenges posed by the complexity of the sample matrix. (Al-Shaibany *et al.*, 2022), where DNA degradation and cross-contamination can occur (Kim *et al.*, 2023).

Sample 3, which contains undenatured Type II porcine collagen, has been successfully detected with CT values of 30.62 ± 0.01. This supports findings by Chen *et al.* (2023), who reported that DNA-based methods, such as PCR, are highly effective for detecting biological origins, especially in minimally processed collagen types. Undenatured collagen, less subjected to extreme processing, retains enough DNA to be detected, reinforcing the importance of preserving molecular integrity for accurate halal authentication.

However, the two other porcine-based samples (Samples 1 and 6) containing hydrolysed collagen peptides yielded no CT values (ND), resulting in non-detection. According to Woo *et al.* (2017). Hydrolysed or denatured collagen undergoes enzymatic, thermal, or pH treatment, which breaks it down into peptides and degrades the DNA, making detection via PCR difficult. This is supported by Erwanto *et al.* (2011), who highlighted that shortened DNA fragments and potential inhibitors within protein-rich matrices pose significant challenges in PCR-based detection, especially when laboratory staff are required to perform complex extraction procedures. Similarly, Septiani (2024) found that DNA purity values in collagen supplement products were frequently below 1.8, indicating contamination by proteins or degradation, which compromises PCR amplification efficiency.

The same issue was observed in Sample 6, a cream-based product, which aligns with findings by Hanum *et al.* (2018) that DNA yields from processed or emulsified products are typically lower than those of raw food matrices. This observation was further supported by Zabidi *et al.* (2020), who confirmed that over-processing and low DNA recovery can significantly limit PCR application for halal authentication.

Interestingly, Samples 2 and 4, labelled fish and marine collagen, respectively, tested positive for porcine DNA. The detection of porcine markers in products labelled as non-porcine or halal was unexpected. While this may indicate the presence of trace-level porcine DNA, the result should be interpreted with caution, as other factors, such as analytical cross-reactivity, matrix effects, or incidental contamination during production, cannot be ruled out (Schröder *et al.*, 2023). No traceability or confirmatory testing was conducted in this study to determine the source of the detected markers. As such, no definitive conclusions regarding mislabelling or halal non-compliance can be drawn solely from these findings.

Table 4: Cycle threshold (CT) value of real-time PCR for porcine DNA detection

Sample no.	Product type	Collagen type[1]	Source	Halal certification status[2]	CT-value[3,4,5,6]		Result[8]
					Result	Spiked sample[7]	
1	Powder	Hydrolysed peptide	Porcine	Non-halal-certified	ND	N/A	-/-
2	Powder	Peptide	Fish	Non-halal-certified	**31.70 ± 0.21[a]**	**21.27**	+/+
3	Powder	Undenatured type II peptide	Porcine	Non-halal-certified	**30.62 ± 0.01[a]**	**19.89**	+/+
4	Powder	Not available	Marine	Non-halal-certified	**30.40 ± 1.26[a]**	**20.25**	+/+
5	Powder	Not available	Fish	Non-halal-certified	ND	N/A	-/-
6	Cream mask	Hydrolysed peptide	Porcine	Non-halal-certified	ND	N/A	-/-
7	Liquid supplement	Not available	Plants	Non-halal-certified	ND	N/A	-/-
8	Jelly	Type I & II peptide	Fish	Non-halal-certified	ND	N/A	-/-
9	Gummy	Type I & III peptide	Not available	Halal-certified	ND	N/A	-/-
10	Porcine (positive control)			NR	**27.54 ± 0.13[a]**	27.50	+/+
11	Bovine (negative control)			NR	ND	N/A	-/-

Note: [1]Not available, as data could not be obtained.
[2]NR = Not related
[3]ND = Not detected, i.e. no CT-value was determined, indicating no detectable amplification of the target DNA.
[4]Bold result indicates positive porcine presence. Values are presented as mean ± standard deviation of duplicate results. Values with different superscripts are statistically significantly different ($p < 0.05$).
[5]N/A = Not applicable, i.e. the result was not applicable since the porcine DNA was not detected in each replicate.
[6]qPCR kit sensitivity was reported as 0.001%, specificity was reported as 100%, and the limit of detection (LOD) was reported as 1 pg DNA, equivalent to less than 10 copies (Global Haltech Sdn. Bhd., 2021b).
[7]The sample was spiked with a positive control.
[8]+ = porcine DNA was detected; - = porcine DNA was not detected.

In contrast, the remaining samples (Samples 5, 7, 8, and 9), including the halal-certified gummy (Sample 9), tested negative for porcine DNA, confirming no cross-reactivity with other animal species and validating the specificity of the PCR assay. The result is consistent with the Porcine DNA Real-Time PCR Halkit II insert specification (Global Haltech Sdn. Bhd., 2021b).

To validate the performance of qPCR, 100% pure porcine and bovine collagen samples were analysed as independent controls. The porcine control produced strong amplification with CT values of 27.45 and 27.63 in duplicate, indicating precise positive detection. The bovine control yielded no detectable CT values, confirming the absence of porcine DNA and demonstrating high specificity. These results confirm that the qPCR assay discriminates between porcine and non-porcine collagen sources under the tested conditions.

Real-time PCR demonstrated strong sensitivity for detecting porcine DNA in undenatured collagen. However, its performance was limited in hydrolysed or heavily processed samples due to DNA degradation and matrix interference. Moreover, false positives in fish- and marine-labelled samples may raise concerns over supply chain traceability and the risk of contamination. These findings suggest that real-time PCR is a valuable tool for halal authentication. However, it may benefit from complementary methods, such as ELISA, to overcome its limitations in detecting porcine residues in complex or denatured matrices.

3.2 Porcine detection by enzyme-linked immunosorbent assay (ELISA)

The enzyme-linked immunosorbent assay (ELISA) is a protein-based analytical approach commonly used to detect the presence of antigenic proteins in food and pharmaceutical products (El Sheikha *et al.*, 2017). This study employed a sandwich ELISA to detect porcine antigen in nine collagen-based samples of various sources and processing forms (Table 5).

Only Sample 1 was successfully detected among the three porcine-labelled samples, with P/N values of 1.34 ± 0.05, both above the threshold cut-off (≥ 1.3). This detection indicates the presence of porcine antigen, confirming the effectiveness of the applied pretreatment and extraction protocols (Global Haltech Sdn. Bhd., 2021a). Sample 1 consisted of hydrolysed porcine collagen peptides, despite their highly processed nature, which yielded a positive result due to optimised sample processing techniques. These steps included cold acetone precipitation, sonication with Radio-Immuno-Precipitation Assay (RIPA) lysis buffer, and replacement of the standard diluent with

Table 5: Porcine collagen P/N ratio for detection of porcine antigen with ELISA

Sample no.	Product type	Collagen type[1]	Source	Halal certification status[2]	P/N ratio[3,4,5]	Result[6]
1	Powder	Hydrolysed peptide	Porcine	Non-halal-certified	**1.34 ± 0.05^{e}**	+/+
2	Powder	Peptide	Fish	Non-halal-certified	1.11 ± 0.03^{cd}	-/-
3	Powder	Undenatured type II peptide	Porcine	Non-halal-certified	0.78 ± 0.02^{a}	-/-
4	Powder	Not available	Marine	Non-halal-certified	1.16 ± 0.01^{d}	-/-
5	Powder	Not available	Fish	Non-halal-certified	0.88 ± 0.05^{ab}	-/-
6	Cream mask	Hydrolysed peptide	Porcine	Non-halal-certified	0.87 ± 0.01^{ab}	-/-
7	Liquid supplement	Not available	Plants	Non-halal-certified	**1.86 ± 0.06^{f}**	+/+
8	Jelly	Type I & II peptide	Fish	Non-halal-certified	0.84 ± 0.03^{ab}	-/-
9	Gummy	Type I & III peptide	Not available	Halal-certified	0.98 ± 0.00^{bc}	-/-
10	Porcine collagen (positive control)			NR	**2.12 ± 0.05^{g}**	+/+
11	Bovine collagen (negative control)			NR	0.89 ± 0.03^{ab}	-/-

Note: [1]Not available, as data could not be obtained.
[2]NR = Not related
[3]A P/N ratio ≥ 1.3 indicates positive detection of porcine collagen, while a value of < 1.3 indicates a negative result.
[4]Bold result indicates positive porcine presence.
[5]ELISA kit sensitivity was reported as 0.5%, specificity was reported as 100%, while the limit of detection was reported as 0.5 mg pig gelatine in 1 mL test buffer (Global Haltech Sdn. Bhd., 2021a).
[6]+ = porcine antigen was detected; - = porcine antigen was not detected.

0.5 M NaCl, a stronger protein extractant. (Jain *et al.*, 2020). In prior trials without these optimisations, the same sample returned negative results, underscoring the crucial role of pretreatment in enhancing protein recovery from complex matrices**.**

The other two porcine-labelled samples (Samples 3 and 6) yielded negative results, likely due to limitations in antigen recovery or the presence of interfering compounds such as salts, lipids, or other coexisting substances. Nhari *et al.* (2019) reported that matrix effects in commercial processed foods can hinder antibody-antigen interactions, particularly when the antigen is below the assay's detection threshold. Although the current study employed pretreatment strategies to overcome this limitation, a lack of standardisation and optimisation for each sample type (solid vs. liquid) may have affected antigen extraction efficiency and assay reproducibility. Samples 3 and 6, despite being labelled as porcine-derived, returned negative results. This outcome is likely due to ELISA's reliance on intact antigenic protein structures**,** which can be significantly affected by extensive processing such as hydrolysis, high heat, or chemical treatment (Zhang *et al.*, 2025). Undenatured collagen in Sample 3 may still contain DNA (hence detectable by PCR) but could have lost conformational epitopes necessary for antibody recognition**,** as Nhari *et al.* (2019) suggested. Likewise, Sample 6, a cream-based formulation, may have yielded poor antigen recovery due to matrix complexity, surfactant interference, or limitations in protein solubility. Lipids and emulsifiers in cream-based formulation can form micelles or coat proteins, reducing their accessibility to the capture antibodies and compromising detection sensitivity (Henao-Ardila *et al.*, 2024). The low P/N values observed (< 0.9) support the interpretation that the detectable antigen was insufficient. This limitation highlights the importance of appropriate sample pretreatment protocols and the potential need for matrix-specific ELISA optimisation.

Other samples, including fish- and marine-derived (Samples 2, 4, 5, and 8) and the halal-certified gummy product (Sample 9), showed negative results**,** indicating no cross reactivity with non-porcine species**.** This agrees with the specificity statement of the Porcine ELISA kit used (Global Haltech Sdn. Bhd., Malaysia).

Similarly, the ELISA assay was validated using the same external controls. The porcine collagen yielded P/N ratios of 2.12 ± 0.05, above the positive threshold (≥ 1.3), confirming strong antigen detection. In contrast, the bovine collagen sample returned P/N ratios of 0.89 ± 0.03, indicating negative detection with no cross-reactivity. These findings support the assay's specificity for porcine collagen proteins and its suitability as a confirmatory tool when used with DNA-based methods.

In summary, ELISA was able to detect porcine antigen in one confirmed porcine-labelled product and one plant-labelled product, but failed to detect the antigen in other porcine-based samples, likely due to low antigen levels or insufficient extraction efficiency. The findings reinforce that while ELISA can serve as a complementary technique for porcine detection, especially in cases where DNA is degraded, its performance is highly dependent on sample processing and pretreatment protocols. This result further supports the manuscript's core proposition that an integrated approach using PCR and ELISA enhances the reliability of halal authentication for highly processed collagen products.

3.3 Comparison of porcine detection by real-time polymerase chain reaction and enzyme-linked immunosorbent assay

A comparative overview of qPCR and ELISA results is summarised in Table 6, highlighting detection discrepancies across different collagen-based samples. Out of nine tested products, agreement between the two methods was observed in only four samples, resulting in an overall agreement rate of 44.4%. qPCR demonstrated greater sensitivity in detecting porcine DNA in undenatured collagen samples (e.g., Sample 3), whereas ELISA was more effective in detecting antigenic proteins in hydrolysed forms (e.g., Sample 1). However, both

Table 6: Comparison of porcine detection results between Real-time Polymerase Chain Reaction (qPCR) and Enzyme-linked Immunosorbent Assay (ELISA), with corresponding false negative identification and method agreement

Sample no.	Product type	Collagen type[1]	Source	Halal certification status	Result[2]		False negative	Method agreement	Remark
					qPCR	ELISA			
1	Powder	Hydrolysed peptide	Porcine	Non-halal certified	-/-	+/+	Yes, missed by qPCR	No	DNA was likely degraded; the antigen was preserved.
2	Powder	Peptide	Fish	Non-halal-certified	+/+	-/-	No	No	DNA was detected; potential contamination or mislabeling.
3	Powder	Undenatured type II peptide	Porcine	Non-halal-certified	+/+	-/-	Yes, missed by ELISA	No	The protein epitope was likely denatured.
4	Powder	Not available	Marine	Non-halal-certified	+/+	-/-	No	No	Possible contamination; unverified label.
5	Powder	Not available	Fish	Non-halal-certified	-/-	-/-	No	Yes	Consistent negative.
6	Cream mask	Hydrolysed peptide	Porcine	Non-halal-certified	-/-	-/-	Yes, missed by qPCR and ELISA	Yes	Likelihood of matrix interference or degradation.
7	Liquid supplement	Not available	Plants	Non-halal-certified	-/-	+/+	No	No	Possible cross-reactivity or label issue.
8	Jelly	Type I & II peptide	Fish	Non-halal-certified	-/-	-/-	No	Yes	Consistent negative.
9	Gummy	Type I & III peptide	Not available	Halal-certified	-/-	-/-	No	Yes	Results were confirmed negative, consistent with the label.

Note: [1]Not available, as data could not be obtained.
[2]+ = porcine was detected; - = porcine was not detected.

methods failed to detect porcine content in Sample 6, likely due to the effects of matrix complexity and protein/DNA degradation. Conversely, mismatches in Samples 2, 4, and 7 suggest cross-contamination or limitations in one method, depending on the sample's processing stage.

These findings reinforce the strengths and limitations of each method: qPCR is highly sensitive to DNA presence but vulnerable to DNA degradation or inhibition. At the same time, ELISA relies on intact or recoverable proteins, which may be lost in highly processed or emulsified matrices. Thus, an integrated approach is recommended for more reliable halal authentication in collagen-based products.

While PCR and ELISA are widely used for porcine detection due to their relatively low cost, sensitivity, and ease of use, advanced techniques such as liquid chromatography-tandem mass spectrometry (LC-MS/MS) offer superior specificity. LC-MS/MS can precisely identify species-specific peptide markers, making it highly effective in detecting trace levels of porcine proteins even in extensively processed products (Yuswan *et al.*, 2025). However, its implementation in routine halal authentication is often limited by high equipment costs, technical complexity, and longer analysis time. In contrast, PCR and ELISA remain more accessible for high-throughput screening, especially in regions where rapid, cost-effective methods are prioritised. Therefore, although LC-MS/MS provides confirmatory strength, PCR and ELISA play a central role in first-line halal compliance testing, especially when complemented as a dual-method strategy.

3.4 False negative rate (FNR)

The performance of the PCR and ELISA methods was further evaluated by calculating the False Negative Rate (FNR), as shown in Table 6. In this study, the false negative rate (FNR) was calculated to evaluate the performance of both real-time PCR and ELISA in detecting porcine derivatives in highly processed collagen samples. FNR is defined as the proportion of actual positive samples that were incorrectly classified as negative, as given by the formula:

$$FNR = FN / (TP + FN)$$

Where FN is the number of false negatives and TP is the number of true positives.

Based on the confirmed porcine-labelled samples (Samples 1, 3, and 6), only one sample (Sample 3) was detected by real-time PCR, and one (Sample 1) by ELISA, while Sample 6 was not detected by either method. This resulted in 2 false negatives out of 3 total positives, yielding:

$$FNR = (2/(1 + 2)) \times 100 = 66.7\%$$

This value indicates that the detection methods missed 66.7% of known porcine-containing samples, even though they were expected to test positive based on their labelled contents.

Such a high false negative rate suggests that both methods, when used alone, may fail to reliably identify porcine contamination in specific collagen matrices, especially those that are extensively processed or hydrolysed.

Ferrer-Urbina *et al.* (2023) state that the FNR is a critical diagnostic performance metric. Cohen (1992) recommended that false negative rates should ideally not exceed 20% in applied research settings. Hence, the 66.7% FNR observed in this study exceeds acceptable thresholds, potentially compromising the reliability of halal authentication if these methods are used independently. This limitation may be attributed to the small sample size, the diverse physical forms of the samples (e.g., powder, cream, gel, liquid), and the complexity of collagen processing**,** which includes heat, enzymatic hydrolysis, and chemical treatment. Such factors are known to degrade DNA and denature proteins, complicating both PCR amplification and antigen detection**.** This study exceeds acceptable thresholds, potentially compromising the reliability of halal authentication if these methods are used independently. This limitation may be attributed to the small sample size, the diverse physical forms of the samples (e.g., powder, cream, gel, liquid), and the complexity of collagen processing**,** which includes heat, enzymatic hydrolysis, and chemical treatment. Such factors are known to degrade DNA and denature proteins, complicating both PCR amplification and antigen detection. These findings emphasise the need for combining DNA- and protein-based methods to minimise false negatives and improve confidence in porcine detection**.** Additionally, method optimisation, sample-specific pretreatment protocols, and validation using larger sample sets are recommended to enhance detection accuracy in future halal authentication work.

While the calculated false negative rate (FNR) provides valuable insights into the limitations of each method, it must be interpreted with caution due to the small sample size (n = 9) and the limited inclusion of externally verified control materials. The study relied primarily on commercial product claims and internal kit controls, which may not fully represent the complexity of porcine detection in diverse real-world matrices. Therefore, the observed FNR and overall agreement rates serve more as preliminary indicators than conclusive diagnostic metrics. Future research should aim to include larger sample sizes and use well-characterised, controlled matrices, both porcine-positive and porcine-free, to strengthen statistical confidence and validation across different product categories.

3.5 Agreement analysis between qPCR and ELISA

The overall agreement rate (OAR) was calculated to evaluate the consistency between the qPCR and ELISA methods across the nine tested collagen-based products (Table 6). OAR is defined as the proportion of total samples for which both methods yielded the same positive or negative result. In this study, agreement was observed in 4 out of 9 samples, specifically in Samples 5, 6, 8, and 9, resulting in an OAR of:

$$OAR = (4/9) \times 100 = 44.4\%$$

The remaining five samples (1, 2, 3, 4, and 7) exhibited mismatched results between the two methods, indicating only moderate alignment.

Several factors may account for this limited agreement. First, the differing analytical targets of the methods (DNA vs protein) inherently influence their detection capabilities. The qPCR targets species-specific DNA, which may degrade during hydrolysis, heating, or chemical processing, limiting its effectiveness in hydrolysed peptides or emulsions. In contrast, ELISA targets antigenic protein structures, which may be denatured or masked by matrix components, or present below the assay's detection threshold, especially in highly processed or diluted products.

Second, the complexity of the sample matrix likely contributed to detection discrepancies. For instance, emulsified or cream-based products (e.g., Sample 6) pose challenges for DNA and protein extraction due to low analyte concentration or interference from fats and surfactants. Third, label inconsistencies or sourcing issues, such as Sample 7 (labelled as plant-based yet ELISA-positive for porcine antigen), may point to cross-contamination, unverified ingredients, or incomplete halal verification in the supply chain.

Ultimately, the 44.4% agreement rate confirms that relying on a single detection method may be insufficient for halal authentication of highly processed collagen-based products. These findings underscore the need for a dual-method verification strategy, which combines the DNA sensitivity of qPCR with the protein-detection capability of ELISA, to reduce false negatives and enhance analytical robustness.

4. Conclusion

This study provides important insight into the performance of PCR- and ELISA-based methods for detecting porcine components in highly processed collagen-based products. While each method has limitations, their combined application can enhance halal authentication's reliability, particularly in products containing degraded DNA or denatured proteins. However, this dual-method strategy should be viewed as a promising approach rather than a definitive solution. Its broader application requires further validation through studies involving larger and more diverse sample sets, as well as harmonised testing protocols. The observed discrepancies between detection methods underscore the importance of matrix-specific validation and greater regulatory emphasis on multimodal screening strategies. These findings also highlight the need for transparent labelling, strict manufacturing controls, and the integration of both molecular and immunoassay tools to support halal integrity in complex consumer goods. Nonetheless, the findings should be interpreted with caution due to the small sample size (n = 9) and the absence of independent positive and negative control samples, which limit the statistical strength and generalisability of the results. These limitations call for more extensive validation studies using well-characterised reference materials and known control matrices. Future research should focus on refining detection thresholds, minimising false negatives, and aligning screening practices with established halal regulatory frameworks.

5. Acknowledgement

The Memorandum of Agreement between Global Haltech Sdn Bhd and the International Islamic University Malaysia supported this work.

6. Data availability

Data is available upon request.

7. Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could be perceived to influence the work reported in this paper.

8. Author contributions statement

Camilla Dewanthy Putri Basuki - Writing original draft; Ruzanna Zainal - Conceptualisation, data curation, and reviewing the manuscript; Muhamad Shirwan Abdullah Sani - Methodology and reviewing the manuscript.

9. Declaration of generative AI in scientific writing

The authors declare that they have used a generative artificial intelligence tool (Grammarly) specifically to improve the readability and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Impact of a nutrient-rich health bar intervention on health and cognitive performance among children and adolescents in the B40 community in Gombak

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Received:8/5/2025
Accepted:8/7/2025
Published:31/7/2025

Keywords:
Health bar intervention, Cognitive performance, Anthropometric measurements, Pediatric Quality of Life (PedsQL), Socioeconomic factors

Abstract

Diet and nutrition are vital in preventing cognitive decline, yet research on their impact on children and adolescents, particularly in Malaysia, remains limited. This study evaluated the effects of a health bar intervention on the health and cognitive performance of children and adolescents from the B40 community. A health bar formulated with date powder, moringa, sacha inchi oil, and pumpkin seeds was assessed for acceptability and efficacy. Seventy participants aged 10–16 from two boarding schools underwent an eight-week intervention, during which anthropometric measurements, PedsQL 4.0, and RAVLT were used to evaluate health and cognitive outcomes. The results revealed significant improvements in physical health, emotional well-being, and mental performance, particularly among males, highlighting the influence of socioeconomic factors on nutrition and cognition. Overall, the health bar intervention led to significant improvements in physical health and cognitive function, suggesting the need for extended study durations and diverse data collection methods for future research.

1. Introduction

Diet and nutrition are well-established modifiable factors that influence the early prevention and delayed progression of age-related cognitive decline (Kristo *et al.,* 2020). Extensive epidemiological research highlighted their crucial role in improving long-term cognitive function (Malek Rivan *et al.,* 2022). Many may concur with the fundamental principles regarding the relationship between food and learning: (1) that consistently consuming an adequate, high-quality diet supports cognitive enhancement; (2) that a nutritious diet is associated with better cognitive function; and (3) that malnutrition, widespread among economically disadvantaged adolescents, is linked to reduced cognitive abilities.

However, despite the widespread acknowledgement of food's importance in learning, empirical research on the precise relationship between overall diet and cognitive achievement in children and adolescents remains scarce. There have been numerous documentations of infants and young children's health and nutritional status in less developed countries, but little attention has been given to the condition of older children. Children and adolescents' health and nutrition in Malaysia have not received much attention, as indicated by the relatively little published information on this topic, primarily in urban areas. Suzana *et al.* (2019) elucidated that the health and nutritional status of those living in the urban sector has been neglected, as the focus has mainly been on people with low incomes and the hardcore poor households in the rural areas of Malaysia. These children and adolescents have been the least studied in evaluating a community's cognitive performance and health status, since they are assumed to be less at risk of being malnourished or having poor health. However, it is known that poor nutrition is associated with poor cognitive performance (Spencer *et al.,* 2017).

Incentives given by policymakers to overcome the issue include a supplementary food programme that helps meet the needs of children and adolescents (Kim & Kang, 2017). The menu selection for this programme is mainly based on the nutrient contents that promote good health and well-being of the children and adolescents (Vilar-Compte *et al.,* 2021). Given this backdrop, this study decided to choose a health bar as part of the food intervention programme due to the components of its ingredients, which are beneficial in promoting human health. The health bar had been developed in a previous study, and its

nutrient content had been determined (Mohd Noor *et al.*, 2024).

Meanwhile, this study had two main objectives: first, to investigate participants' acceptability towards the health bar; second, to assess the improvement of health and cognitive performance of the participants after the intervention. It was hypothesised that regular consumption of the health bar would lead to significant improvements in physical health indicators and cognitive test scores. The health bar has the potential to improve cognitive performance and overall health due to its combination of functional ingredients—date powder, Sacha Inchi (*Plukenetia volubilis*) oil, Moringa (*Moringa oleifera*) powder, and pumpkin seed—each known for its neuroprotective and brain-boosting properties. Dates are rich in ferulic acid, an antioxidant that helps protect against amyloid-beta (αß) fibrils, enhancing learning and memory, improving cognitive flexibility and reversal learning of left-right discrimination (Subash *et al.*, 2015). Sacha inchi oil supports brain function by increasing theta, alpha, and beta brainwaves, which activate the inferior frontal cortex, enhancing cognitive performance in areas such as memory and attention. Moringa (*Moringa oleifera*) contributes vigorous antioxidant activity through its high flavonoid and phenol content, reducing oxidative stress by inhibiting lipid peroxidation (Brilhante *et al.*, 2017). Furthermore, moringa leaf extract promotes neuroprotection by enhancing neurite outgrowth and increasing the number and length of dendrites and axonal branches in hippocampal neurons (Hannan *et al.*, 2014). Pumpkin seeds, rich in magnesium and zinc, are known to support children with learning disabilities; magnesium improves oxygen transport to cells, boosting focus and task attention, while zinc aids memory by facilitating neuron communication in the hippocampus (George, 2014; Hoane, 2011).

2. Materials and methods

2.1 Materials

The health bar formulation incorporated several key components, including exceptionally functional ingredients. Date powder, Sacha Inchi (*Plukenetia volubilis*) oil, and Moringa (*Moringa oleifera*) powder were sourced from local manufacturers in Selangor. The core structure of the health bar, consisting of bubble rice, pumpkin seeds, and oats, was procured from a manufacturer in Klang, Selangor. Furthermore, Beryl's dark chocolate compound and sugar alcohols (maltitol and isomalt) were used as coatings for the health bar.

2.2 Methods

2.2.1 Acceptance test (5-point hedonic scale)

The hedonic test was conducted following the method outlined by Meilgaard *et al.* (2007) to assess participants' acceptance of the health bar samples. Seventy untrained panellists, aged 10 to 16 years, were asked to evaluate two health bar formulations with the most optimal proximate composition based on prior analysis. A five-point picture hedonic scale, ranging from 1 (Extremely Dislike) to 5 (Extremely Like), was used for assessment. Referring to Stone, Bleibaum & Thomas (2021), a five-point picture hedonic scale was the most suitable scale to test the acceptability of food products among children and adolescents (5 to 16 years) due to its simplicity and directness. A minimum explanation was required to help the panellists understand the point of the test. All samples were standardised to approximately 3.0 g to minimise bias and presented on plates with unique three-digit random codes. These codes were not repeated, and their sequence was recorded in a master list, accessible only to the researcher.

2.2.2 Study design

The school selection criteria included being a boarding school (*Madrasah*), located near Gombak, and having a majority of B40 students. Two schools meeting these criteria were chosen (through purposive sampling based on school location and B40 demographic profile), and data collection involved interviewing teachers and administrators to recruit participants aged 10 to 16 years. Academic and health records were reviewed to analyse their background, academic performance, and health status, including allergies. Teachers and administrators were also interviewed to assess students' behaviour in the classroom before consuming the health bar. The sample size was calculated as Whyte & Williams (2015) suggested, suggesting 51 participants for this study. However, to boost confidence in the result, the sample size was adjusted to an 80% response rate, giving 70 participants while considering 80% power and 5% significance level. Finally, selected participants (54 male and 16 female) received health declarations and informed consent forms to confirm eligibility.

2.2.3 Measurements

All selected participants were assessed before the start of the study (pre-intervention) and every two weeks right after the healthy bar intervention (post-intervention) for two months. The questionnaires were prepared in Malay to help participants understand them better. The questionnaires used in this study were pre-existing, previously tested, and validated in earlier research. They asked about participants' socio-demographic backgrounds, including sex, age, ethnicity, and date of birth (Teo *et al.,* 2019). The collected information was gathered for further study at a later stage.

2.2.4 Health bar pilot food intervention study

The pilot intervention study on the health bar was conducted over eight weeks (approximately two months), with participants receiving one health bar each morning to assess improvements in cognitive function (Ferry *et al.,* 2013), and the data collection took place every two weeks. All participants were instructed to refrain from consuming supplements or '*sunnah* food' during the intervention period to minimise bias. As Pribis *et al.* (2012) noted, the human body typically requires two to three months to respond to a consistent dietary intake. The intervention was divided into two phases: pre-intervention (before the study) and post-intervention (during the study). Data collection assessed participants' health status, health-related quality of life, and cognitive performance following two months of health bar consumption (Teo *et al.,* 2019). This study aimed to investigate the potential changes between the pre-intervention and post-intervention of the health bar. Therefore, the biweekly data were analysed by comparing baseline measurements with the final results. Finally, statistical analysis was performed to evaluate the collected data.

2.2.5 Pre-intervention of health bar

A briefing session was held for all participants and teachers one day before the health bar intervention to explain the study's objectives and procedures. Participants received a form to track their health bar consumption over two weeks. They were

instructed to maintain their regular daily diet, consuming meals of similar composition and quantity to reduce individual variability (Al Mana & Robertson, 2018). To ensure dietary habits remained unchanged throughout the study, participants recorded 24-hour dietary recalls (food logs) for accuracy and completeness. The form was designed for daily, weekly, and monthly entries. Since participants were in a boarding school, their food intake was generally consistent. Any uncertainties were addressed immediately. Lastly, all participants underwent assessments for anthropometric measurements, health-related quality of life, and cognitive performance.

2.2.6 Anthropometric measurements

At first, participants' body weight and height were measured using a weighing scale and stadiometer and recorded to the nearest 0.1 kg and 0.1 cm, respectively. These measurements were used to compute Body Mass Index (BMI). The z-scores for weight-for-age (WAZ), height-for-age (HAZ), and BMI-for-age (BAZ) were determined using WHO AnthroPlus software (World Health Organisation, 2009) to assess the nutritional status of children by comparing the z-scores against the WHO Growth Reference 2007 tables (World Health Organisation, 2009).

2.2.7 Health-related quality of life

The Pediatric Quality of Life Inventory 4.0 (PedsQL 4.0) was utilised to evaluate the health-related quality of life (HRQoL) of the participants (Varni *et al.,* 2001). To ensure better alignment with the participants, this study used the validated Bahasa Melayu version of the PedsQL 4.0 (Ab. Rahman *et al.,* 2011), allowing participants to complete the inventory in Malay. This instrument consisted of 23 items divided into four subscales: My health and activities, My feelings, I can get along with others, and About school. Participants were instructed to recall any health-related issues experienced over the past month and rate each item on a 5-point Likert scale ranging from 0 (never) to 4 (almost always). Subsequently, scores were transformed onto a 0–100-point scale, with 0 representing the highest level of impairment and 100 indicating the absence of impairment.

2.2.8 Cognitive performance

All participants were assessed using Rey's Auditory-Verbal Learning Test (RAVLT) to evaluate their cognitive performance before the health bar intervention. The recruited participants listened to 15 words (List A) followed by immediate recall of the words five times. After that, an interference list of 15 words (List B) was provided to the participants for immediate recall. The participants were then asked to perform short (2 mins) delayed recall of the 15 words (List A). At the end of the test, each participant was provided a printed list of 50 words (15 words from List A, 15 from List B, and an additional 20 words) and was required to circle only the 15 words from List A. The score was analysed using a t-test and analysis of variance (ANOVA) (Whyte & Williams, 2015). The assessment results were recorded and compared with the post-intervention results later.

2.2.9 Post-intervention of health bar

The school teachers were thoroughly briefed on the procedures for administering the health bar. This ensured that all participants consistently consumed the health bar daily throughout the study. The teachers closely monitored the consumption and recorded each intake using a designated form, thereby maintaining adherence and ensuring the integrity of the intervention. According to Whyte & Williams (2015), the consumption frequency of 5-6 days for two weeks can be included for further assessments. Post-intervention of the health bar was conducted every two weeks by collecting the forms to assess the frequency of health bar consumption. Due to the consistent and careful monitoring by the teachers, all participants demonstrated full compliance with the health bar consumption protocol, thereby facilitating the reliable execution of subsequent assessments. After that, all participants were re-evaluated for health-related quality of life and cognitive performance. The results were compared against the pre-intervention of a health bar to assess the differences in both results.

2.3 Ethical approval

It was important to highlight that this research had applied and obtained ethical approval from the International Islamic University of Malaysia (IIUM) Research Ethics Committee (IREC) concerning IREC No: IREC 2022-197 expiring on 28th November 2023.

3. Results and discussion

3.1 Acceptance test (5-point hedonic scale)

The acceptance test involved evaluating the palatability of two health bar samples. A 5-point hedonic scale (visual rating) was applied due to the suitability with the age of the panellists (10 to 16 years). A simple graphic hedonic scale of 5-point was distributed to 70 untrained panellists with a range of 1 = Very bad, 2 = Bad, 3 = Maybe good or maybe bad, 4 = Good, and 5 = Very good (Stone *et al.,* 2008). All panellists were to rate two health bar formulations (Formulation 12 and Formulation 14) based on their acceptability of the samples. The results obtained were as shown in Table 1.

The data in Table 1 indicates that most panellists preferred the health bar from Formulation 14, with 74.3% rating it as "very good," compared to 21.4% for Formulation 12. Additionally, 71.4% rated Formulation 12 as "good," while 21.4% gave the same rating to Formulation 14. A small percentage (7.2% for Formulation 12 and 4.3% for Formulation 14) was neutral. Despite Formulation 12 receiving a high "good" rating, Formulation 14 was selected for mass production due to its highest acceptance rating. The higher content of date powder enhanced sweetness, while the reduced moringa powder minimised the aftertaste. Both formulations contained beneficial nutrients for cognitive function, but only Formulation 14 was chosen for the pilot food intervention study.

3.2 Anthropometric measurements information

Their physical and health education teacher recorded the weight and height of each participant. The related data was computed into the WHO AnthroPlus Software to generate the body mass index (BMI), weight-for-age z-score (WAZ), height-for-age z-score (HAZ), and BMI-for-age z-score (BAZ). The obtained z-scores were compared against the WHO Growth Reference 2007 for children and adolescents aged 5 to 19 years to assess the health and nutrient status of the participants (Teo *et al.,* 2019). Tables 2, 3, and 4 present the anthropometric data of the

Table 1. Acceptance test result of the health bar

Attribute	Health Bar Formulation	Frequency n = 70	Per cent (%)
Very bad	Formulation 12	-	-
	Formulation 14	-	-
Bad	Formulation 12	-	-
	Formulation 14	-	-
Maybe good or maybe bad	Formulation 12	5	7.2
	Formulation 14	3	4.3
Good	Formulation 12	50	71.4
	Formulation 14	15	21.4
Very good	Formulation 12	15	21.4
	Formulation 14	52	74.3

Table 2. Anthropometric data of participants aged 12 to 13 years

Parameter	n (%) / Mean ± SD		
	Male (n = 4)	**Female (n = 2)**	***p*-value**
Body weight (kg)	29.95 ± 6.98	37.00 ± 0.78	0.296
Height (cm)	154.00 ± 2.58	149.00 ± 1.41	0.615
BMI (kg/m²)	12.60 ± 3.12	15.70 ± 0.07	0.286
WAZ	NA	NA	-
HAZ	-0.28 ± 1.22	-1.06 ± 0.77	0.110
BAZ	-4.04 ± 2.34	-0.97 ± 0.81	0.432
Severe thinness	3 (75.00)	-	-
Thinness	-	-	-
Normal	1 (25.00)	2 (100.00)	-
Overweight	-	-	-
Obesity	-	-	-

Table 3. Anthropometric data of participants aged 14 to 15 years

Parameter	n (%) / Mean ± SD		
	Male (n = 36)	**Female (n = 14)**	***p*-value**
Body weight (kg)	58.26 ± 12.50	52.87 ± 8.53	0.398
Height (cm)	166.20 ± 5.59	152.30 ± 6.84	1.000
BMI (kg/m²)	21.02 ± 3.96	22.69 ± 2.46	0.416
WAZ	NA	NA	-
HAZ	0.39 ± 1.34	-1.08 ± 2.21	0.593
BAZ	0.79 ± 1.46	1.02 ± 1.54	0.075
Severe thinness	-	-	-
Thinness	4 (11.11)	-	-
Normal	16 (44.44)	7 (50.00)	-
Overweight	11 (30.56)	7 (50.00)	-
Obesity	5 (13.89)	-	-

Table 4. Anthropometric data of participants aged 16 to 17 years

Parameter	n (%) / Mean ± SD	
	Male (n = 14)	***p*-value**
Body weight (kg)	58.21 ± 12.96	1.000
Height (cm)	166.71 ± 4.94	1.000
BMI (kg/m²)	20.76 ± 3.86	1.000
WAZ	NA	-
HAZ	-0.80 ± 1.54	0.437
BAZ	0.17 ± 2.34	0.057

Severe thinness	-	-
Thinness	1 (7.14)	-
Normal	11 (78.58)	-
Overweight	1 (7.14)	-
Obesity	1 (7.14)	-

participants aged 12 to 13 years, 14 to 15 years, and 16 to 17 years, respectively.

Table 2 indicates no statistically significant differences between male and female participants aged 12 to 13 regarding body weight, height, or nutritional status as measured by HAZ and BAZ scores. However, a general pattern suggests that females tend to have slightly higher body weight and better nutritional status than males. Notably, while both genders fell within the expected growth ranges, the broader variability in male scores—particularly in BAZ—may point to greater disparities in nutritional conditions among boys. These findings suggest similar growth profiles, with minor gender-based differences in nutritional patterns worth further investigation. Compared to the WHO Growth Reference 2007, 5.56% of male participants were classified as severely thin despite having a normal height, similar to findings by Cheah *et al.* (2022), which linked severe thinness in urban children to financial hardship. Additionally, 1.85% of males and 12.50% of females had normal BAZ and HAZ scores.

Table 3 shows that the average body weight and height for male and female participants aged 14 to 15 were 58.26 ± 12.50 kg, 52.87 ± 8.53 kg, 166.20 ± 5.59 cm, and 152.30 ± 6.84 cm, respectively, with no significant difference ($p > 0.05$) between genders. Similarly, the HAZ and BAZ z-scores showed no significant variation. According to the WHO Growth Reference, over half of the male participants had normal BAZ scores, while 20.37% were overweight, 7.41% slightly thin, and 9.25% obese. Among females, 43.75% were classified as either usual or overweight. Research by Teo *et al.* (2019) suggests that adolescents in this age group can make balanced dietary choices, though some may struggle due to financial constraints (Suzana *et al.,* 2019).

The presented data in Table 4 were for male participants aged 16 to 17. Participants were selected randomly, but no female participants from this age group were included. The participants' mean body weight and height were 58.21 ± 12.96 kg and 166.71 ± 4.94 cm, respectively, with a 20.76 ± 3.86 kg/m2 BMI. The HAZ and BAZ mean z-scores were -0.80 ± 1.54 and 0.17 ± 2.34. Comparison with the WHO Growth Reference indicated that over half of the participants fell within the normal BAZ category. Meanwhile, another 5.56% were either slightly thin, overweight or obese.

These findings highlight the importance of continuously monitoring adolescents' growth and nutritional status across age groups. While most participants fell within the normal ranges, undernutrition (severe thinness among younger males) and overnutrition (overweight and obesity in mid-adolescents) suggest a dual burden of malnutrition. This pattern reflects broader public health concerns, particularly in urban or economically diverse settings, where dietary habits may vary widely due to food availability, education, and socioeconomic status. The data further reinforces the need for school-age and gender-sensitive nutritional interventions to promote healthy growth trajectories and reduce long-term health risks.

3.3 Result on health-related quality of life

The participants' health-related quality of life (HRQoL) was evaluated using Pediatric Quality of Life Inventory 4.0 (PedsQL 4.0). Health-Related Quality of Life (HRQoL) was a crucial healthcare metric. It comprehensively assessed the participants' physical, emotional, social, and functional well-being regarding their health status and medical interventions (Teo *et al.,* 2019). All participants were required to answer 23 items from four dimensions: physical, emotional, social, and school. They were requested to recall the health-related dimensions for the past month and rate the items on a scale of 0 to 4, and the scores were plotted on a different scale, with 0 = 100, 1 = 75, 2 = 50, 3 = 25, and 4 = 0. The results for HRQoL for male participants using one-way analysis of variance (ANOVA) were recorded before the intervention, after one month, and after two months of intervention and are presented in Table 5.

One-way ANOVA analysis of PedsQL 4.0 showed significant differences in physical well-being scores across intervention periods ($F = 24.181$, $p < .001$), suggesting the intervention positively impacted participants' overall health and functioning.

Similarly, the analysis also found significant differences in emotional well-being scores ($F = 14.460$, $p < .001$), indicating the intervention influenced mood, stress levels, and coping mechanisms. Similar results were reported by Cheah *et al.* (2022), highlighting improvements in emotional well-being.

Moreover, social well-being scores showed significant variations ($F = 34.409$, $p < .001$), reflecting changes in peer relationships and social interactions. As Allang *et al.* (2019) noted, strong peer support is essential for boarding school students' quality of life.

Notably, the most substantial improvement was observed in school-related functioning, indicating increased academic engagement and performance.

The effect size was calculated based on eta squared (η^2), which further supports the significant impact of the intervention. Physical well-being showed a large effect size ($\eta^2 = 0.317$), reflecting strong improvements in participants' physical health. Emotional well-being also demonstrated a significant effect ($\eta^2 = 0.218$), indicating meaningful changes in mood and coping. Social well-being exhibited an even more substantial effect ($\eta^2 = 0.398$), suggesting enhanced peer relationships and social support. Most notably, school-related functioning yielded a huge effect size ($\eta^2 = 0.920$), highlighting the substantial influence of the intervention on academic engagement and performance. These effect sizes affirm that the intervention meaningfully improved quality of life across multiple domains.

One-way ANOVA results showed significant improvements in physical well-being among female participants ($F = 45.500$, $p < .001$), indicating the intervention positively influenced their overall health and vitality.

Similarly, the analysis revealed significant enhancements in emotional well-being ($F = 19.891$, $p < .001$), suggesting the intervention strengthened coping mechanisms and emotional resilience over time.

Significant improvements were observed in social functioning ($F = 27.036$, $p < .001$), highlighting the intervention's role in fostering stronger relationships and social support. Qiao *et al.* (2021) noted that female adolescents often face greater peer interaction challenges, making social support crucial.

Although the impact was minor, school-related functioning also improved ($F = 6.980$, $p = .002$), indicating positive effects on academic performance and school engagement, though to a lesser degree than other dimensions.

Table 5. Pediatric Quality of Life Inventory (PedsQL 4.0) - result for male participants

Dimension	Intervention Period	Mean (%)	Std. Deviation	F	Sig.	η^2
Physical	Pre-intervention	93.25	0.167	24.181	<.001	0.317
	1-month intervention	95.00	0.151			
	2-month intervention	97.50	0.063			
	Total	95.00	0.153			
Emotional	Pre-intervention	89.00	0.313	14.460	<.001	0.218
	1-month intervention	91.25	0.226			
	2-month intervention	95.00	0.110			
	Total	91.75	0.251			
Social	Pre-intervention	83.00	0.335	34.409	<.001	0.398
	1-month intervention	86.00	0.215			
	2-month intervention	94.00	0.282			
	Total	87.75	0.335			
School	Pre-intervention	86.00	0.000	598.881	<.001	0.920
	1-month intervention	87.75	0.107			
	2-month intervention	95.00	0.000			
	Total	89.25	0.180			

Table 6. Pediatric Quality of Life Inventory (PedsQL 4.0) - result for female participants

Dimension	Intervention Period	Mean (%)	Std. Deviation	F	Sig.	η^2
Physical	Pre-intervention	92.50	0.062	45.500	<.001	0.765
	1-month intervention	95.00	0.062			
	2-month intervention	96.75	0.000			
	Total	94.75	0.087			
Emotional	Pre-intervention	83.75	0.339	19.891	<.001	0.587
	1-month intervention	88.75	0.089			
	2-month intervention	95.00	0.000			
	Total	89.25	0.272			
Social	Pre-intervention	88.75	0.089	27.036	<.001	0.659
	1-month intervention	91.50	0.120			
	2-month intervention	95.00	0.073			
	Total	91.75	0.140			
School	Pre-intervention	87.50	0.310	6.980	.002	0.333
	1-month	90.00	0.207			

	intervention					
	2-month intervention	94.75	0.089			
	Total	90.75	0.248			

Table 7. Rey's Auditory Verbal Learning Test (RAVLT) - Result for male participants

Total Recall	Intervention	Mean	Std. Deviation	F	Sig.
A1	PI	5.0	0.116	2.760	<.001
	I2	6.2	0.231		
	I4	7.3	0.116		
	I6	8.9	0.058		
	I8	9.2	0.288		
	Total	7.4	1.629		
A2	PI	7.2	0.116	1.001	.451
	I2	8.4	0.231		
	I4	38.7	50.518		
	I6	11.4	0.231		
	I8	12.5	0.173		
	Total	10.3	22.597		
A3	PI	9.9	0.173	2.814	<.001
	I2	10.6	0.116		
	I4	11.4	0.116		
	I6	13.3	0.289		
	I8	14.1	0.173		
	Total	11.8	1.660		
A4	PI	10.6	0.116	2.836	<.001
	I2	11.8	0.173		
	I4	12.5	0.173		
	I6	14.5	0.173		
	I8	15.2	0.404		
	Total	12.9	1.793		
A5	PI	10.9	0.173	1.173	<.001
	I2	11.9	0.116		
	I4	13.4	0.173		
	I6	14.9	0.404		
	I8	15.2	0.462		
	Total	13.2	1.756		
B1	PI	4.9	0.115	3.436	<.001
	I2	5.8	0.289		
	I4	7.2	0.231		
	I6	10.1	0.346		
	I8	10.6	0.115		
	Total	7.7	2.367		
A6	PI	10.0	0.173	1.600	<.001
	I2	10.7	0.404		
	I4	11.8	0.173		
	I6	13.6	0.115		
	I8	14.4	0.288		
	Total	12.1	1.724		
A7	PI	10.5	0.173	8.422	<.001
	I2	11.4	0.115		
	I4	12.6	0.115		
	I6	14.7	0.115		
	I8	15.0	0.000		

	Total	12.8	1.838		
Sum	PI	43.2	1.039	2.398	<.001
	I2	49.0	0.866		
	I4	54.2	0.692		
	I6	63.1	1.097		
	I8	66.3	1.501		
	Total	55.2	8.937		
Recognition	PI	10.4	0.231	4.713	<.001
	I2	11.6	0.115		
	I4	12.7	0.173		
	I6	14.8	0.173		
	I8	15.0	0.000		
	Total	12.9	1.852		

A1 – A5: Number of recalls for List A (5 times), B1: Number of recalls for List B (1 time), A6 – A7: Immediate recalls for List A (2 times), Recognition: Number of words from List A.

Table 8: Rey's Auditory Verbal Learning Test (RAVLT) - Results for female participants

Total Recall	Intervention	Mean	Std. Deviation	F	Sig.
A1	PI	5.8	0.289	1.497	<.001
	I2	6.4	0.231		
	I4	7.4	0.058		
	I6	9.0	0.000		
	I8	9.1	0.289		
	Total	7.6	1.394		
A2	PI	7.4	0.116	4.687	<.001
	I2	8.7	0.289		
	I4	9.7	0.000		
	I6	11.6	0.116		
	I8	12.5	0.173		
	Total	9.9	1.942		
A3	PI	10.1	0.173	3.321	<.001
	I2	10.8	0.173		
	I4	11.4	0.116		
	I6	13.4	0.173		
	I8	14.1	0.173		
	Total	11.9	1.597		
A4	PI	10.8	0.173	1.964	<.001
	I2	11.8	0.173		
	I4	12.5	0.173		
	I6	14.6	0.116		
	I8	15.2	0.404		
	Total	12.9	1.741		
A5	PI	11.0	0.058	1.518	<.001
	I2	11.9	0.116		
	I4	13.4	0.173		
	I6	15.1	0.289		
	I8	15.3	0.462		
	Total	13.3	1.740		
B1	PI	5.0	0.000	3.502	<.001
	I2	5.8	0.289		
	I4	7.2	0.231		
	I6	10.1	0.346		
	I8	10.6	0.115		
	Total	7.7	2.332		

A6	PI	10.2	0.289	1.096	<.001
	I2	10.9	0.462		
	I4	11.8	0.173		
	I6	13.6	0.115		
	I8	14.4	0.289		
	Total	12.2	1.647		

A1 – A5: Number of recalls for List A (5 times), B1: Number of recalls for List B (1 time), A6 – A7: Immediate recalls for List A (2 times), Recognition: Number of words from List A.

The favourable outcome observed in the health bar intervention's impact on Health-Related Quality of Life (HRQoL) was primarily attributed to the beneficial components presented in the health bar formula. This included the incorporation of dark chocolate compound, known to enhance mood according to research by Spencer *et al.* (2017), alongside date powder, recognised for its potential to bolster mental well-being based on findings by Moslemi *et al.* (2023). Over two months, the dietary intervention involving the consumption of health bars showed potential for improving individuals' overall quality of life.

Based on a sample size of 16 participants (df_between = 1, df_within = 14), the calculated effect sizes using eta squared (η^2) demonstrated the substantial impact of the health bar intervention. Physical well-being showed a huge effect size ($\eta^2 = 0.765$), indicating strong physical and vitality improvements. Emotional well-being ($\eta^2 = 0.587$) and social functioning ($\eta^2 = 0.659$) also reflected large effect sizes, suggesting significant enhancements in emotional resilience and social interactions. Meanwhile, school-related functioning showed a moderate to large effect size ($\eta^2 = 0.333$), indicating a noticeable, though comparatively more minor, improvement in academic engagement. These effect sizes highlight the meaningful influence of the intervention, even within a small sample.

3.4 Result on Rey's auditory verbal learning test

Before the intervention, rey's auditory verbal learning test (ravlt) was conducted every two weeks for two months. the results are tabulated in Table 7.

The Rey Auditory Verbal Learning Test (RAVLT) results for male participants following several weeks of intervention offer insights into the impact of the intervention on their memory performance. across different intervention periods, significant improvements were observed in total recall scores, as evidenced by notable increases in mean scores from the pre-intervention (p1) phase to subsequent intervention periods (12 (2-weeks of intervention), 14 (4-weeks of intervention), 16 (6-weeks of intervention), and 18 (8-weeks of intervention)) for each recall trial (a1 to a7). for instance, in trial a1, the mean recall score rose steadily from 5.0 in the pre-intervention phase to 9.2 in the final intervention phase (18). this pattern of improvement is consistent across all recall trials, demonstrating the effectiveness of the intervention in enhancing participants' ability to recall verbal information. these gains in verbal memory suggest improved capacity to retain instructions, remember learning material, and perform better in academic settings. enhanced memory supports everyday functioning, such as recalling schedules, organising tasks, and managing responsibilities more effectively.

Furthermore, recall scores across all trials significantly increased over the intervention periods, indicating a cumulative enhancement in memory performance. from a mean score of 43.2 in the pre-intervention phase, the total recall score rose to 66.3 in the final intervention phase (18), underscoring the overall efficacy of the intervention in improving memory function among male participants.

Additionally, in the recognition phase, significant improvements in recognition memory were observed across intervention periods. similar to the recall trials, there was a consistent upward trend in mean recognition scores from the pre-intervention phase to subsequent intervention phases (12, 14, 16, and 18). this suggested that the intervention enhanced participants' recall of information and improved their ability to recognise previously presented verbal stimuli. the result for ravlt for female participants was displayed in table 8.

The rey auditory verbal learning test (ravlt) results for female participants following several weeks of intervention shed light on the effects of the intervention on their memory performance. across various intervention periods, significant improvements were evident in total recall scores, underscoring the intervention's positive impact on memory function among female participants. notably, in each recall trial (a1 to a7), mean recall scores exhibited consistent increases from the pre-intervention (p1) phase to subsequent intervention phases (12, 14, 16, and 18). for example, in trial a1, the mean recall score rose steadily from 5.8 during the pre-intervention phase to 9.1 in the final intervention phase (18). this trend persisted across all recall trials, reflecting the effectiveness of the intervention in enhancing participants' ability to retrieve verbal information from memory.

Moreover, recall scores across all trials significantly increased over the intervention periods, indicating a cumulative improvement in memory performance among female participants. from a mean score of 45.1 in the pre-intervention phase, the total recall score escalated to 66.3 in the final intervention phase (18), highlighting the overall efficacy of the intervention in enhancing memory function. Furthermore, in the recognition phase, significant enhancements in recognition memory were observed across intervention periods. Similar to the recall trials, there was a consistent upward trajectory in mean recognition scores from the pre-intervention phase to subsequent intervention phases (I2, I4, I6, and I8). This indicated that the intervention enhanced participants' recall of previously presented verbal stimuli and improved their ability to recognise them when presented again.

The Rey Auditory Verbal Learning Test (RAVLT) results exhibited notable influence from the health bar intervention, attributed to its exceptional nutrient composition. The health bars, enriched with 1152 mg/kg magnesium, 0.80 mg/100g vitamin E, 8.91% DPPH inhibition, 6797.84 linoleic acid, and 3011.79 alpha-linolenic acid, showcased a robust combination of essential nutrients (Mohd Noor *et al.,* 2024). These nutrients were renowned for their potential cognitive benefits, including improved memory function and cognitive performance (Hashimoto & Hossain, 2011).

The observed gender differences in memory performance improvements may be attributed to several cognitive and neurobiological factors. Research suggests that females often exhibit stronger verbal memory and language-related processing, possibly due to differences in brain structure and hormonal influences such as oestrogen, which is known to affect hippocampal function—a key region for memory (Yasinta *et al.,* 2021). These biological advantages could partly explain why female participants demonstrated slightly higher baseline recall scores and more pronounced gains during the intervention (Spencer *et al.,* 2017). A similar study explained that social and behavioural factors, such as greater attentiveness, task engagement, or verbal rehearsal strategies commonly employed by female students, may have further contributed to their improved performance. These distinctions highlight the importance of considering gender-specific cognitive strengths when designing and evaluating memory-enhancing interventions.

Magnesium supports synaptic plasticity and neurotransmitter release, while vitamin E protects neurons from oxidative stress (Yasinta *et al.,* 2021). The health bars' antioxidant properties (8.91% DPPH inhibition) may further prevent neuronal damage and support cognitive health. Essential fatty acids also contribute to synaptic integrity and cognitive function.

Moreover, ingredients like date powder, moringa powder, sacha inchi oil, and pumpkin seeds provide antioxidants, polyphenols, flavonoids, omega-3s, zinc, and magnesium, all essential for neuroprotection and cognitive processing.

The intervention led to notable improvements in recall and recognition memory, highlighting the intervention's effectiveness in enhancing cognitive function and overall mental well-being among male participants. Female participants demonstrated parallel gains, further supporting the potential of the health bar intervention to enhance cognitive performance.

4. Conclusion

The study assessed health and cognitive performance improvements among children and adolescents through a combined survey and health bar intervention. Anthropometric data and cognitive function were evaluated across different age groups. The study analysed body weight, height, and BMI, identifying variations in nutritional status, including cases of malnutrition, obesity, and growth patterns, which highlighted the diverse nutritional challenges within the community.

Moreover, cognitive function was measured using PedsQL and RAVLT. The PedsQL results showed improvements in physical, emotional, social, and school-related well-being, particularly among males. The RAVLT indicated enhanced recall and recognition memory in both genders.

The intervention significantly improved health and cognitive performance, with notable benefits for both male and female participants. The study emphasised the role of socioeconomic and environmental factors in influencing these outcomes, highlighting the need for targeted interventions to address food insecurity.

Overall, the health bar intervention positively impacted health and cognitive performance in children and adolescents from the B40 community, demonstrating measurable improvement in nutritional programs in mitigating socioeconomic disparities in health and development. Otherwise, several adjustments are recommended for future research, including extending the intervention period for more robust results and considering combining multiple methods to collect data.

This study highlights the crucial link between nutrition and cognitive performance, particularly in children and adolescents, emphasising its impact on academic success. It underscores the importance of a holistic educational approach that integrates health promotion—such as nutrition education, access to healthy meals, and physical activity—into school settings. By doing so, educators and policymakers can better support students' physical, mental, and emotional well-being, ultimately enhancing learning outcomes. The findings also call for institutional and government-level policy changes prioritising student nutrition, particularly for low-income communities. These include increased funding for school meal programs, stricter nutrition standards, and collaborative strategies between the health and education sectors. Professional development for educators on nutrition and health can further strengthen their ability to foster supportive and healthy learning environments.

5. Acknowledgement

The authors acknowledge their gratitude for the funding provided by the Ministry of Education, associated with Ministry Project ID: RACER/1/2019/STG03/UIAM/1.

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HALALSPHERE
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Revisiting contemporary halal research from the perspective of the *tawhidic* paradigm

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Received:17/3/2025
Accepted:13/7/2025
Published:31/7/2025

Keywords:
Tawhidic, Islamization of knowledge, Relevantization, Halal, Integration

Abstract

The concept of halal, established over 1,400 years ago in the *Qur'an*, has only recently developed into a commercial industry within the global Islamic economy. This evolution has placed the halal industry within a capitalist ecosystem, which has helped it expand into sectors beyond food but has also raised concerns about potential economic exploitation that may dilute its faith-based values. Recognising this, the study investigates whether halal research aligns with the *tawhidic* paradigm—rooted in the unity of God and Islamic values—through an analysis of halal-related publications. Using thematic analysis, the study categorises publications within halal science and education, guided by the framework of the Islamization of knowledge. Data sourced from Scopus and Google Scholar is classified into five categories: un-Islamic, conventional studies, conventional halal studies, relevantization, and Islamization. Findings reveal that most articles fall within the "relevantization" category, indicating applications of Islamic teachings in modern issues. However, the degree of relevantization may still be minimal, portraying only limited *tawhidic* elements. This suggests that current halal research does not consistently safeguard halal as a divinely ordained system. Focusing on articles aligned with 'conventional halal studies' could help emphasise the *tawhidic* elements in halal-related work. By fostering more faith-based halal research, the study proposes that the industry can better retain its spiritual integrity, highlighting halal's unique religious and ethical dimensions. This approach is essential for preserving halal's sanctity as a faith-bound system while addressing contemporary challenges in science and education.

1. Introduction

The demand for halal products has increased significantly over the past decades, with Muslim spending rising from US$1.62 trillion in 2012 to US$2.29 trillion in 2022. (Dinar Standard, 2023). Halal has been inherently present in all aspects of life as commanded by *Allah* SWT in the *Qur'an*, revealed more than 1400 years ago but its industry only emerged as market reality and commercially lucrative sector of the Islamic economy in the last few decades (Kamali, 2021), implying that the industry was 'created in' or 'born into' a capitalist ecosystem. While this industrialised ecosystem seems to support the expansion of halal and its industry into various sectors (in addition to food as a readily visible sector for halal), there is a growing concern that it is riding on religious platform (intentionally or unintentionally) to gain economic benefits and regrettably losing the *roh* (soul, spirit) and the faith-bound values. The mere adoption and adaptation of the halal industry to the capitalistic ecosystem has resulted in unfavourable consequences, such as the halal market monopoly by only a particular segment of the population. For instance, data from the Malaysian Islamic Development Department (Jabatan Kemajuan Islam Malaysia, JAKIM) showed that more than 60% of halal product manufacturers in Malaysia were multinational companies owned by non-Muslims (The Malay Mail, 2019).

Delving into the above crisis, the root cause could be the unclear current halal body of knowledge (tainted with secular and capitalist concepts rather than abiding by the *tawhidic* paradigm). In contrast, if the intention and processes revolving around the development of halal products and services are based on the *tawhidic* foundation, it could solve the crisis of halal being trapped in the secularistic and capitalistic paradigm. As such, a 'true' halal body of knowledge based on a *tawhidic* paradigm is important to uphold the religious aspects of halal from being manipulated.

1.1 *Tawhidic* paradigm and the Islamization of knowledge

A *tawhidic* paradigm has been described as having the components of faith, theory, and practice, which include ethics and behaviour related to the absolute oneness of *Allah* SWT (Mohd Khalid *et al.*, 2021).

In a speech given by almarhum Tan Sri Distinguished Professor Dr Mohd Kamal Hassan in 2009 (and published in 2010), the *tawhidic* paradigm was defined to encapsulate the expected character and way of life that one should lead to attain a harmonious life here in the world and the hereafter, where, according to this definition.

> "Tawhid - the uncompromising Islamic monotheism based upon the absolute oneness of *Allah* as the Most Compassionate, Most Merciful, Omnipresent Master of the universe and the Living Ruler of all mankind, who has laid down the Divine Path for (a) the proper growth and well-being of human beings as His servants (*'ibad al Rahman*), vicegerents (*khulafa fi al ard*), believers (*al-mu'minin*), and (b) the best form of social grouping, social solidarity and transnational community with the attribute of the best community brought forth (by *Allah* (SWT) for mankind (*khaira ummatin ukhrijat lil-nas*) (*Qur'an* 3:110) and the justly balanced community to be a witness to all people (*ummatan wasatan li takunushuhada 'ala al-nas* (*Qur'an* 2:143)."
>
> (Hassan, 2010)

Islamization of knowledge (or, interchangeably, Islamization of human knowledge) ensures that knowledge is created and disseminated in the *tawhidic* paradigm. The concept of 'Islamization of knowledge' was first introduced in the late 1970s by Syed Muhammad Naquib al-Attas, a contemporary Malaysian philosopher (Al-Attas, 1993), in response to secularisation. The concept of Islamization of knowledge was further built upon by other eminent scholars like Ismail Raji al-Faruqi and Syed Hossien Nasr using varied approaches. However, the core values remain the same, i.e. the *tawhidic* paradigm (Ahsan et al, 2013).

Within the overarching effort of Islamization of knowledge, integration and relevantization have been described as critical processes (CENTRIS, 2013). Islamization is the liberation of human beings from various old traditions that bind them, such as magical traditions, mythology and so on, so that human beings are free and do not depend on the occult, mythology, animism, superstition and free from secularism (al-Attas, 2018). Integration is a means to realise the Islamization of knowledge by unifying religious and non-religious sciences (Abu Sulayman, 1997). Meanwhile, relevantization is referred to as reforming (*islah*), renewing (*tajdid*) and constant improvement in areas of religious sciences to maintain their relevance to the contemporary issues of humanity, environment and civilisation (Hassan, 2009).

1.2 Research and knowledge creation in the halal industry

Research, development, and innovation (R&D&I) are fundamental in the knowledge creation and academic pursuits. Ideally, the R&D&I outputs could and should be translated into real applications and solutions in the industry (Papalampropoulou-Tsiridou, 2021). In the halal industry, research contributes to expanding knowledge and discovering new findings, which can assist in fulfilling the needs and providing solutions to halal industry stakeholders. Ahmad *et al.*, (2011) argued that halal-related studies and knowledge should also not be overlooked to ensure the sustainability of the halal industry (Aziz *et al.*, 2015). In Malaysia, for instance, the halal industry has been reported to receive support from academia in terms of research and development, as well as nurturing human resources (Zain *et al.*, 2017). However, other studies reported imbalances between research in halal areas and the growth of the halal industry, with the former not being able to catch up with the latter. (Mohamed Ismail *et al.*, 2020).

In a recent development, the Malaysian National Industry Masterplan (NIMP) identified research as one of the strategies in the mission to advance the economic complexity towards a competitive industry, including the halal sector (MITI, 2023). This is a response to the challenge identified where R&D activities in the halal industry mainly focus on strengthening halal compliance, while a minimal focus is given on innovation (MITI, 2023). It is also a positive development considering that the action plans related to research as elements or strategies were not explicitly mentioned in the Malaysian Halal Industry Master Plan (HIMP) 2030 (which was launched prior to NIMP) (Ministry of Economic Affairs), despite R&D&I being the backbone of a progressive halal ecosystem.

To this end, it can be seen that although there are pockets of research looking at halal industry from the perspective of studies on halal industry sectors such as work by Putera *et al.* (2023), Mohd Zaki *et al.* (2023) and Hashim *et al.* (2022) as well as numerous other bibliometric work on specific halal sub-sectors, work on identifying its translational impact to the real world is very scarce while work on examining the paradigm of which the halal research is being carried out is far more scarce or non-existence.

Reiterating the concern that the halal industry, including its R&D&I, is being created in the secular and capitalist worldview, this study aims to classify halal-related publications based on the *tawhidic* paradigm guided by the concept of Islamization of knowledge. The insights revealed through the process would enable a better understanding of the current knowledge of halal science and education. This would help answer whether the current halal-related research is being carried out within the framework of the *tawhidic* paradigm, thus safeguarding the sanctity of halal as a divine system bestowed on humankind.

2. Methodology

This study used thematic analysis, a qualitative research method, to identify patterns and themes within a dataset to uncover the underlying meaning, gain insights into halal science and halal education body of knowledge, and integrate *tawhidic* concepts and modern knowledge. The data set used in this study was systematically obtained from Scopus and Google Scholar in the scope of halal science and halal education. The definition of 'halal science' varies, but it generally refers to applying conventional science and technology (S&T) in areas related to halal. Some researchers emphasise that S&T in this context should be approached with an awareness of religious principles, given that halal is a faith-based system ordained by *Allah* SWT (Hashim *et al.*, 2024).

Meanwhile, in this work, a general operational definition of halal education refers to halal knowledge and curriculum at any educational level. In a work reported by Jais (2014) a decade ago, the author argued that despite its critical role in

developing talent and human capital for the halal industry, the area of halal education, particularly in curriculum and syllabus design, remains underexplored. Research in halal education and curriculum and halal studies has been very scarce. The Malaysian Qualification Agency (MQA) Programme Standard on Halal Studies has been categorised into two main halal fields: management and applied Science (MQA, 2022). However, no specific reference to halal education or curriculum exists except for the recommended body of knowledge. One recent bibliometric work reported that halal knowledge and education clusters were centred on perceived knowledge and consumer behaviour studies, not the halal curriculum or syllabus (Hashim *et al.*, 2024).

Before generating the initial codes, which are labels or tags assigned to data segments that represent important concepts or ideas, researchers worked to understand the context and content of the data to capture meaningful units of information within the dataset. To guide the process, this study adopted a framework on Islamisation of Knowledge and Islamic Knowledge Management developed by the Centre for Islamisation (CENTRIS), International Islamic University Malaysia. The CENTRIS framework was aimed at classifying academic publication outputs (theses and books) based on three categories: conventional study, relevantization and Islamization. In this work, the dataset was already in the scope of halal, so there was a need to expand the categories, as shown in Table 1.

Guided by the framework, the similarity, patterns and connections between the data set were identified. Each article was reviewed, and justification was made about the identified categories. Related codes were then grouped to form potential themes, which are the overarching concepts or patterns that emerge from the data and provide a higher level of interpretation. Each theme was further defined, and the finalised themes were systematically applied to the entire dataset. The themes were validated by examining the supporting evidence from the dataset to extract meaningful insights and interpretations. The key patterns, variations, or connections were identified within and across themes. Being an iterative process, the steps outlined above were revisited and refined throughout the thematic analysis.

3. Results and discussion

The section below describes the classification of halal-related publications based on the *tawhidic* paradigm guided by the concept of Islamization of knowledge. The discussions are based on the identified categories of un-Islamic, conventional studies, conventional halal studies, relevantization and Islamization.

3.1 Categories of halal research

Table 2 shows categories of halal research based on the expanded framework of Islamisation of Human Knowledge and Islamic Knowledge Management. It was observed that most articles from Google Scholar were categorised in the relevantization category. In contrast, for Scopus, almost an even number of articles were found to be in conventional halal studies and relevantization. No articles were categorised as un-Islamic. This meets the requirement as the corpus of data was obtained using the keywords halal science and/or halal education.

3.2 Conventional studies

Based on the framework in Table 1, the studies were classified into the 'conventional studies' category when they are based on sensual experience (observational), scientific procedures, processes of logic and rely upon observable objects derived via empirical methods of enquiry without any reference to religion or being critical of religion. No articles from Google Scholar were found to fit these criteria. Meanwhile, most articles from Scopus were from the natural sciences in gelatin, collagen and species detection using analytical and molecular techniques. For instance, Nurilmala *et al.* (2023) studied the toxicity of gelatin capsule materials from Pangasius skin (*Pangasius sp.*) on mice (*Mus musculus*). This fish gelatin is a halal gelatin that can be an alternative to porcine-based gelatin. However, the halal issue was not the study's main highlight, as the prohibition of porcine-based gelatin was mentioned only once. Another study reported the development of the mitochondrial 12S rRNA gene for identifying dog and rat in beef using multiplex PCR (Cahyadi *et al.*, 2019). The technique helps detect adulteration of halal beef. However, this study did not discuss its potential use in halal.

3.3 Conventional halal studies

In this work, the 'conventional halal studies' criteria were set to extend to the 'conventional studies' but with a more elaborate reference to religion/Islam/halal as described in Table 1. Compared to 67 Scopus articles classified into this category, only three articles from Google Scholar fit this category.

The earliest article in this category was from 2010. The article 'Gap Analysis of MS1500: 2009 Implementation: Malaysia Industry' by Daud *et al.* (2011) discussed the implementation of halal guidelines in food products. Most articles were from science and technology, including authentication using various techniques and developing alternative halal ingredients for food, pharmaceuticals, and cosmetic products.

No articles discussed the academic body of knowledge, philosophy, pedagogy, or curriculum of halal studies as a discipline. This scope of work has been reported to be less explored despite the enhancement of the halal ecosystem, the growth of the halal industry (Hashim *et al.*, 2024 and Jais, 2014) and the effort in developing halal talent, as evident in the MS2691: 2021 Halal Profession – General Requirements (Department of Standards Malaysia, 2021). This may explain the absence of a specific academic definition and authoritative reference on halal education and curriculum. This also calls for a more scholarly work to establish a framework to provide a clear direction for this area of research.

Nevertheless, in science and technology, the reference to religion/Islam/halal is apparent in these articles. This is

Table 1: Framework to classify the dataset (adopted and adapted from CENTRIS framework of Islamisation of Human Knowledge and Islamic Knowledge Management (CENTRIS, n.d)

Unislamic (UI)	Conventional Studies (CS)	Conventional Halal Studies (CHS)	Relevantisation (R)	Islamisation (I)
Emphasises individual freedom of choice **Setting norms/models/standards /which contradict the *Qur'an*, the *Sunnah* and the practice of the early Muslim society**	Studies based upon: • Sensual experience (observational) • Scientific procedure • Processes of logic • Relies upon observable objects derived via empirical methods of enquiry No reference to religion or critical of religion	May include the elements below, but referred to religion/Islam/halal Studies based upon: • Sensual experience (observational) • Scientific procedure • Processes of logic • Relies upon observable objects derived via empirical methods of enquiry	Studies on: • Islam as a religion and civilisation • The historical and current forms of Islam • Understanding of Islam and society • *'Ulum al-din* (religious sciences) pursued by the ulama • Application of Islamic teachings in contemporary times.	Studies with • Critical evaluation of Western knowledge • Incorporation of revelation into different fields of research • Reflection on Islamic objectives and values • Setting norms/models/standards /which are derived from the *Qur'an*, the *Sunnah* and the practice of the early Muslim society
• **LGBT+, Animal rights against Islamic practices,** • **Human rights against Islamic values**	• Purchase intention of conventional product	• Alternative halal ingredient • Authentication	• Application of Islam in contemporary times (Purchase intention of Islamic Marketing; Muslim friendly tourism, Islamic banking)	• Concept and Principle – e.g, friendly tourism, Islamic Marketing, Islamic banking) • Development of guidelines/fatwa for halal vaccine, cultured meat and emerging products and service trends

Table 2: Categories of halal research based on the expanded framework of Islamisation of Human Knowledge and Islamic Knowledge Management (Islamization of knowledge)

	Google Scholar	Scopus
Unislamic (UI)	0	0
Conventional Studies (CS)	0	9
Conventional Halal Studies (CHS)	3	67
Relevantisation (R)	84	60
Islamisation (I)	6	21
TOTAL	93	157

evident in the earlier articles as well as the later ones. For instance, in 2012, when halal laboratories were in their early establishment, Rohman and Che Man reported an analytical technique to detect pork derivatives (Rohman & Che Man, 2012). The halal authentication techniques have evolved over the years. More advanced techniques were studied, such as using LC-Orbitrap HRMS untargeted metabolomics combined with chemometrics to analyse the presence of pork in beef sausages (Windarsih, 2023). Both research works clearly stated that halal authentication was the objective of the studies.

3.4 Relevantization

The 'relevantization' category had the most significant publications, with 144 articles across Google Scholar and Scopus. Most articles were studies from the social sciences and humanities, meeting at least one of these criteria: i) understanding of Islamic society or ii) application of Islamic teachings in contemporary times. Within the social science and humanities areas, the articles discussed, among other topics, topics of halal knowledge, halal awareness, perceived behaviour, and purchase intention.

It was observed that the context of halal knowledge in these articles differed from halal education, where the latter referred to a more structured syllabus of halal curriculum at any educational level. At this juncture, it can be argued that the effort to make relevantization optimal can be made if it is infused in a structured curriculum (Maulana, 2014). The dearth of halal education/curriculum-related research seen in this study could signal a sub-par relevantization effort in the halal-related areas.

Although most of the articles in this category were from a social science background, the earliest article (2009) was a scientific study by researchers at the Halal Science Centre, Chulalongkorn University, Bangkok, Thailand. The group reported the development of clay liquid detergent to clean *najs* (Angkatavanich *et al.*, 2009). This article meets the relevantization category based on its focus on applying Islamic rituals in contemporary times using a modern approach.

The application of Islam in contemporary times can also be seen in social science-related research. For instance, Aziz and Najmudin (2023) studied the influence of halal knowledge on the intention of tourists to visit a *Shari'ah* tourism spot in Indonesia. In recent years, *Shari'ah*-compliant tourism (also referred to as Islamic tourism, halal tourism and Muslim-friendly tourism) has been flourishing. It has been reported that halal travel in 2022 reached US$133 billion, up 17% from US$114 billion in 2021, and is forecasted to reach US$174 billion in 2027 at a CAGR of 5.5% between 2022 and 2027 (Dinar Standard, 2023). This upward trend is also seen in the research work related to this area, as Suban *et al.* (2021) described in their bibliometric work.

A recent scientific study investigated how religious affiliation and knowledge of halal practices affect the decision to take the COVID-19 vaccination (Nurrahmi *et al.*, 2023). This work showed that Islamic tenets are being applied in responding to the recent pandemic, a global-scale contemporary issue that has not occurred before. As such, this work fulfils the criteria of the relevantization category.

From the perspective of Islamization of Knowledge, the works (halal-related research) analysed in this study are inherently faith-bound such that they fit the relevantization elements as described in the IIUM Policies and Guidelines on Islamisation (CENTRIS, 2013)

> "…of *taghyir* (individual or societal change), *islah* (reform and improvement, *tajdid* (renewal, revitalization, restoration and reconstrucation), *ihya'* (revival, regeneration, revivification), *takamul* (integration of practical knowledge or skills from other disciplines, including those from human, social or natural sciences) and *ijtihad* (exercise of independent legal reasoning in facing new issues not covered by the revealed texts) to bring about the necessary changes in Muslim and human societies."
>
> "…the terms *taghyir, islah, tajdid, ihya', takamul* and *ijtihad* or contextualization are more appropriate than Islamisation or Islamicisation. However, the English word preferred to be used in the Kulliyyah to represent all the five Arabic terms put together is "relevantisation…"

(note: the description was referred to the case of Islamic Revealed Knowledge departments at the Kulliyyah of Islamic Revealed Knowledge and Human Sciences at the International Islamic University Malaysia (IIUM))

3.5 Islamization

There were 27 articles in the Islamization category. The earliest article was published in 2012, in which the author discussed the Islamic principle of *Istihalah* (transformation or conversion of material that involves changes in its composition and properties) process and knowledge and how it can be set as a norm in the Muslim community (Aris *et al.*, 2012).

Studies on halal science concepts from the *Qur'an* dominated the Google Scholar source. This could be a response from researchers to refute some views on the significance of halal science as an academic discipline or whether halal science is even a valid term. Meanwhile, articles in Scopus were observed to include setting the standard/norms using *Shari'ah* and *Qur'anic* teaching in areas of halal industry in general, and in more specific fields like medical tourism, and scenarios like multiculturalism. Other articles described incorporating revelation as an approach in various fields, such as environmental protection and reflection on Islamic objectives and values, such as finding a spouse.

3.6 The current landscape, challenges and strategies

Based on the findings presented above, it was observed that around 58% of the articles are classified in the relevantization category and 28% in the conventional halal studies category. This suggests that topics of interest in the halal research are i) contemporary, addressing the current needs of industry and society, and ii) being referred to Islamic legacy to some extent. However, the body of knowledge in these articles may not be substantially aligned with the *tawhidic* paradigm. A push towards articles that fulfilled the 'conventional halal studies' may help elevate the *tawhidic* elements in the halal-related work. In this category, the aim to propel halal as a faith-based system is explicit.

Several challenges can be drawn from the data obtained. Since halal is a faith-based system, research on halal should be *Shari'ah*-abiding. However, since halal covers a wide range of topics (from science and technology to social science and humanities and religious studies), references to *Shari'ah* aspects could be sub-par. This is especially true for science and technology studies, where the topics are commonly discussed using a modern scientific approach. This is mainly due to the conventional structure of the body of knowledge adopted in journal publications, where the sciences and religion are separated. To be publishable in a high-impact journal (often owned by international publishers), the research article must meet the specific scope or focus of the journal, which renders religious matters secondary or not mentioned at all. The race for the fulfilment of key performance index (KPI) of publication in reputable journals could also be a factor that hinders the integration of sciences and religion. This calls for a higher-

Table 3: Articles categorised under 'Conventional studies'

Title	Justification	Reference
Google scholar		
Not available		
Scopus		
***Rhodopseudomonas palustris* Collagen-like Recombinant Protein Purification using an Aqueous Two-Phase System**	Scientific procedure for collagen, halal was not explicitly mentioned	Awang *et al.* (2023)
Toxicity Test of Gelatin Capsule Materials from Pangasius Skin (Pangasius sp.) on Mice (*Mus musculus*)	Scientific procedure to test the toxicity of gelatin, and alternative ingredients to use other than porcine. Mentioned the prohibition to Muslims one time (not the main objective of this paper)	Nurilmala *et al.* (2023)
Exploring Gastronomic Tourism Experiences through Online Platforms: Evidence from Thai Local Communities	Explore tourists' local gastronomic experiences and their impacts on local communities	Kattiyapornpong *et al.* (2022)
Pangasius Fish Skin and Swim Bladder as Gelatin Sources for Hard Capsule Material	Scientific procedures were used to make gelatin from fish skin, and alternative ingredients were used to make gelatine other than lard, but they did not mention Islamic thought/halal	Nurilmala *et al.* (2021)
Reducing Musculoskeletal Complaints and Fatigue through Participatory Ergonomics on the table and Chair Design of Participants of Halal Assurance System (HAS) Training in IPPOM MUI of Banten, Indonesia	Sensual experience, duration, and condition in the HAS class did not relate to the Islamic approach	Susihono *et al.* (2020)
Comparing the Effect of Heat on Tropomyosin Isoforms Patterns from Water Buffalo and Wild Boar Meat by Two-Dimensional Gel Electrophoresis	Scientific procedure differentiates water buffalo and wild boar following the application of heat; no reference to religion	Junoh *et al.* (2019)
Development of Mitochondrial 12S rRNA Gene for Identification of Dog and Rat in Beef using Multiplex PCR	A scientific procedure to detect species of rat and dog in beef by simplex and multiplex PCR assays	Cahyadi *et al.* (2019)
Development of Antipeptide Enzyme-linked Immunosorbent Assay for Determination of Gelatin in Confectionery Products	Scientific procedure: analysis of types of gelatin. One time only mention about halal (conclusion, line 10)	Tukiran *et al.* (2016)
Determination of Porcine Gelatin in Edible Bird's Nest by Competitive Indirect ELISA based on Anti-peptide Polyclonal Antibody	Scientific procedure to evaluate the efficiency of polyclonal antibodies (pAbs) against peptide immunogens in detecting porcine gelatin in EBN by competitive indirect ELISA	Tukiran *et al.* (2016)

Table 4: Articles categorised under 'Conventional halal studies'. Only articles from 2020-present are shown.

Title	Justification	Reference
Google scholar		
A Comparison of High School Students' Knowledge and Satisfaction Regarding Basic Science and Halal Science Literacy Training Course	It may include conventional elements such as science and technology, but refer to halal/religion; it may also include observing students' knowledge	Mhamad *et al.* (2022)
Urgensi Halal Knowledge dan Kasus Faktual Kontaminasi Produk Haram di Masyarakat	It may include conventional elements such as contamination, but refers to halal/religion	Nusran (2021)
Zebrafish Nutrition: Promoting Fish Health and Welfare of the Animal Model in Halal Science Research	Scientific procedure; May include conventional elements but refers to religion (halal science)	Idris *et al.* (2022)
Scopus		
A Bibliometric Analysis of Applied Technology Development of Halal Food Sciences	May include conventional elements (bibliometric) but made reference to religion/Islam/halal	Hastuti *et al.* (2023)
Analysis of Pork in Beef Sausages using LC-Orbitrap HRMS Untargeted Metabolomics Combined with Chemometrics for Halal Authentication Study	Scientific procedure on halal authentication of adulterated meat	Windarsih *et al.* (2023)
Response Surface Methodology (RSM) for Optimization of Gelatin Extraction from Pangasius Fish Skin and Its Utilization for Hard Capsules	Alternative ingredients for gelatin	Nurilmala *et al.* (2023)
Multiplex Platforms in Biosensor-based Analytical Approaches: Opportunities and Challenges for the Speciation of Animal Species in the Food Chain	May include conventional elements (authentication techniques) but refer to Islamic approaches	Sultana *et al.* (2023)
CRISPR/Cas12a-mediated Enzymatic Recombinase Amplification for Rapid Visual Quantitative Authentication of Halal Food	Scientific procedure; detection platform for the authentication of halal food	Wang *et al.* (2023)
Duplex Droplet Digital PCR (ddPCR) for Simultaneous Quantification of Bovine and Porcine Gelatin in Capsules	Scientific procedure; Concerns about health and religious beliefs have been raised regarding the intake of gelatin	Mahamad *et al.* (2023)
Potential Technical Parameters for the Authentication of Carrion Meat (Tiren): A Review	Scientific procedure; authentication of meat	Purwanto *et al.* (2023)
Analysis of Lard in Palm Oil using Long-Wave Near-Infrared (LW-NIR) Spectroscopy and Gas Chromatography-Mass Spectroscopy (GC–MS)	Scientific procedure: adulteration of palm oil with lard. Mentioned about halal/ haram	Hussain *et al.* (2023)

The Competitiveness, Challenges and Opportunities to Accommodate the Halal Tourism Market: A Sharia-law Tourism Destination Perspectives	It relies upon an observable objective and explores the stakeholders' perception of Halal tourism	Hariani *et al.* (2023)
Halal Authentication using Lateral Flow Devices for Detection of Pork Adulteration in Meat Products: A Review	Scientific procedure on halal authentication of adulterated meat	Raja Nhari *et al.* (2023)
Halal Research Streams: A Systematic and Bibliometric Review	Bibliometric review on research streams regarding Halal literature: Consumer Behaviour, Islamic Branding, Islamic Marketing, Halal Supply Chain, Halal Certification, and Halal Tourism	Putera and Rakhel (2023)
Detection of Porcine DNA in Korean Processed Foods by Real-Time PCR	Scientific procedures for detecting pork DNA refer to Islamic thought	Kim *et al.* (2023)
Some Insights Concerning the Halal Tourism Research. A Bibliometric Analysis	An analysis of halal tourism	Riduan and Syamsurrijal (2022)
Determination of Alcohols in Various Fermented Food Matrices using Gas Chromatography-Flame Ionisation Detector for Halal Certification	Scientific procedure: analysis of alcohol in fermented food	Kim *et al.* (2022)
Volatile Compounds, Texture, and Colour Characterisation of Meatballs made from Beef, Rat, Wild Boar, and Their Mixtures	Scientific procedure to characterise the volatile compounds, texture, and colour profile of meatballs made from beef, rat, wild boar, and their combinations. Concern about the Muslim majority in Indonesia	Amalia *et al*. (2022)
Profiling of Volatile Compounds in Beef, Rat, and Wild Boar Meat using SPME-GC/ MS [Pemprofilan Sebatian Meruap dalam Daging Lembu, Tikus dan Babi Hutan menggunakan SPME-GC/MS]	Scientific procedure; identified the volatile compound markers, reference to Islamic approaches (halal/non-halal)	Amalia *et al*. (2022)
Halal-Tayyiban and Sustainable Development Goals: A SWOT Analysis	Discuss and uncover the various strengths, weaknesses, opportunities, and threats in incorporating the concept of toyyiban in the halal food industry	Idris *et al*. (2022)
Fish Skin as a Biomaterial for Halal Collagen and Gelatin	Scientific procedure for making fish skin as a halal gelatin	Nurilmala *et al.* (2022)
Modern on-site Tool for Monitoring Contamination of Halal Meat with Products from Five Non-Halal Animals using Multiplex Polymerase Chain Reaction Coupled with DNA Strip	Scientific procedure to detect meat contamination	Denyingyhot *et al.* (2022)
A New Tool for Quality Control to Monitor Contamination of Six Non-Halal Meats in the Food Industry by Multiplex High-Resolution Melting Analysis (HRMA)	Scientific procedure, new tool to detect the non-Halal ingredients, valuable tools for HAS in halal production	Denyingyhot *et al.* (2021)

Online Traceability of Halal Food Information to Protect Muslim Consumers in the Cyber Era	May include conventional elements (traceability) but referred to religion/Islam/halal (halal food information)	Azizah (2021)
Volatilomics for Halal and Non-Halal Meatball Authentication using Solid-Phase Microextraction–Gas Chromatography–Mass Spectrometry	Scientific procedure to detect the adulteration of beef meatballs with wild boar, mentioned regarding Muslim concerns	Pranata *et al.* (2021)
Good Idea but Not Here! A Pilot Study of Swedish Tourism Stakeholders' Perceptions of Halal Tourism	Observation to get the perception of halal tourism in Sweden among representatives of tourism stakeholders	Abbasian (2021)
Implementation of Halal Product Assurance in the Pharmaceutical Sector in Indonesia	Implementation of halal certification for the pharmaceutical business	Luthviati Jenvitchuwong (2021)
Real-Time PCR to Identify Porcine DNA in Prosthodontic Materials	Scientific procedure: to detect halal materials contaminated by haram materials (porcine)	Hutasoit *et al.* (2021)
Application of Spectroscopic and Chromatographic Methods for the Analysis of Non-Halal Meats in Food Products	Scientific procedure to analyse non-halal meat in food products	Rohman and Fadzillah (2021)
Heuristic Evaluation on Mobile Halal Detection Application	Alternative for halal: evaluating the halal MUI application using a heuristic evaluation approach	Ridwan *et al.* (2020)
Review on Analytical Methods for Analysis of Porcine Gelatine in Food and Pharmaceutical Products for Halal Authentication	Scientific procedure: halal authentication on gelatin	Rohman *et al.* (2020)
Detection of Porcine Pepsin in Model Cheese using Polyclonal Antibody-based ELISA	Scientific procedure; established the ELISA used for the detection of porcine pepsin in a model cheese	Raja Nhari *et al.* (2020)
Potential Authentication of Various Meat-based Products using a Simple and Efficient DNA Extraction Method	Scientific procedure implemented to assist the halal authentication of various meat-based products	Khairil Mokhtar *et al.* (2020)
Potentiality of Analytical Approaches to Determine Gelatin Authenticity in Food Systems: A Review	May include conventional elements (authenticity of gelatin) but referred to religion (halal, Islamic approaches)	Ishaq *et. al.* (2020)
Detecting Adulteration in Halal Foods	Scientific procedure on adulteration	Farag (2020)

Reducing Musculoskeletal Complaints and Fatigue through Participatory Ergonomics on the table and Chair Design of Participants of Halal Assurance System (HAS) Training in IPPOM MUI of Banten, Indonesia	Sensual experience, duration, and condition in the HAS class did not relate to Islamic approaches.	Susihono *et al.* (2020)
A Literature Review and Classification of the Studies on "Halal" in Islamic Business Journals (2010-2018)	A literature review of findings that focus on halal in Islamic business	Baran (2020)
Postmarket Laboratory Surveillance for Forbidden Substances in Halal-Certified Foods in Thailand	May include conventional elements (lab surveillance), but referred to religion/Islam/halal (halal certified food)	Mahama *et al.* (2020)

Table 5: Articles categorised under 'Relevantization'. Only articles from 2020-present are shown.

Title	Justification	Reference
Google scholar		
An Intention to Visit Sharia Tourism in Banten: An Effect of Halal Knowledge and Awareness	Application of Islamic teachings in contemporary times, influence of halal knowledge on the intention of tourists to visit *Shari'ah* tourism spots	Aziz and Najmudin (2023)
Determinant of Employment and Employability Attributes in the Halal Sector for Halal Science Graduates in Brunei Darussalam	Application of Islamic teachings (halal science) in contemporary times	Raffi *et al.* (2023)
Effects of Religiosity, Halal Knowledge and Halal Certification on the Intention of Muslims to use the Halal Vaccine during the Covid-19 Pandemic	Application of Islamic teachings (halal knowledge and halal certification) in contemporary times, related to intention	Sudarsono *et al.* (2023)
Exploring Halal Awareness and Halal Knowledge of the Information and Communications Technologies Industry in Bangladesh	Application of Islamic teachings (halal knowledge and halal awareness) in contemporary times	Islam *et al.* (2023)
Exploring the Impact of Religiosity, Halal Knowledge, and Subjective Norms on Purchase Intention of Japanese Food in Indonesia	Application of Islamic teachings (halal knowledge) in contemporary times, related to intention	Ardiyanto *et al.* (2023)
Halal Food Knowledge among Non-Muslim Food-Services Workers in General Santos City, Philippines	Understanding Islam (halal) and society	Jasa (2023)
Integrating Halal Knowledge towards Selection of Islamic Banking Product: The Perspective of Muslim Students	Application of Islamic teachings (Islamic banking) in contemporary times, to examine the halal knowledge and financial information disclosure in the selection of Islamic banking products among Muslim students	Rosli *et al.* (2023)

Makanan Halal pada Street Food: Halal Awareness, Halal Knowledge, Label Halal terhadap Keputusan Pembelian (Studi Kasus Di Kota Malang)	Application of Islamic teachings (halal awareness, halal knowledge on purchasing decisions for halal food at street food) in contemporary times	Sayyaf (2023)
Pemberdayaan Kewirausahaan Berbasis Halal Knowledge pada Pekerja Migran Indonesia (PMI) di Taiwan	Application of Islamic teachings (halal knowledge) in contemporary times	Juwitaningtyas *et al.* (2023)
Pengaruh Brand Awareness, Daya Tarik Iklan, Perceived Quality, dan Knowledge Halal Product terhadap Keputusan Pembelian Geprek Kak Rose di Kota Malang	Application of Islamic teachings (halal products) in contemporary times, related to knowledge and intention	Maghfira *et al.* (2023)
Pengaruh Halal Knowledge, Islamic Religiosity, dan Halal Lifestyle terhadap Penilaian Produk Kosmetik dan Keputusan Pembelian Kosmetik Halal	Application of Islamic teachings (halal cosmetic and skincare) in contemporary times, related to knowledge and intention	Risdiyani (2023)
Pengaruh Halal Lifestyle, Halal Knowledge, dan Promosi terhadap Keputusan Pembelian Brand Merk Rabbani	Application of Islamic teachings (halal knowledge and halal lifestyle) in contemporary times	Anisa (2023)
Relationship between Individual Characteristics and Information Exposed with Halal Food Knowledge for Business Actors	Application of Islamic teachings (halal food products) in contemporary times, related to intention	Syilvia and Putri (2023)
The Effects of Religiosity and Halal Knowledge on the Decision to use the Covid-19 Vaccine	To investigate how religious affiliation and knowledge of halal practices affect the decision to take the COVID-19 vaccination	Nurrahmi *et al.* (2023)
The Hidden Influence of Halal Labeling and Product Knowledge on Customer Loyalty: Unraveling Religiosity's Role among Cosmetic Consumers in Malang	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Akbar *et al.* (2023)
Pengaruh Religiusitas, Halal Knowledge, Halal Awareness, dan Sikap Konsumen terhadap Niat Beli Produk Skincare BLP Skin di Kota Surabaya	Application of Islamic teachings (halal skincare) in contemporary times, related to knowledge and intention	Balqis and Zulaikha (2023)
The Relationship between Halal Knowledge and Perception with the Attitude of Buying Halal Food in the Consumer Community in Jambi City	Application of Islamic teachings (halal knowledge) in contemporary times, related to intention	Triana *et al.* (2023)

The Relationship between Halal Status Knowledge and the Korean Food Products Purchasing Practices in DIY's Muslim Society	Application of Islamic teachings (halal knowledge) in contemporary times, related to intention	Widyaningrum (2023)
Do Knowledge, Perceived Usefulness of Halal Label and Religiosity Affect Attitude and Intention to Buy Halal-Labelled Detergent?	Application of Islamic teachings (halal labelled detergent) in contemporary times, customer purchasing intention	Rizkitysha and Hananto (2022)
Buying Intentions: Do Knowledge, Religiosity, and Halal Certification Matter?	Related to the intention of purchasing a product and knowledge	Hasim *et al.* (2022)
Enhanced Knowledge Sharing Adoption Model in the Halal Food Industry	Application of Islamic teachings (halal food products) in contemporary times, related to the implementation of knowledge	Samsi (2022)
Halal Food Producer as an Alternative Employment Job for Halal Science Graduates in Brunei Darussalam	Application of Islamic teachings in contemporary times, how halal science graduates could get themselves employed in the halal food sector	Deuraseh *et al.* (2022)
Hubungan Tingkat Pengetahuan terhadap Sikap dan Perilaku Mengenai Produk Farmasi Halal pada Apoteker di Apotek Kota Yogyakarta	Application of Islamic teachings (halal pharmaceutical) in contemporary times	Octavia (2022)
Keputusan Konsumen dalam Memilih Hotel Syariah: Ditinjau dari Halal Lifestyle, Muslim Friendly Facilities, dan Knowledge	Application of Islamic teachings (*Shari'ah* hotels) in contemporary times, related to knowledge and intention	Tyas and Supriyanto (2022)
Local Halal Cosmetic Products Purchase Intention: Knowledge, Religiosity, Attitude, and Islamic Advertising Factors	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Najib *et al.* (2022)
Muslim Sellers' Knowledge of Halal Cosmetics Awareness: Regression Analysis Approach Muslim Sellers' Knowledge of Halal Cosmetics Awareness: Regression Analysis Approach	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Jabar *et al.* (2022)
Pengaruh Halal Knowledge, Religiusitas, Sikap Konsumen Generasi Z terhadap Perilaku Konsumen Produk Kosmetik Halal dalam Negeri Studi Kuantitatif di Lingkungan Kota Tangerang	Application of Islamic teachings (halal cosmetic and skincare) in contemporary times, related to knowledge and intention	Kusuma and Kurniawati (2022)
Pengetahuan, Persepsi dan Perilaku Konsumer Mualaf di negeri Terengganu dalam Menggunakan Produk Makanan Halal	Application of Islamic teachings (halal food products) in contemporary times, related to intention	Awang and Izudin (2022)
Relationship between Knowledge and Religiosity with Attitudes towards Halal Food in Muslim Students	Application of Islamic teachings (halal food products) in contemporary times, related to intention	Kurniati (2022)

The Effect of Halal Awareness, Religiosity, Product Ingredients Knowledge, and Halal Certification on the Purchase Decision of Halal Fast Food	Application of Islamic teachings (halal knowledge) in contemporary times	Santosa and Rizaldy (2022)
The Effect of Halal Product Knowledge, Halal Awareness, Perceived Psychological Risk and Halal Product Attitude on Purchasing Intention	Application of Islamic teachings (halal products knowledge) in contemporary times	Öztürk (2022)
The Effect of Knowledge, Religiosity, and Halal Certification on Halal Traceability with Halal Awareness as an Intervening Variable (Case Study of Muslim Traders in Malang Traditional Market)	Application of Islamic teachings (halal traceability) in contemporary times	Pertiwi *et al.* (2022)
The Influence of Halal Knowledge and Labelling on Food Product Purchase Decisions	Application of Islamic teachings (halal knowledge) in contemporary times, related to intention	Febrilyantri (2022)
The Influence of Knowledge, Innovation Compatibility and Social Influence on the Adoption of Halal Cosmetics: An Empirical Evidence from Pakistan	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Sohail *et al.* (2022)
The Intention of the Young Muslim Generation to Purchase Halal Cosmetics: Do Religiosity and Halal Knowledge Matter?	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Riswandi *et al.* (2022)
The Potential Job Opportunities for Halal Science Graduates in the Education Sector in Negara Brunei Darussalam	Application of Islamic teachings (halal science) in contemporary times	Deuraseh *et al.* (2022)
The Relationship of Halal Awareness, Selection of Menu Variation and Nutrition Knowledge with Purchase Decisions: A Study on Chatime Consumers in Surabaya	Application of Islamic teachings (halal knowledge) in contemporary times, related to intention	Palupi and Putri (2022)
The Role of Millennial Knowledge in the Application of Halal Lifestyle	Application of Islamic teachings (halal knowledge and halal lifestyle) in contemporary times	Soehardi (2022)
Do Religiosity, Halal Knowledge, and Halal Certification Affect Muslim Students' Intention to Purchase Halal Packaged Food?	Application of Islamic teachings (halal packaged food) in contemporary times, related to knowledge and intention	Wirakurnia *et al.* (2021)
Effectiveness of Public Service Announcements on Halal Knowledge among Muslim Teenagers during the Time of Pandemic	Application of Islamic teachings (halal knowledge) in contemporary times	Rahim and Saperiz (2021)

Does Halal Science Meet the Criteria of an Academic Discipline?	This article discusses the application of Islamic teachings (halal science) in contemporary times, the definitions of halal science, the current use of the term, and its philosophy	Hashim *et al.* (2021)
The Role of Islamic Banking in the Development of Halal Science and Industry in Nigeria	Application of Islamic teachings (halal science and industry) in contemporary times	Bello and Jaiyeoba (2021)
Transferring Knowledge on Halal Awareness amongst the Orang Asli Community	Application of Islamic teachings (halal knowledge and halal lifestyle) in contemporary times	Othman and Jamaludin (2021)
Faktor Halal Awareness, Religiosity, dan Knowledge terhadap Consumer Decisions dan Implikasinya terhadap Consumer Loyalty	Application of Islamic teachings (halal knowledge and halal awareness) in contemporary times	Sartika and Motik (2021)
Impact of Knowledge, Religiosity, Awareness and Halal Logistics on Purchase Intention	Application of Islamic teachings (halal logistics) in contemporary times, related to knowledge and intention	Yaakub and Sham (2021)
Pengaruh Halal Knowledge, Islamic Religiosity dan Kualitas Produk terhadap Keputusan Pembelian Produk Wardah	Application of Islamic teachings (halal cosmetic and skincare) in contemporary times, related to knowledge and intention	Achmad and Fikriyah (2021)
The Influence of Product Knowledge, Religiosity, Halal Awareness of Purchasing Decisions on Halal Products with Attitude as a Mediation Variable	Application of Islamic teachings (halal products) in contemporary times, related to intention	Fauziah and Al Amin, (2021)
Consumer Knowledge toward Purchasing Halal Label Products in Selangor	Application of Islamic teachings (halal products) in contemporary times, customer purchasing intention	Latiff *et al.* (2020)
Do Religiosity and Knowledge Affect the Attitude and Intention to Use Halal Cosmetic Products? Evidence from Indonesia	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Divianjella *et al.* (2020)
Factors Influencing Malaysians' Halal Knowledge in Purchasing Halal Pharmaceutical Products/Wan Nur Khaleda W. Hassan	Application of Islamic teachings (halal pharmaceutical) in contemporary times	Hassan (2020)
Halal Knowledge Integrity Model (HaKIM) in intensifying the integrity of the Halal industry	Application of Islamic teachings (halal industry) in contemporary times	Mohammad *et al.* (2020)
Halal Knowledge, Religiosity and Celebrity Worship in Determining Muslim Consumers' Purchase Intention on Halal Cosmetics: A Conceptual Model	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Abd Malek (2020)

Meningkatkan Repurchase Intention Kosmetik Halal melalui Halal Knowledge dan Religiusitas Intrinsik dengan Halal Product Attitude sebagai Variable Intervening	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Iliyyin (2020)
Pengaruh Islamic Religiosity dan Halal Knowledge terhadap Purchase Intention Kosmetik Halal Dimediasi oleh Attitude terhadap Produk Halal di Indonesia	Application of Islamic teachings (halal cosmetics) in contemporary times, related to knowledge and intention	Adriani (2020)
Peningkatan Purchase Intention melalui Brand Image Berbasis Halal Knowledge, Brand Knowledge dan Religiusitas pada Produk Indomie	Application of Islamic teachings (halal knowledge) in contemporary times	Widyatni (2020)
Relationship between Awareness, Knowledge, and Attitude of Behavioural Intention Towards Halal Jobs among Malaysian Muslim University Students	Application of Islamic teachings (halal jobs) in contemporary times, related to intention	Hashim et al (2020)
The Deeper of Consumer Knowledge towards Intention to Purchase Halal Food Products in Indonesia	Application of Islamic teachings (halal food products) in contemporary times, related to intention	Riptiono and Bangsa (2020)
The Effect of Consumer Psychology, Halal Knowledge and Religiosity on Halal Purchase Decisions in Indonesia	Application of Islamic teachings (halal knowledge) in contemporary times	Ernasari *et al.* (2020)
Scopus		
Islamic Financial Literacy and Islamic Banks Selection: An Exploratory Study using Multiple Correspondence Analysis on Banks' Small Business Customers	Application of Islam (Islamic financial literacy) in contemporary times	Al-Awlaqi and Aamer (2023)
Corporate Social Responsibility and Islamic Social Finance Impact on Banking Sustainability Post-COVID-19 Pandemic	Application of Islamic teachings in contemporary times; exploring Corporate Social Responsibility (CSR) and Islamic Social Finance activities in banks	Marzuki *et al.* (2023)
Transnational Halal Networks: INHART and the Islamic Cultural Economy in Malaysia and Beyond	The application of Islamic teachings in contemporary times, concern for piety among contemporary middle-class Muslims, has led to efforts to establish a halal ecosystem	Nisa (2023)
Charting Future Growth for Islamic Finance Talents in Malaysia: A Bibliometric Analysis on the Islamic Finance Domains and Future Research Gaps	Application of Islamic domains (*Shari'ah*-based, Islamic Finance, Islamic Economics, Islamic Accounting, Islamic Management and Halal Management) in contemporary times	Abd. Wahab *et al.* (2023)

The Influence of Halal Awareness, Halal Certificate, Subjective Norms, Perceived Behavioral Control, Attitude and Trust on Purchase Intention of Culinary Products among Muslim Costumers in Turkey	Understanding Islam and society: purchase of intention	Aslan (2023)
Between Awareness of Halal Food Products and Awareness of Halal-Certified Food Products	Application of Islamic teachings in contemporary times; difference between halal awareness in general and awareness of halal-certified products	Usman *et al.* (2023)
Empowerment of SME's Sustainability in Halal Cosmetics' Ecosystem by Diagnosing Growth Constraints	Application of Islamic teachings (halal cosmetics) in contemporary times; to identify and examine the growth constraints of the halal cosmetics ecosystem	Masood and Zaidi (2023)
An Expansion of the Technology Acceptance Model Applied to the Halal Tourism Sector	Application of Islamic teachings in contemporary times; technology acceptance model by incorporating the key constructs of halal knowledge	Berakon *et al.* (2023)
Designing and Assessing an Islamic Entrepreneurship Education Model for Islamic Higher Education (IHE)	Implementation of Islamic entrepreneurship education	Lailatussaadah *et al.* (2023)
Implementation of a Hospitality-Oriented Patient Experience (HOPE) Concept to Service Standards of Muslim-friendly Medical Tourism	Application of Islamic teachings in contemporary times; implementation of Islamic medical tourism	Teerakunpisut and Kongpiam (2023)
Muslim Women Switching Intention to Halal Cosmetics: Push-Pull-Mooring Model Application	Application of Islamic teachings in purchasing cosmetics in contemporary times.	Pambekti *et al.* (2023)
Integrating Country of Origin, Brand Image, and Halal Product Knowledge: The Case of the South Korean Skincare in Indonesia	Application of Islamic teachings (halal skincare) in contemporary time; effect of the value of country of origin and brand image on the purchasing decision of South Korean skincare with halal product knowledge	Mahri *et al.* (2023)
Effects of Religiosity, Halal Knowledge, and Halal Certification on the Intention of Muslims to use the Halal Vaccine during the COVID-19 Pandemic	Application of Islamic teachings (halal vaccine) in contemporary times	Sudarsono *et al.* (2023)
The Effect of Halal Brand Awareness on Purchase Intention in Indonesia: The Mediating Role of Attitude	Application of Islamic teachings (halal brand) awareness in contemporary times	Pratama *et al.* (2023)
Multiculturalism in Japan Halal Tourism: Localising the Concept of Halal	Application of halal tourism in contemporary times in Japan to meet the demand from tourists	Aminah and Bhakti (2023)

Knowledge of Halal Foods by University Students Enrolled in a Dietitian Training Course in Japan	Application of Islamic teachings (halal food) in contemporary times; the study investigated the knowledge of halal foods among university students enrolled in a training course for registered dietitians	Yazawa and Kikuoka (2023)
Constructing an Integrated Sustainable Halal Policy (ISHP) in Brunei Darussalam: Refiguring the Domains of Conventional Policy Multiverses	Application of Islamic teachings (halal policy) in contemporary times, refiguring the domains of conventional policy multiverses	Azalie (2023)
Halal Industry 4.0 Model for SMEs	Application of Islamic teachings (halal industry) in contemporary times	Ahmad *et al.* (2022)
Customer Behaviour towards Halal Food: A Systematic Review and Agenda for Future Research	Understanding previous studies on behaviour towards halal food and shedding light on future studies, the food market	Iranmanesh *et al.* (2022)
Challenges of the Indonesian Halal Industry in the Digital Economic Era	Application of Islamic teachings (halal Industry) in Indonesia in contemporary times	Hasan and Pasyah (2022)
Muslim Millennials' Purchase Intention of Halal-Certified Cosmetics and Pharmaceutical Products: The Mediating Effect of Attitude	Application of Islamic teachings (cosmetic and pharmaceutical) in contemporary times	Widyanto and Sitohang (2022)
Factors Affecting the Halal Cosmetics Purchasing Behaviour in Klang Valley, Malaysia	Application of Islamic teachings in contemporary issues (cosmetic)	Osman *et al.* (2022)
Bleeding Time and False Aneurysm Incidence on Cattle Slaughtering using Non-Penetrative Pre-Slaughter Stunning in Indonesia	Application of Islamic teachings in contemporary issues (non-penetrative pre-slaughter stunning)	Supratikno *et al.* (2022)
Analysis of Determinants of Consumer Intentions to Purchase Halal Bakery Products	The influence of halal marketing on purchase intention	Zhafirah *et al.* (2022)
Strategic Perspectives of Islamic Entrepreneurship and Marketing (p. 183)	Application of Islamic teachings (Islamic entrepreneurship) in contemporary times	Islam (2022)
Halal Travel "2.0" and Beyond COVID-19	Application of Islamic teachings (halal tourism) in contemporary times	Rehman (2022)
Evaluation of Knowledge, Attitudes, and Perceptions on Halal Pharmaceuticals among Pharmacy Students from Malaysian Private Universities	Application of Islamic teachings (halal pharmaceuticals) in contemporary times	Xuan *et al.* (2022)
The Acceptance of Halal Food Products among Non-Muslim Consumers in Indonesia	Understanding Islam (halal concept) and society	Farhan and Sutikno (2022)

The Determinants of Muslim Travellers' Intention to Visit Non-Islamic Countries: A Halal Tourism Implication	Application of Islamic teachings (halal tourism) in contemporary times, related to intention	Aji *et al.* (2021)
Representations of Halal and Haram in Malaysian Parliamentary Discourse [Representasi Halal dan Haram dalam Wacana Parlimen Malaysia]	Application of Islamic teachings, halal, and haram in contemporary times	Awal *et al.* (2021)
Contemporary Issues in Islamic Social Finance	Application of Islamic teachings (Islamic finance and other issues related) in contemporary times	Qadri and Bhatti (2021)
Integrating the Internet of Things in the Halal Food Supply Chain: A Systematic Literature Review and Research Agenda	In contemporary times, the application of Islamic teachings addresses consumers' concerns regarding food integrity. Halal food businesses must rethink their conventional supply chains and leverage new technologies	Rejeb *et al.* (2021)
A Mediator of Consumers' Willingness to Pay for Halal Logistics	Application of Islamic teachings on the intention of purchasing halal products, concern, knowledge, and awareness of halal	Ag Majid *et al.* (2021)
Analysis of Pharmacists' Knowledge and Attitude in the Pharmaceutical Industry of Halal Certification and Their Readiness to Produce Halal Medicine	Application of Islamic teachings (halal medicine) in contemporary times	Rahem *et al.* (2021)
Exploring the Potential of Pondok Institutions as an Islamic Spiritual Tourism Product- The Case of Malaysia	Application of Islamic teaching (halal tourism) in contemporary times	Yusof and Simpong (2021)
Thai Flight Attendants' Intercultural Sensitivity and Topics in Intercultural Communication with Muslim Passengers	Understanding Islam and society in India: Observations on the growth of the halal product market	Semchuchot *et al.* (2021)
The Emergence of Halal Food Industry in Non-Muslim Countries: A Case Study of Thailand	Application of Islamic teachings (halal industry) in Thailand. The halal industry is developing in Thailand in contemporary times	Mohd Nawawi *et al.* (2020)
Does Intention Influence the Financial Literacy of Depositors of Islamic Banking? A Case of Malaysia	Understanding customers who chose Islamic banking and the differences between Islamic and conventional banking /intention	Ganesan *et al.* (2020)
"Halal Tourism": Is the same trend in non-Islamic destinations as in Islamic destinations?	Understanding of Islam and society; exploring Muslim tourists' needs and tourism practitioners' responses in China	Jia and Chaozhi (2020)
Religion and Entrepreneurship in Hospitality and Tourism	Application of Islamic teachings in contemporary times; hospitality and tourism by considering the influences of religion on entrepreneurial motivation	Farmaki *et al.* (2020)

Table 6: Articles categorised under 'Islamization'

Title	Justification	Reference
Google scholar		
Islamic Perspective in Halal Science: Analysis of *Ijtihad* Methodology of Halal and Haram in Contemporary Realities	Reflecting on Islamic objectives and values, the study explicates contemporary *Ijtihad* methodology of *Taḥqīq manāt al-hukm* (verifying causal effect existence) and *Takhrīj manāt al-hukm* (coming up with effective cause) in the medicine, pharmaceutical, food, entertainment, and service industries	Busari (2023)
Islamic Philosophy of Science as a Halal Science Framework: Literature Review	Setting a standard which is derived from Islamic approaches	Said *et al.* (2023)
Pembangunan Lestari Menerusi Sains Halal: Kajian Ayat *al-Qur'an* Terpilih [Sustainable Development Through Halal Science: A Study on Selected Verses From the *al-Qur'an*]	Setting a standard which is derived from Islamic approaches with references to *Qur'anic* verses	Said *et al.* (2023)
Philosophical Concept of Halal Science: Thematic Exegesis Research	Reflection of halal science on Islamic objectives and *Qur'anic* terms	Said and Hanapi (2019)
The Philosophy of Halal Science Concept in *Al-Qur'an*: A Study of Thematic Exegesis	Setting norms/models/standards /which are derived from the *Qur'an*, the Sunnah	Said and Hanapi (2019)
The Philosophical Concept of Halal Science: A Conceptual Analysis	Setting the norms derived from Islamic thought, the philosophy of halal science hinges on *tawhid* and *wahyu*, while humans need to play the role of *khalifah* and subjects of *Allah* SWT, as decreed	Said and Hanapi (2018)
Scopus		
Overview of Halal Issues	Setting standards on halal, containing reviews on some halal industry issues	Farouk (2023)
"We're Trying to Raise Muslim Kids, right?" Muslim Educators' Narratives of Human Development	Interpretations of Islam, Islamic teachings in the Western society	Alkouatli (2023)
Halal Wastewater Recycling: Environmental Solution or Religious Complication?	Discussion on several religious views, ideological and historical differences in the field of wastewater recycling	Jamil (2022)
Enhanced Knowledge Sharing Adoption Model in the Halal Food Industry	Setting standards is derived from Islamic principles, the halal food industry	Samsi (2022)

Islamic Ethical Principles to Protect the Environment Affected by Modern Biotechnology	Incorporation of revelation into different fields of research	Hasim *et al.* (2022)
Recycling Ablution Water (*Wudu'*) using Membrane Water Treatment: A Study from *Fiqh* Halal Perspective	Incorporation of revelation into different fields of research; discussion on issues of water for ablution	Zahari *et al.* (2022)
Advancing Learners' Islamic Knowledge through a Parenting Education Module	Implementation of Islamic-based parenting activities in schools	Kosim *et al.* (2022)
Halal Tourism to Promote Community's Economic Growth: A Model for Aceh, Indonesia	Reflection on Islamic objective: model of tourism within the framework of Islamic *Shari'ah* enforcement	Yusuf *et al.* (2021)
Legal and Compliance Reform for Islamic Financial Benchmarking	Reflection and understanding the nature and workings of Islamic banking and/or Islamic finance	Muneeza and Mustapha (2021)
Islamic Religious Education in German State Schools	Implementation of Islamic values in education in Europe	Euchner and Hackner (2021)
The Need for International Islamic Standards for Medical Tourism Providers: A Malaysian Experience	Setting a standard on Muslim-friendly hospitals and Islamic practices among medical tourism providers according to *Shari'ah*	Kamassi *et al.* (2021)
Keep it Halal! A Smartphone Ethnography of Muslim Dating	Reflection on Islamic objectives and values to find a spouse in Islam	Hasan (2021)
Managing the Symbolic Power of Halal Meat in Swedish Preschools: Food for Thought in Discussions on Diversity	Setting norms and standards of Islamic thought in a multicultural community	Stier and Sandström (2020)
***Fatwa* Debate on Porcine Derivatives in Vaccine from the Concept of Physical and Chemical Transformation (*Istihalah*) in Islamic Jurisprudence and Science**	Incorporation of revelation into different fields of research	Rosman *et al.* (2020)

-quality homegrown journal to provide an ample platform to publish inter-theme halal-related articles in the *tawhidic* paradigm.

Another challenge lies within the researchers themselves. Researchers may not be aware of the *tawhidic* paradigm. Most researchers are trained in the Western worldview that uses conventional, so-called modern Westernised methods. In other circumstances, researchers may be aware of the *tawhidic* paradigm, but they do not understand the importance of conducting halal research in the *tawhidic* paradigm. Therefore, these researchers continue to use the approach commonly done in the respective disciplines. Modern methods are not entirely un-Islamic, though what is missing is the *roh* of doing the research towards fulfilling the *amanah* (trust, responsibility), stewardship and attaining the *mardhatillah* (blessing from *Allah* SWT).

To this end, it is crucial to establish awareness and training programmes or modules to empower researchers to conduct their halal-related research work in the *tawhidic* paradigm. More research is needed to systematically develop methods to synthesise legacy and modern knowledge through the Islamization of Knowledge approach. One possible approach is using the *Maqasid* methodology described by Professor Jasser Auda of the *Maqasid* Institute (Auda, 2021). Hashim et al (2024) in a work investigating the halal science research output of a halal academic programme at master level, proposed that the *Maqasid* methodology can be used to overcome the currently limited discussion about belief in the oneness of *Allah* SWT (*tawhid*) or the trustworthy source of knowledge (*Allah* SWT) in the halal science research.

3.7 Implications of research

The current work is foreseen to pave the way for rekindling the Islamic legacy with modern knowledge towards mastery of halal science and halal education that shall uphold the sustainability of halal industry in the genuine realm of *tawhidic* paradigm. Halal science and education body of knowledge in the *tawhidic* paradigm can be rightly positioned as a foundation for developing curriculum, teaching methodologies, and educational resources related to the halal ecosystem. This, in turn, would fulfil the needs of the halal industry and halal economy through the nurturing of skilled human resources and professionals moulded in the *tawhidic* worldview. Taken together, this preserves Islamic values and fosters thought leadership in halal research and education. As an Islamic nation, Malaysia can leverage its expertise in this field to establish partnerships, exchange ideas, and participate in global halal industry development and standardisation initiatives. This enhances Malaysia's international reputation, strengthens diplomatic relations, and contributes to the nation's soft power on a global scale. Finally, a halal living and lifestyle guided by the *tawhidic*-based halal science and education shall help ensure *duniawi* (worldly) and *ukhrawi* (hereafter) success of all members of the society

4. Conclusion

Guided by the concept of Islamization, this study presented a *tawhidic* paradigm-based classification of halal-related publications in the scope of halal science and halal education into five categories: un-Islamic, conventional studies, conventional halal studies, relevantization and Islamization. More than half of the articles are classified into the relevantization category, which suggests applications of Islamic teachings in contemporary issues. However, the degree of relevantization may still be minimal, portraying only limited *tawhidic* elements. Focusing on articles aligned with 'conventional halal studies' could help emphasise the *tawhidic* elements in halal-related work. In this context, the intention to promote halal as a faith-based system is explicit. Halal research undertaken within the *tawhidic* paradigm will aid in preserving the sanctity of halal as a divine system granted to humanity.

5. Conflict of interest statement

We declare that we have no conflict of interest.

6. Acknowledgement

The research work was funded by the International Institute of Islamic Thought (IIIT) East and South East Asia Office Strategic Research Programme Grant (IIIT-ESEA-SRP), Grant No. IIIT-SRP23-018-0018.

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HALALSPHERE
International Islamic University Malaysia - INHART

Cultured meat and halal: A comprehensive analysis from jurisprudence, biology, and ethics

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Received:24/2/2025
Accepted:14/6/2025
Published:31/7/2025

Keywords:
Halal-*tayyib*, Cultured meat, Islamic dietary law, Food ethics, Spiritual integrity

Abstract

With the growing global Muslim population, dietary practices remain firmly rooted in the principles of halal and *tayyib*. The rise of cultured meat, produced through cellular agriculture without traditional slaughter, presents significant ethical, spiritual, and jurisprudential challenges. This research evaluates the halal status of cultured meat by examining its production processes, scientific complexities, and alignment with Islamic dietary laws. Through a qualitative review of scientific literature, Islamic jurisprudence, and consumer perspectives, the study focuses on cell-based meat production techniques, health and ethical concerns, and theological positions regarding halal compliance. The findings reveal that cultured meat lacks essential components of natural meat, such as a functional immune system and inherent biological processes, and does not fulfil critical *zabiha* requirements, including invoking *Allah's* name and proper blood drainage. Additionally, the absence of these spiritual and biological elements creates a disconnect from *tayyib* principles, contributing to scepticism and uncertainty among Muslim consumers. Despite its sustainability potential, cultured meat does not meet the criteria for halal status under current Islamic jurisprudence.

1. Introduction

With a global population exceeding 1.8 billion, Muslims adhere to Islamic dietary laws that distinguish between halal (permissible) and *haram* (forbidden) foods. At the heart of these dietary regulations is the process of *zabiha*, a method of slaughter that ensures the meat consumed aligns with Islamic jurisprudence (Abdullah *et al.*, 2019). However, the emergence of cultured meat, lab-grown or cell-based meat, introduces a challenge to traditional halal food standards. This scientific innovation, which produces meat by cultivating animal cells in a controlled laboratory environment without the need for conventional slaughter, has sparked debates within the Muslim community regarding its compliance with halal and *tayyib* principles (Alzeer *et al.*, 2018; Ho *et al.*, 2023). The key question for the Islamic community revolves around whether cultured meat aligns with Islamic dietary laws and should be classified as halal, based on Islamic principles.

As the global demand for sustainable and ethical food sources rises, cultured meat presents a potential alternative to traditional livestock farming, offering environmental and animal welfare benefits. The production process involves extracting a small sample of cells from a live animal and growing them in a nutrient-rich medium to develop muscle tissue resembling conventional meat. The entire process typically takes between two and eight weeks, depending on the type of meat being produced (Franceković *et al.*, 2021). While this method eliminates many concerns related to industrial farming, contamination, and disease, it raises fundamental questions about whether cultured meat can be classified as halal under Islamic dietary laws (Kashim *et al.*, 2024).

For Muslim consumers, halal compliance extends beyond just the ingredients to include the method of production, processing, and ethical considerations (Alzeer *et al.*, 2025). Since cultured meat does not undergo the traditional *zabiha* process, there is an ongoing debate among Islamic scholars regarding its legitimacy. Some argue that it represents an ethical and sustainable innovation, while others question whether it meets the spiritual and ritualistic criteria of halal meat (Chandia & Soon, 2018). This uncertainty highlights the need for a comprehensive examination of cultured meat through the lens of Islamic jurisprudence, ethical considerations, and consumer perceptions (Kouarfaté & Durif, 2023).

Despite advancements in cellular agriculture and increasing interest in sustainable food alternatives, no scholarly consensus exists on whether cultured meat can satisfy the *Qur'anic* and jurisprudential requirements for halal. Furthermore, while studies indicate that cultured meat may produce up to 78% fewer greenhouse gas emissions, use 45% less energy, and require 99% less land compared to conventional beef production (Tuomisto & Teixeira de Mattos, 2011), its alignment with Islamic principles remains unresolved.

This article aims to independently study the halal status of cultured meat by analysing its production process, evaluating

its alignment with Islamic principles of halal and *tayyib*, and integrating scholarly opinions. While references such as Ho *et al.* (2023), Rejeb (2018), and Boereboom *et al.* (2022) inform parts of the literature study, the conclusions and critical evaluation herein reflect the author's interpretation and contribution.

2. Materials and methods

This study adopted a qualitative narrative review approach to explore the halal permissibility and broader ethical, theological, and scientific implications of cultured meat. Recognising the issue's multidimensional nature, the methodology combined sources from contemporary scientific literature and classical Islamic jurisprudence, allowing for a comprehensive analysis across theological, technological, and ethical domains.

2.1 Search strategy and data sources

A structured search was conducted across academic databases including Scopus, Web of Science, JSTOR, and Google Scholar, to identify peer-reviewed studies on cultured meat production, its associated health and environmental risks, and ethical evaluations. In parallel, authoritative Islamic legal texts and fatwa were retrieved from classical fiqh compendia as well as institutional repositories of fatwa and legal opinions, including those from *Dar Al-Ifta* (Egypt), JAKIM (Malaysia), IFANCA (USA), and the International Islamic Fiqh Academy (IIFA).

The search covered materials published between 2000 and 2023, using combinations of the following keywords:

- "Cultured meat" OR "cell-based meat" AND "Halal"
- "Islamic jurisprudence" AND "biotechnology"
- "Fatwa" AND "Lab-grown meat"
- "*Tayyib*" AND "Synthetic food"

2.2 Inclusion and exclusion criteria

Included sources met the following criteria: (1) English-language texts or verified translations, (2) peer-reviewed scientific studies, official fatwa, or recognised Islamic legal analyses, and (3) relevance to halal principles or scientific risks/benefits related to cultured meat or novel food technologies. Excluded sources included duplicate records, non-scholarly editorials, and texts without proper citations or verified translations.

2.3 Data analysis and synthesis

A thematic synthesis method was used to extract and organise insights into two central domains:

1. Scientific and technological themes include stem cell sourcing, growth media, bioreactor conditions, environmental impact, and health considerations.
2. Islamic legal and theological themes — including halal slaughter requirements, blood removal, transformation (istihalah), impurity (najasah), and alignment with the objectives of *Shari'ah* (*Maqasid Al-Shari'ah*).
3.

Themes were coded iteratively and grouped according to relevance and recurrence. This allowed the identification of points of convergence and conflict between Islamic law and cultured meat science.

2.4 Corpus overview

An initial pool of 137 sources was identified. After applying the inclusion criteria and assessing relevance, 100 sources were retained and analysed in depth:

- 40 scientific studies addressing cultured meat production, environmental and nutritional impact, and associated risks.
- 35 ethical or philosophical analyses exploring moral frameworks, religious ethics, food justice, and consumer perception.
- 25 jurisprudential sources, including classical legal opinions and contemporary fatwa, focus on cultured meat's permissibility and novel food technologies.

This curated body of literature provides the foundation for the manuscript's analytical framework and supports the critical discussion of cultured meat through empirical and jurisprudential lenses.

3. Cell-based meat production

Cellular agriculture has revolutionised the potential for meat production by introducing cultured meat, also known as cell-based or lab-grown meat. This innovative technology offers a compelling alternative to traditional animal agriculture, addressing pressing ethical, environmental, and food security concerns. Instead of raising and slaughtering animals, cultured meat is produced by cultivating animal cells directly, essentially growing meat in a controlled laboratory setting. The environmental benefits of cultured meat are significant, as it is estimated that it could require up to 99% less land than conventional meat production, thus alleviating some of the pressures on agricultural land and resources (Jönsson, 2020; Post *et al.*, 2020).

The process begins with the careful and ethical sourcing of animal cells. A small tissue sample is typically taken from a live animal, often through a minimally invasive biopsy designed to minimise discomfort. The cells of interest, muscle progenitor cells (myoblasts) or stem cells, are then isolated and selected. These cells have the remarkable ability to self-renew and differentiate, which is fundamental to cultured meat production (Reiss *et al.*, 2021; Bhat *et al.*, 2019). Researchers are also exploring advanced biotechnological methods, such as the use of induced pluripotent stem cells (iPSCs), which offer a potentially more versatile and efficient platform for meat production due to their ability to differentiate into a broader range of cell lineages (Tuomisto *et al.*, 2022).

After isolation, the selected cells are transferred to a bioreactor, a carefully controlled and sterile system designed to replicate the ideal conditions in a living organism. This environment is crucial for cell proliferation, providing the nutrients and growth factors in a liquid medium (Allan *et al.*, 2019; Ge *et al.*, 2023). Historically, fetal bovine serum (FBS) was a common supplement used to provide essential growth factors; however, ethical considerations and high costs have led the industry to pursue plant-based and recombinant alternatives (Escobar *et al.*, 2021). These alternatives promise to make the process more sustainable and ethically sound, aligning with the broader goals of cellular agriculture to reduce animal suffering and environmental impact (Munteanu *et al.*, 2021).

The next critical step is differentiation, where the rapidly multiplying cells are guided to mature into organised muscle fibres. This transformation is essential for replicating conventional meat's texture, structure, and functional properties. Researchers are exploring various techniques to

enhance this differentiation process, including mechanical stretching to align muscle fibres, electrical stimulation to promote muscle development, and scaffold-based structuring (Gome *et al.*, 2024; Zagury *et al.*, 2022). Scaffolds, which are edible or biodegradable matrices, provide a three-dimensional support system for the cells to attach to and grow upon, mimicking the natural architecture of muscle tissue (Kulus *et al.*, 2023; Yun *et al.*, 2024). In conjunction with bioprinting, these techniques enable the creation of complex cuts of meat with realistic textures and structures, moving beyond simple, amorphous cell masses (Roy *et al.*, 2023).

4. Challenges in cultured meat

The development of cultured meat presents several scientific and health-related challenges that must be addressed before widespread consumer adoption. One of the primary concerns is cellular instability and mutations that can occur during the rapid cell division process required for *in vitro* meat production. While many mutations may be harmless, others could produce undesirable changes in the final product, potentially introducing unknown health risks (Stephens *et al.*, 2018). The reliance on growth factors and hormones to stimulate cell growth raises concerns about their safety, residual presence in the final product, and long-term effects on human health (Gu *et al.*, 2022; Bhat *et al.*, 2019). Moreover, ensuring that cultured meat provides a complete and balanced nutritional profile, comparable to traditional meat, remains a significant obstacle. Deficiencies in essential micronutrients or the absence of naturally occurring beneficial compounds could affect its overall suitability as an essential food (Naraoka *et al.*, 2024; Bryant, 2020).

Beyond direct health concerns, contamination risks also pose a significant challenge. Although produced in a controlled environment, cultured meat is still susceptible to bacterial, viral, or prion contamination, necessitating stringent hygiene and sterility protocols (Post *et al.*, 2020). Introducing novel cell lines, growth media, or scaffolding materials could also lead to unexpected allergic reactions in consumers, requiring comprehensive allergenicity testing and transparent labelling (Shaikh *et al.*, 2021). Furthermore, using processing aids and additives to enhance texture, flavour, and structure in cultured meat products raises questions about their long-term safety and potential health impacts (Treich, 2021). Since this technology is still in its early stages, long-term studies are essential to assess the potential effects of regular consumption on gut health, immune function, and overall human physiology (Melzener *et al.*, 2020). Another pressing concern is antibiotic resistance, as using antibiotics to prevent contamination in cell cultures could contribute to developing resistant bacterial strains, posing broader public health risks (Mattick *et al.*, 2015).

In addition to scientific and health considerations, cultured meat presents ethical and environmental challenges. While it is often promoted as a sustainable alternative to traditional livestock farming, the shift toward lab-grown meat production could have unforeseen ecological consequences (Tuomisto & Mattos, 2011). The potential decline in traditional farming may disrupt existing agricultural systems, affecting rural economies and biodiversity (Alzeer et.al., 2020; Guo & Wiwattanadate, 2023). Additionally, reducing reliance on livestock raises ethical questions about the future role of animals in food production, particularly in cultures where animal husbandry is deeply linked with livelihoods and traditions (Pilařová *et al.*, 2023). To ensure a responsible and ethical transition, policymakers, scientists, and industry leaders must engage in transparent discussions, develop robust regulatory frameworks, and prioritise long-term sustainability and consumer well-being in the evolution of food production systems.

5. Islamic views on cultured meat

Islamic scholars are engaged in extensive discussions regarding the permissibility of cultured meat within Islamic dietary laws. This discourse is necessitated by the absence of explicit directives on cultured meat in the *Qur'an* and *Hadith*, requiring contemporary religious scholars to interpret halal principles in a modern context (Kashim *et al.*, 2024).

A segment of scholars posits that cultured meat could be considered halal if specific conditions are met. Their arguments primarily centre on the initial cells being derived from an animal slaughtered according to Islamic rites, and the cultivation process strictly avoiding *haram* (forbidden) substances, such as blood or ingredients originating from pigs. Under these prerequisites, cultured meat is deemed potentially permissible for consumption (Hamdan *et al.*, 2024; Ho *et al.*, 2023). Research indicates that Muslim acceptance of cultured meat is contingent mainly upon using halal-certified stem cells or tissues (Hamdan *et al.*, 2021).

Conversely, other scholars express significant reservations, primarily due to the absence of traditional slaughtering practices, which they consider integral to halal meat. They emphasise the ritual slaughter's profound spiritual and ethical importance, arguing that its omission in cultured meat production raises fundamental questions about permissibility (Hamdan *et al.*, 2017). Furthermore, concerns persist regarding the use of fetal bovine serum (FBS) or other blood components in cultivation media, as Islam strictly prohibits the intake of animal blood (Kashim *et al.*, 2022; Kashim *et al.*, 2023).

Given the novelty of cultured meat technology, a unanimous consensus among Islamic scholars on its halal status is currently lacking. The ongoing scholarly deliberation reflects a meticulous examination of this emerging food technology's ethical, spiritual, and legal implications. As the field evolves, further theological guidance and scientific collaboration will be crucial for providing clear directives to the Muslim community (Qotadah *et al.*, 2022).

6. Cultured meat and halal concern

The emergence of cultured meat has spurred critical comparisons with conventionally farmed meat, revealing profound distinctions across fundamental dimensions. Natural meat, derived from animals raised through traditional agriculture, necessitates the entire lifecycle of animal husbandry, culminating in slaughter. This established practice, however, generates considerable ethical concerns regarding animal welfare and significant environmental impacts, including substantial greenhouse gas emissions and extensive land utilisation (Sánchez-Sabaté & Sabaté, 2019; Malek *et al.*, 2018). In contrast, cultured meat, produced via cellular agriculture in controlled laboratory environments, circumvents the need for animal rearing and slaughter. This innovative approach effectively addresses some inherent animal welfare issues and offers potential environmental benefits, such as reduced land use, although its production demands considerable energy inputs (Mattick & Allenby, 2012; Ahmad

et al., 2023; Kim *et al.*, 2024).

From a biological perspective, conventionally produced meat results from intricate natural processes, including robust immune system activity, complex hormonal regulation, and efficient nutrient absorption, all contributing to its unique structure and comprehensive nutritional profile (Wolk, 2016; Godfray *et al.*, 2018). This natural development endows it with essential proteins, vitamins, and bioactive compounds. Cultured meat, conversely, seeks to replicate muscle tissue in a synthetic environment, lacking the physiological complexities of a living organism. Consequently, its nutritional composition is heavily dependent on the artificial formulations of its growth media, potentially leading to deficiencies if not carefully engineered to mimic the comprehensive nutritional benefits of natural meat (Kim *et al.*, 2024; Ahmad *et al.*, 2023).

These intrinsic differences extend to specific religious and ethical compliance frameworks. Traditional Islamic jurisprudence, for instance, mandates that permissible (halal) meat must adhere to strict criteria concerning the animal's species, the method of slaughter, and the overall wholesomeness (*tayyib*) of the product. Central to *zabiha*, the ritual slaughter, is the prerequisite that the act be performed on a whole, living animal possessing all its natural biological systems, including a fully functional immune system. This integrated system is paramount for disease resistance and maintaining natural biological ratios (Wilujeng *et al.*, 2024). Cultured meat, originating from isolated cells cultivated *in vitro*, inherently lacks these complex, interconnected defence mechanisms of a living animal (Badu *et al.*, 2021), raising a fundamental question about its accommodation within the traditional understanding of a "permissible animal."

Further challenging halal compliance is the critical element of blood drainage, an indispensable part of the *zabiha* process. This practice carries profound hygienic and spiritual significance in Islamic tradition, symbolising purification and the animal's sacred transition to permissible food (Fuseini *et al.*, 2020). Cultured meat, by its very design, lacks a circulatory system and therefore cannot undergo this fundamental act of purification. The absence of blood drainage is not merely a procedural oversight but a significant deviation from a divinely ordained requirement that distinguishes permissible meat from the impure (Bonne & Verbeke, 2007). Thus, the circumvention of an integrated immune system and the necessary blood drainage process represents a substantial departure from the established paradigm of halal slaughter (Bouzraa *et al.*, 2023).

Finally, the potential for unnatural manipulation in cultured meat production poses additional concerns for its *tayyib* status. Unlike conventional farming, where natural biological frameworks limit compositional alterations (Hakim *et al.*, 2020), cultured meat bypasses these constraints, allowing producers to precisely control and manipulate cellular growth and composition (Fuseini *et al.*, 2017). This capacity for unnaturally altered ratios of muscle to fat or the introduction of synthetic compounds, even for perceived health benefits, could undermine the *tayyib* principle of purity, wholesomeness, and natural balance by prioritising profit-driven modifications over inherent integrity (Jalil *et al.*, 2018) (Table 1). The concept of *istihala* (transformation) in Islamic law becomes crucial here, as the halal status often hinges on the source of the initial cells and the permissibility of growth media, such as fetal bovine serum, which may raise ethical and religious concerns (Kashim *et al.*, 2024; Kashim *et al.*, 2022).

7. The Islamic perspective on cultured meat

In Islam, food transcends physical sustenance, embodying deep spiritual significance governed by divine guidance. The concept of halal dictates requirements for lawful consumption, encompassing *zabiha* (ritual slaughter), the supplication of *Allah's* name (*tasmiyah*), and the elimination of prohibited substances like blood and pork. The *Qur'an* explicitly forbids specific categories of meat (*Surah Al-Ma'idah* 5:3), underscoring that these prohibitions cultivate discipline and trust in divine wisdom, and are not subject to modification by scientific or societal trends (Lau *et al.*, 2016).

This foundational principle is particularly relevant when evaluating cultured meat, which bypasses core requirements of Islamic dietary law despite being presented as a sustainable alternative (Arsil *et al.*, 2018). The *hadiths* of Prophet Muhammad (PBUH) further emphasise *zabiha* as an essential condition for halal meat, instructing precision and humane treatment ("When you slaughter, slaughter well," *Sahih Muslim*, 1955; Dahlal *et al.*, 2024). Crucially, the Prophet (PBUH) warned against consuming meat on which *Allah's* name has not been pronounced, signifying that halal slaughter is an act of obedience and devotion (Rashid & Bojei, 2019). Cultured meat from isolated cells in a laboratory without ritual slaughter circumvents these essential spiritual requirements, rendering it invalid under halal law (Sansinova *et al.*, 2023). The spiritual essence of halal sustenance is rooted in *tasmiyah*, humane methods, and natural blood drainage, which collectively imbue the meat with *barakah* (blessing).

Beyond halal, the principle of *tayyib* (purity, wholesomeness) holds equal significance. The Prophet (PBUH) stated, "*Allah* is pure and only accepts that which is pure" (*Sahih Muslim*, 1015), emphasising the importance of food's inherent goodness. Cultured meat, being artificially engineered with potential genetic modifications and synthetic substances, introduces uncertainty regarding its purity and wholesomeness, raising concerns about its Islamic permissibility. Furthermore, the Prophet Muhammad (PBUH) warned against doubtful matters (*shubuhat*), advising avoidance to preserve one's religion and honour. Cultured meat's biological novelty and ethical ambiguities place it within this realm of *shubuhat*, which Islam advises avoiding.

Islam teaches that all living creatures are manifestations of *Allah's* divine creation, possessing both biological and spiritual significance. Cultured meat, in contrast, circumvents this natural order by artificially extracting and multiplying animal cells in a controlled laboratory. This process yields a substance detached from the divine cycle of life and sustenance, lacking the inherent spiritual connection fostered by respecting a creature's life and acknowledging its sacrifice through proper slaughter. By bypassing this sacred process, cultured meat disrupts the *fitrah* (natural order) and weakens this spiritual bond. Moreover, Islam cautions against human attempts to imitate divine creation. The *Qur'an* recounts *iblis's* vow to mislead humanity and alter *Allah's* creation (*Surah An-Nisa* 4:119; Harwati *et al.*, 2023). The artificial engineering of cultured meat can be viewed through this lens, where human intervention manipulates the natural cycle of life rather than aligning with it. While scientific advancements are encouraged within Islamic ethics, the mass production of synthetic meat blurs the line between creation and imitation, potentially desensitising believers to the sanctity of life

Table 1: Aspect natural meat and cultured meat

Aspect	Natural Meat	Cultured Meat
Origin & Production	Derived from live animals raised through natural farming processes	Produced in laboratories through cellular agriculture (Mattick & Allenby, 2012).
Biological Perspective	The natural immune system, hormonal activity, and nutrient absorption contribute to the meat's final structure and composition. Muscle tissue forms within a living organism via cellular growth, metabolism, and interactions with the surrounding biological environment. Naturally contains proteins, vitamins (B12, iron, zinc), and bioactive compounds (creatine, taurine).	While it replicates muscle tissue structure, it lacks the complex interplay of immune responses, metabolic processes, and natural nutrient assimilation found in traditionally grown meat. Nutrients are artificially introduced through growth media (Kim *et al.*, 2024).
Ethical Considerations	Animal welfare concerns are due to slaughtering practices.	Eliminates animal suffering as cells are grown without raising or slaughtering animals (Ahmad *et al.*, 2023).
Environmental Impact	Contributes to deforestation, greenhouse gas emissions, and water depletion.	Reduces land, water, and feed usage but requires high energy for lab operations (Kim *et al.*, 2024).
Halal Slaughter (*zabiha*)	Requires *tasmiyah* (invocation of *Allah's* name) during slaughter.	No traditional slaughter occurs.
Growth Medium	Meat grows naturally through metabolic processes using nutrients from feed and water.	Requires synthetic growth media with potentially non-halal components (e.g., fetal bovine serum) (Kashim *et al.*, 2022).
Spiritual Significance	Represents life, sacrifice, and divine providence. Maintains connection to natural life cycles.	Lacks the spiritual essence of life and sacrifice. Viewed as spiritually disconnected from natural processes (Arora *et al.*, 2023).
Principle of *Tayyib*	Naturally obtained through ecological balance. No chemical additives required.	Produced with synthetic additives (e.g., growth factors, chemical scaffolds).
***Istihala* (Transformation)**	Halal if derived from halal-slaughtered animals. Natural transformation	Cell transformation occurs artificially. Meat does not undergo complete Istihala (Kashim *et al.*, 2024).
Psychological Perception	Familiar and culturally accepted due to longstanding historical consumption.	Due to its laboratory origin triggers scepticism and psychological aversion (Ahmad *et al.*, 2023).
Metaphysical Perspective	Part of the divine natural cycle of life.	Lacks connection to natural ecosystems.
***Qur'anic* Perspective**	Aligned with natural processes described in the *Qur'an*. "So eat of that upon which *Allah's* name has been mentioned." (*Surah Al-An'am* 6:118).	Involves artificial interventions in natural creation. "And I will command them so that they will change the creation of *Allah*."

		(*Surah An-Nisa* 4:119).
Economic Impact	Supports traditional farming industries.	Threatens traditional livestock industries.
Long-Term Safety	Meat safety is evaluated through traditional hygiene standards.	Long-term health effects of cultured meat remain uncertain.

8. Halal status of cultured meat

From an Islamic perspective, health and vitality are holistically approached, extending beyond the physical composition of food to encompass its spiritual significance and alignment with one's lifestyle and beliefs (Alzeer, 2025). Traditional meat, as a product of natural biological processes, embodies this holistic enrichment, forming within an animal's self-regulated system with naturally balanced composition and essential nutrients. This process involves the animal's metabolism, immune system, and natural diet, yielding a biologically sound and spiritually significant product.

In contrast, advancements in food technology have introduced cultured meat, which is regenerated unnaturally in laboratory environments. This process involves extracting and cultivating cells in bioreactors with significant human intervention, determining quality, composition, and nutrient ratios. Unlike naturally optimised meat, lab-grown meat requires external regulation of texture, fat content, and nutrient enrichment. It bypasses the inherent biological and spiritual elements of naturally produced meat. This fundamental shift towards engineered meat represents a significant departure from the natural paradigm.

Cultured meat, derived from isolated animal cells in a laboratory, fundamentally lacks the essential elements of holistic enrichment as defined in Islamic principles. It is disconnected from the natural biological processes that contribute to the purity, integrity, and spiritual significance of halal food. Specifically, cultured meat does not possess a fully functional immune system, which is crucial for the health and integrity of natural meat. Furthermore, its production bypasses the critical steps of the *zabiha* procedure, including the invocation of *Allah's* name (*tasmiyah*) during slaughter and the complete drainage of blood, both of which are fundamental to purification in Islamic dietary law. This disconnection from the natural life cycle and the absence of these essential spiritual and ethical elements result in a product processed by the human body as an artificial substitute for natural meat. The spiritual and ethical dimensions confer halal status, inseparable from natural growth and proper slaughter and notably absent in cultured meat.

While the *Qur'an* offers broad principles for halal and non-halal matters, meat consumption is a notable exception, with explicit and detailed conditions specified. The emphasis on the slaughter process, *tasmiyah*, and blood removal is not merely technical but a spiritual necessity, ensuring purity and harmony with divine law. Meat, in Islam, represents sacred sustenance, deeply connected to life, sacrifice, and gratitude. By circumventing these natural and spiritual processes, cultured meat becomes a materially engineered product devoid of the inherent purity required by halal and *tayyib* principles. Regardless of branding or marketing claims, our understanding suggests that the absence of natural growth, functional immunity, and proper slaughter raises significant concerns, ultimately rendering cultured meat non-halal-*tayyib* under current Islamic jurisprudence.

Given the evolving nature of cultured meat technology and the complexities of Islamic jurisprudence, the acceptance of cultured meat as halal food for Muslim consumption remains uncertain until scientific advancements comprehensively align with the divine principles outlined in the *Qur'an* and *hadith*, and until scholars reach a broad consensus based on sound theological reasoning. Our analysis aims to contribute to this critical discourse by thoroughly evaluating the specific production processes and existing theological arguments to provide a more nuanced understanding of halal permissibility's prerequisites and foster this much-needed consensus.

9. Discussion and critical analysis

Cultured meat presents a novel intersection between technological advancement and Islamic dietary law. While proponents argue for its environmental and ethical benefits, this paper highlights that such innovations cannot bypass Islam's essential theological, biological, and spiritual standards. The absence of a fully developed immune system, the lack of ritual slaughter, and the artificial manipulation of biological processes compromise both Halal compliance and Tayyib integrity.

Furthermore, the spiritual significance of meat in Islam is deeply tied to the process of life, sacrifice, and divine invocation. Cultured meat, by design, circumvents this natural and metaphysical continuum, resulting in what can be perceived as a biologically engineered but spiritually void substance. The invocation of Allah's name (*Tasmiyah*), the removal of blood, and the recognition of the animal's soul are not procedural details; they are theological pillars that confer spiritual legitimacy to food.

This critical analysis suggests that current methods of cultured meat production, especially those relying on non-Halal growth media or avoiding ritual slaughter, cannot fulfil the integrated Halal-Tayyib framework. Until these theological and technical gaps are addressed, cultured meat should not be classified as Halal for Muslim consumption. Importantly, this discussion aims not to stifle innovation but to call for deeper collaboration between scientists, jurists, and ethicists to align biotechnological progress with sacred dietary principles.

10. Conclusion

Introducing cultured meat presents a significant intersection between scientific innovation and Islamic dietary principles. While this lab-grown alternative offers potential benefits for environmental sustainability and animal welfare, it challenges fundamental aspects of halal and *tayyib* guidelines, which extend beyond technical criteria to encompass the natural lifecycle, biological integrity, and spiritual significance of the slaughtering process. The absence of slaughter, the lack of a functional immune system, and the artificial manipulation of cellular structures diverge from the *Qur'anic* concept of

permissible food. Moreover, food in Islam is considered divine sustenance, deeply connected to life, sacrifice, and gratitude, an essence that cultured meat, produced without the natural processes of growth and slaughter, fails to replicate. This disconnect raises concerns about the meat's spiritual authenticity, reinforcing its non-halal status under current Islamic jurisprudence. Moving forward, meaningful collaboration between scholars and scientists is essential to address these concerns, ensuring that technological advancements in food production align with religious principles without compromising spiritual integrity.

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Reevaluating the halal status of Carmine (E120): A scientific and Islamic legal review

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Received:19/3/2025
Accepted:14/6/2025
Published:31/7/2025

Keywords:
Insect, Halal, Cochineal, Carminic acid, carmine

Abstract

Carmine (E120), a natural red dye extracted from cochineal insects (*Dactylopius coccus*), has long been questioned in its halal status due to its insect origin. Traditional Islamic legal principles generally classify insects as *khabīth* (impure or repugnant), thus non-halal, based on interpretations rooted in scriptural sources and early dietary norms. However, emerging scientific insights, particularly from entomology and food chemistry, challenge the broad generalisation of this classification. Cochineal insects are herbivorous, feed solely on plants, and are cultivated under clean, controlled conditions. Moreover, the process of producing carmine involves *istihālah* (chemical transformation), wherein carminic acid undergoes metal complexation, resulting in altered physical and chemical properties that may meet classical criteria for purification. This study reevaluates carmine through an integrative framework that includes Islamic legal principles (such as *al-aṣl fī al-ashyāʾ al-ibāḥah* and *maqāṣid al-sharīʿah*), scientific evidence, allergenic considerations, and cultural perceptions (*ʿurf*). We argue that carmine can be considered halal when derived from herbivorous cochineal insects and processed with high hygiene and transformative techniques. However, due to potential allergic reactions, transparent labelling remains essential to protect consumers and uphold ethical responsibility. This review encourages refining halal certification practices by integrating jurisprudential tradition with contemporary scientific advancements.

1. Introduction

Pigments play a crucial role in the food industry by enhancing the visual appeal of products, significantly influencing consumer perception and preference. They restore colour lost during processing, ensure uniformity, and sometimes indicate flavour or quality (Hisano, 2016). The sources of these pigments can be broadly categorised into synthetic and natural origins. Synthetic dyes, such as Brillant Blue R and Procion Red MX-5B, are chemically manufactured and widely used due to their vibrant colours and stability. However, concerns over potential health risks associated with artificial dyes have led to a growing interest in natural alternatives (Scotter, 2011; Silva *et al.*, 2022).

Numerous studies have evaluated the efficacy and safety of natural pigments as alternatives to synthetic dyes. For instance, carotenoids from carrots and tomatoes offer yellow to orange hues with antioxidant properties but are sensitive to light and oxygen (Lis & Bartuzi, 2023). Anthocyanins in berries and purple corn yield vibrant reds and purples in acidic conditions but lose stability near neutral pH (Luzardo-Ocampo *et al.*, 2021). Betanin from beets provides a bright red colour but is highly sensitive to heat. These limitations have driven interest in carmine, which provides superior stability across pH and temperature ranges, although its animal origin presents ethical and religious concerns (Rakić *et al.*, 2018; Müller-Maatsch *et al.*, 2018).

Carmine provides a rich, deep red that is difficult to achieve with plant-based dyes. While carmine is not considered toxic, studies have documented rare allergic reactions and hypersensitivity cases, particularly among individuals with pre-existing sensitivities to insect proteins or related compounds (Sadowska *et al.*, 2022; Nakayama *et al.*, 2015). Regulatory toxicology assessments, such as those conducted by the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA), classify carmine as Generally Recognised As Safe (GRAS) for both topical and dietary use.

The use of carmine presents complexities regarding its compliance with halal dietary laws, primarily due to its insect origin, which has led to divergent opinions among Islamic scholars and halal certification bodies. This study employs a narrative review methodology, synthesising insights from scientific publications, Islamic jurisprudential sources, and ethical discourse. Rather than adhering to a systematic review protocol, this approach facilitates a multidisciplinary analysis of carmine's halal status by integrating diverse perspectives.

2. Carminic acid to carmine: Extraction, transformation, and applications

Carminic acid, the primary pigment responsible for carmine's vibrant red colour, is extracted from cochineal insects and subsequently transformed into a more stable form for industrial use. This pigment serves a critical defence function for the cochineal, constituting 18% to 30% of the insect's dry weight and offering deterrence against predators. Notably, carminic acid is produced exclusively by female cochineal insects as a chemical defence mechanism. Unlike males, which do not feed and live only briefly after maturing, females remain stationary on cactus pads, making them more vulnerable and dependent on carminic acid for protection (Bustamante-Brito *et al.*, 2019).

Introducing metal ions into the carmine structure significantly alters its solubility profile: it reduces solubility in hot water and alkaline solutions, while the compound remains insoluble in cold water and dilute acids. This phenomenon is rooted in the molecule's polarity. In the absence of metal ions, hydrogen atoms bonded to oxygen in carmine's hydroxyl groups increase the molecule's inherent polarity, enabling it to dissolve readily in highly polar solvents such as water. However, when metal ions replace these hydrogen atoms through coordination bonding, the molecule's overall polarity is reduced, decreasing its solubility in polar solvents.

This chemical transformation directly affects its permissibility under Islamic dietary laws, particularly concerning the legal concept of *istihālah*. The concept refers to converting a prohibited or impure substance into a new, pure form with entirely different properties. In the case of carmine, the transition from an insect-derived acid to a metal-complexed pigment represents a substantial change in chemical structure, function, and identity. According to many Islamic scholars, such a transformation can render an otherwise impure substance permissible if deemed complete. However, this interpretation varies among different schools of thought, with some scholars emphasising the origin of the substance over its end form. Thus, while the chemical evidence strongly supports the notion of a significant transformation, its full legal recognition within Islamic jurisprudence remains a matter of ongoing scholarly debate.

The production of carmine, the metal-complexed pigment, involves a detailed industrial process. This extraction typically begins with harvesting mature female cochineal insects from cactus plants. Subsequently, the insects undergo a drying process, often sun-drying or oven-drying, to significantly reduce their moisture content. The dried insects are then finely ground into powder, from which carminic acid is extracted by boiling it in water or alcohol-based solvents that effectively dissolve the pigment. The resulting solution is then filtered to eliminate any insoluble material. The pigment is precipitated by adjusting the pH or adding specific metal salts, such as aluminium or calcium, to create the final carmine product (Figure 1). Further purification steps, including centrifugation and spray-drying, yield a concentrated dye suitable for various industrial applications (Dapson, 2007).

Once extracted and processed, the resulting carmine pigment exhibits distinct structural differences from its precursor, carminic acid, significantly influencing its thermal resistance and functional applications. Specifically, carmine demonstrates enhanced heat resistance, with a slightly higher degradation point than carminic acid. This property renders carmine particularly advantageous for industrial applications requiring long-lasting pigmentation, notably in the cosmetics, textiles, and food sectors. Moreover, the complexed molecular framework of carmine effectively minimises adverse interactions with light and other environmental factors. This inherent stability broadens its usability, making it suitable for heat-treated and light-exposed products where the greater inherent instability of carminic acid would otherwise be a limiting factor (Liu *et al.*, 2020).

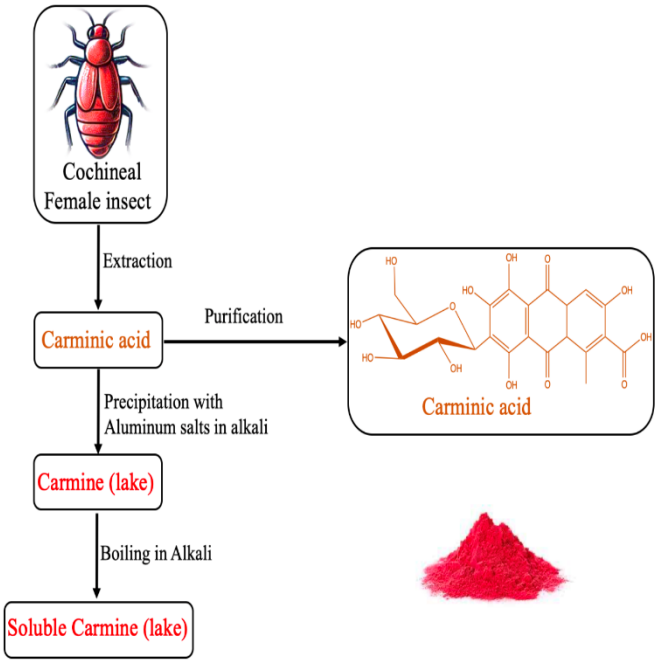

Figure 1: Extraction and purification of carminic acid and carmine.

Beyond its established properties and applications, ongoing scientific advancements are vital to ensure quality control and purity of carminic acid and carmine products. Analytical methodologies, such as spectrophotometric techniques, are vital as they enable the detection of potential adulterants that could compromise the stability and safety of these colourants (Nakayama *et al.*, 2015). Concurrently, driven by increasing consumer preference for natural colourants, substantial research is being conducted into biotechnological methods for synthesising insect-derived pigments. Studies have demonstrated the feasibility of engineering microorganisms to produce carminic acid through biosynthetic pathways, offering a sustainable alternative to traditional insect harvesting while retaining the desirable properties associated with carminic acid and carmine (Gabrielli *et al.*, 2018).

3. Carmine: Properties, perceptions, and concerns

Carmine, a vibrant red pigment, holds significant industrial value across food, cosmetics, and textiles due to its exceptional colour stability and natural origin. A primary advantage lies in its superior resistance to heat, light, and oxidation, which contributes to its durability and ensures consistent colour vibrancy in products, surpassing many synthetic dyes. Furthermore, its non-toxic nature makes it a preferred option for health-conscious consumers, especially given concerns linking some synthetic dyes to adverse health effects.

However, carmine's animal-derived composition is limited, restricting its use in vegetarian, vegan, kosher, and specific Halal diets. This inherent characteristic significantly impedes

accessibility in diverse global markets, particularly as demand for plant-based and ethically sourced ingredients grows. Manufacturers striving for inclusive product formulations often must seek alternative plant-based or synthetic red dyes, despite these often lacking the superior stability characteristic of carmine (Müller-Maatsch *et al.*, 2018). This ongoing challenge underscores the dynamic interplay between traditional ingredient usage and the evolving landscape of consumer ethics and dietary preferences.

In addition to ethical and market limitations, carmine presents significant health-related concerns, particularly regarding its potential allergenicity. Although generally recognised as safe (GRAS) by regulatory bodies like the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), carmine has been associated with allergic reactions in sensitive individuals (EFSA, 2015). These reactions span from mild symptoms, such as skin irritation and urticaria, to more severe conditions like asthma and, in rare instances, anaphylactic shock (Çatlı *et al.*, 2015; Ferrer *et al.*, 2005). This hypersensitivity is primarily believed to be IgE-mediated, triggered by residual insect proteins or carminic acid. Consequently, regulatory agencies have mandated clear labelling: the FDA required carmine declaration on food and cosmetic ingredient labels in 2011, and the European Union similarly mandates its identification under the additive code E120, ensuring consumer awareness and transparency.

Beyond its scientific and regulatory implications, the allergenicity of carmine also carries specific considerations within Islamic dietary law. In this framework, allergenicity does not render a substance *najis* (impure) or inherently non-halal. However, it can inform assessments of *ḍarar* (harm), a crucial principle that may affect permissibility in specific instances, particularly when harm is probable or medically confirmed. Therefore, while allergenicity alone typically does not alter halal classification in most jurisprudential frameworks, it can influence rulings where significant or unavoidable health risks are present.

Despite its favourable safety profile compared to some artificial dyes, specifically its lack of linkage to carcinogenicity and lower association with hyperactivity, carmine's market acceptance is notably complicated by consumer perception. Many individuals exhibit a psychological aversion to insect-derived substances, a sentiment particularly pronounced in cultures where entomophagy is uncommon. This discomfort is especially prevalent among consumers prioritising ethical, religious, or lifestyle-driven dietary restrictions. Such public attitudes significantly influence product marketability, often compelling brands to explore synthetic or plant-based alternatives, even if these options frequently come at the cost of reduced colour stability.

The growing ethical restrictions, allergenic potential, and shifting consumer perceptions have increasingly encouraged the exploration of alternative production methods. Biotechnology represents a promising avenue to replicate carmine's desirable properties while overcoming these limitations. While various other natural red colourants are available, such as beetroot red (betanin) and anthocyanins, they often present their challenges, like susceptibility to heat degradation or pH-dependent colour shifts. In contrast, carminic acid maintains its colour integrity across a broad pH range (4 to 9) and moderate heat exposure, underscoring its unique stability profile for diverse applications (Müller-Maatsch *et al.*, 2018). Despite these diverse sourcing options, its continued use is mainly due to its proven performance. However, the pressing need for ethically sourced and allergy-free alternatives persists as industries and consumers evolve towards greater sustainability and safety (Rakić *et al.*, 2018).

4. Islamic perspectives on carmine

Building on consumer perceptions and ethical considerations, the halal status of carmine (E120) remains a subject of diverse interpretations within Islamic jurisprudence, making a definitive ruling difficult. Traditional Islamic legal thought presents a spectrum of views regarding insect consumption, a divergence that directly impacts carmine's permissibility. The *Hanafi, Shafi'i*, and *Hanbali* schools, representing the majority, generally prohibit insect consumption, classifying them as *khabīth* (filthy) and thus forbidden. This prohibition often stems from interpretations of *Qur'anic* verse 7:157, coupled with the perception of insects as inherently disagreeable. In contrast, the *Maliki* school adopts a more inclusive position, holding that insects can be permissible if they are killed adequately with the intent of consumption, akin to ritual slaughter (Campana *et al.*, 2015). Within *Maliki* jurisprudence, non-poisonous insects are not automatically non-halal; for instance, while locusts are explicitly permitted by authentic *Hadith* (Faridah, 2019), other insects, such as grasshoppers, silkworms, and bees, may also be deemed permissible if prepared correctly, such as through drying or boiling to be used medically (Soumena, 2024) (Table 1). These divergent views ultimately reflect broader differences in interpreting fundamental concepts like purity (*ṭahārah*) and harm (*ḍarar*) across the various Islamic legal schools.

This classical divergence in jurisprudential thought regarding insect consumption is mirrored in contemporary Islamic rulings concerning carmine. Many modern scholars issue fatwas declaring carmine non-halal due to its insect origin. For instance, a *fatwa* from Islamweb explicitly prohibits carmine extracted from dried cochineal beetles, citing not only the insect origin but also the classification of these insects as *maytah* (unslaughtered carrion) and the potential involvement of alcohol in the extraction process (Aidulsyah & Mizuno, 2020). Similarly, a *Hanafi fatwa* from Trinidad's *Darul Uloom* deems carmine impermissible, asserting that "the consumption of insects is not permitted" and falls within the *Qur'anic* prohibition of filthy substances, extending this to carmine-based lipstick due to ingestion risk (Vanany *et al.*, 2019). Conversely, some scholars argue that carmine's chemical processing constitutes *istihālah*. The Jordanian General *Iftaa* Department, while acknowledging the dominant prohibitory view on insect consumption, emphasised that a complete transformation of a substance's nature can render it pure and permissible (Table 2). Accordingly, they ruled that E120 undergoes a substantial chemical change and may be considered halal, provided no suitable alternatives exist, and it is used in necessary amounts. It poses no harm to consumers (Pabbajah *et al.*, 2022).

For *istihālah* to be considered valid in classical Islamic jurisprudence, the original characteristics—such as taste, smell, colour, and physical form—must be entirely lost and replaced by new, permissible qualities. The canonical analogy for this principle is the transformation of wine into vinegar, which becomes lawful once its intoxicating properties are completely altered.

Table 1. Classical Islamic schools of thought on insects

Islamic School / Scholar	General Ruling on Insects	Basis of Classification
***Hanafi* School**	Non-halal: Only locusts are halal	Insects are classified as *khabith* unless explicitly permitted in Islamic texts. The consumption of locusts is allowed based on authenticated *Hadith*, but other insects are prohibited due to their association with filth and impurity.
***Shafi'i* School**	Non-halal: Locusts and certain water insects (e.g., small shrimp, sea insects)	Insects are considered not *tayyib* (pure) and are therefore non-halal unless specifically mentioned in Islamic texts as permissible. Water insects that are not repulsive and do not pose harm are sometimes permitted.
***Maliki* School**	Generally halal: No explicit exceptions needed	Anything not explicitly prohibited in Islamic texts is considered halal by default. The *Maliki* school adopts a more lenient approach, allowing the consumption of all insects unless evidence from the *Qur'an* or *Hadith* indicates impurity or harm.
***Hanbali* School**	Non-halal: Only locusts are halal	Similar to the *Hanafi* stance, insects are deemed impure (*khabith*) except for locusts, which are mentioned in *Hadith* as an exception.

Table 2: Summary of *Fatwa* positions on the halal status of carmine (E120)

Fatwa Body	Country	Position	Basis of Ruling
Jordan General Iftaa Department	Jordan	Halal	Complete transformation (*istihālah*)
IFANCA	USA	Cautiously halal	Under strict conditions
Dar al-Ifta Egypt	Egypt	*Haram*	Source is insect

In the specific case of carmine, scholars remain divided: some contend that the metal complexation of carminic acid fulfils the criteria of *istihālah*. In contrast, others maintain that residual traces linked to the insect's origin prevent complete purification and thus preserve its impure status.

This classical divergence in jurisprudential thought regarding insect consumption is mirrored in contemporary Islamic rulings concerning carmine. The halal status of carmine (E120) is, therefore, not uniformly recognised worldwide, with various national halal authorities and certifiers issuing conflicting guidelines. Notably, several prominent certifiers in Muslim-majority countries have, in recent years, ruled carmine to be permissible, often diverging from earlier stances (Qodir *et al.*, 2023). For instance, the Indonesian Council of Ulama (MUI) issued *Fatwa* No. 33/2011, declaring carmine-derived food and drink colourings halal, reasoning that cochineal insects—likened to grasshoppers—lack a larval stage and flowing blood, live on clean plants, and are not explicitly forbidden in *Qur'an* or *Hadith*, provided the dye is beneficial and non-harmful. Similarly, Malaysia's National *Fatwa* Committee, after revisiting the issue in 2012, allowed cochineal-based colouring, citing the insects' non-toxicity, human benefit, and the classical legal principle that carcasses of insects without flowing blood are ritually pure, and thus not considered *najis* (impure) (Syahnan *et al.*, 2021). Consequently, products containing E120 can be halal-certified in Malaysia under JAKIM's standards, with both MUI and JAKIM's approvals holding significant global influence (Setiawan, 2022; Sultoni *et al.*, 2021). In contrast, other halal standard bodies, such as the Standards and Metrology Institute for Islamic Countries (SMIIC), which includes Turkey and other OIC members, classify carmine as non-halal for edible use (Mufid & Muhammad, 2023). This position aligns with more conservative scholarly views, exemplified by countries like Iran, which also tend to regard carmine as impermissible (Moslemi, 2024; Rohim *et al.*, 2023) (Table 3).

5. Halal status of insects in general and Cochineal in particular

Traditional Islamic *Fiqh* has typically categorised insects under *khabīth*—a *Qur'anic* term signifying impurity, filth, or harm (*Surah Al-Aʿrāf*: 157)—thereby rendering them non-halal (Faridah, 2019). This ruling is rooted in the concept of *fiṭrah* (natural disposition), favouring *tayyib* (pure, wholesome) foods and avoiding what is repugnant or harmful. The dichotomy of *tayyib–khabīth* underpins Islamic dietary law: *Tayyib* includes the intrinsic purity of a substance and its production process, requiring maximum hygiene and minimal contamination. Conversely, *khabīth* refers to substances that are either biologically impure, processed under unhygienic conditions, or naturally harmful. This classification extends to animal products: meat from herbivorous animals (plant-eaters) is halal, while carnivorous or waste-eating animals are deemed *khabīth* and thus *haram*.

Modern entomological research, however, offers a more detailed classification of insects based on their dietary behaviour. Scavenging insects—such as flies and cockroaches—consume waste, blood, or filth, strengthening their association with impurity and disease (Rainford & Mayhew, 2015). In contrast, herbivorous insects like cochineals (*Dactylopius coccus*) feed exclusively on *Opuntia* cactus, a clean, plant-based food source (Kelly *et al.*, 2022). This dietary distinction is crucial: Insects that consume *tayyib* substances and are raised in hygienic environments no longer fit the classical *khabīth* definition. Cochineals fall within this category, aligning them more with the *tayyib* side of the spectrum (Neves *et al.*, 2010; Kuchenbecker & Fagundes, 2018).

The permissibility of carmine is further supported by the principle of *istihālah* (transformation). During processing, cochineal-derived carminic acid undergoes chemical transformation through metal complexation—most commonly with aluminium salts—resulting in carmine (Liu *et al.*, 2020). This transformation alters the substance's solubility, acidity, and chemical identity, aligning with the juristic concept of *istihālah kāmila* (complete

Table 3. Contemporary halal authorities and scientific perspectives on insects and carmine

Authority / Perspective	Position	Basis of Classification
Contemporary Halal Certification Authorities	Varies by country and scholar: Some allow carmine from cochineal, others reject it	Some scholars and halal certifiers differentiate between herbivorous and scavenging insects. Cochineal insects feed on cacti (*tayyib* food), unlike flies or cockroaches that thrive in filth. Some halal authorities, such as Indonesia's MUI, accept carmine as halal due to its purification process, while others, such as Turkey's SMIIC, reject it due to its insect origin.
Modern Scientific & Logical Approach to Insect Classification	Requires differentiation: Herbivorous vs. scavenging/blood-feeding insects	Advancements in entomology suggest that not all insects should be classified under the same ruling. Insects feeding on impure substances (e.g., decaying matter, blood, feces) are more likely to be considered *khabith*, while those feeding on clean, plant-based diets (e.g., cochineal, grasshoppers, silkworms) do not fit the classical definition of impurity and are more likely to be considered *tayyib*.

transformation), which removes the impurity and permits the end product to precipitate in high purity (Pabbajah *et al.*, 2022). Classical scholars use the wine-to-vinegar transformation as a canonical example of *istihālah*. Following this model, the transformation of carminic acid into carmine can be viewed as purifying, especially when the final product no longer retains the properties of the original impure substance.

Importantly, Islamic rulings also consider cultural norms (*ʿurf*) and societal perception when textual evidence is absent or ambiguous. While some societies find insect-based products repulsive, others accept them as sustainable food sources. Islamic law accommodates such variance: the Prophet Muhammad refrained from eating roasted lizard (*ḍabb*) but clarified it was not forbidden—he did not prefer it (Ṣaḥīḥ al-Bukhārī, *Hadith* no. 5537). This example underscores that aversion does not equal prohibition and highlights the legal principle that abstention due to custom does not amount to a ruling of *haram*. In the context of carmine, cultural discomfort should not override religious principles or scientific evidence. Instead, rulings should reflect the higher objectives of Islamic law (*Maqāṣid al-Sharīʿah*), such as preserving health, ensuring purity, and upholding dignity (Rahim, 2018).

From a legal standpoint, the principle of *al-aṣl fī al-ashyāʾ al-ibāḥah*—that the default status of things is permissibility unless proven otherwise—further strengthens the case for carmine. Regulatory bodies such as the FDA and EFSA classify carmine as Generally Recognised as Safe (GRAS), while it may cause allergic reactions in some individuals (Sadowska *et al.*, 2022). Allergenicity alone does not render a product non-halal, just as locusts are permitted despite potential allergic effects. Transparent labelling allows consumers to avoid the ingredient when needed, respecting individual sensitivities without enforcing a generalised religious restriction on all users.

In light of these converging scientific, legal, and ethical considerations, carmine—when derived from herbivorous cochineal insects and processed under hygienic and chemically transformative conditions—qualifies as halal according to both classical principles and contemporary fatwa bodies, with the additional requirement of transparent labelling to uphold consumer trust.

6. Conclusion

The halal status of carmine should not be determined solely based on its origin from insects. From which carmine is derived, cochineal insects (*D. coccus*) are herbivorous—feeding exclusively on plant matter such as cactus—and are typically cultivated in clean, controlled environments. This plant-based diet distinguishes them from scavenging or blood-feeding insects traditionally associated with impurity (*khabīth*) in Islamic law. Moreover, the production of carmine involves a substantial chemical transformation through metal complexation of carminic acid, fulfilling the classical jurisprudential concept of *istihālah kāmila* (complete transformation), which permits the transition from impure to pure substances. Given the absence of explicit scriptural prohibition, the application of the Islamic legal maxim *al-aṣl fī al-ashyāʾ al-ibāḥah* (the default ruling on things is permissibility), and alignment with the higher objectives of *Sharīʾah* (*Maqāṣid al-Sharīʿah*), carmine—when derived from herbivorous insects and processed under hygienic and transformative conditions—qualifies as halal. Transparent labelling remains essential to accommodate consumer sensitivities and potential allergenic concerns. Going forward, greater scholarly collaboration is needed to develop unified, evidence-based halal standards incorporating contemporary scientific understanding and legal reasoning, particularly for ingredients derived from unconventional sources.

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Integration of spectroscopy and chemometric analysis for food authentication: A review

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Received:30/4/2025
Accepted:22/7/2025
Published:31/7/2025

Keywords:
Spectroscopy;
Chemometrics;
Food;
Classification;
Regression.

Abstract

The high demand in the food sector necessitates an authentication process to verify products and prevent food fraud. In the food industry, applying spectroscopy techniques combined with chemometric analysis has become an efficient tool for authentication, thanks to its rapid results, cost-effectiveness, and reliability. Among the spectroscopy techniques reviewed in this paper are near-infrared (NIR), Fourier transform infrared (FTIR), ultraviolet (UV), and Raman spectroscopy. This paper reviews recent spectroscopy applications to food, such as oils, agricultural products, and beverages. This paper reviews various types of classification and regression algorithms in chemometric analysis to demonstrate the capabilities of these algorithms for use in food authentication processes. The chemometric model can accurately identify authentic samples with minimal risk of misclassification. This review presents a comparative synthesis of algorithms for various types of food samples, highlighting the performance of predictive algorithms. This review will provide a practical framework for researchers seeking to develop a robust predictive system for food authentication using spectroscopy and chemometrics. The review discusses the emerging trend of integrating spectroscopy into real-time authentication systems, particularly in the application of data fusion and deep learning techniques.

1. Introduction

Food authentication is a crucial issue for consumers due to religious motivations (Musfiroh *et al.*, 2025), economic reasons, and the assurance of the food's quality and safety. In Islam, followers are obliged to eat permissible and good food, per Islamic dietary laws, also known as halal, as stated in the *Qur'an*, verse 2:168. In addition to religious considerations, vegan consumers ensure that their food is not mixed with any animal-derived ingredients. Certification schemes on the Protected Designation of Origin (PDO) play a crucial role in assuring consumers of product authenticity to guarantee that the product is entirely produced, processed, and prepared in a specific geographical region (Candeias *et al.*, 2025; Mohammadi *et al.*, 2024; Özdemir *et al.*, 2024). Additionally, the authentication process ensures a trustworthy relationship between producers and consumers. The flow process of food authentication is as illustrated in Figure 1. After selecting the product, the sample will be prepared and analysed. The data obtained will be interpreted and verified by the regulatory body.

"O mankind, eat from whatever is on earth [that is] lawful (halal) and good (tayyib)"
Qur'an 2:168

Ensuring the authenticity of food products, such as verifying their geographic origin, species, and purity, is crucial in determining their halal status. Food authentication can help prevent food fraud, including adulteration, misbranding, or tampering. Adulteration involves the replacement of high-cost ingredients with lower-grade and cheaper substitutes. Adulteration cases in food products can lead to health problems for consumers (Aslam *et al.*, 2024; Dahimi *et al.*, 2014). The authentication process enables consumers to check for any forbidden substance, allergen or unsafe ingredients. Examples of analytical methods to detect cases of adulteration include chromatography, polymerase chain reaction (PCR) and spectroscopy techniques.

Food authentication may take some time, depending on the analytical method used. Thus, finding a rapid analysis method to save time and cost is crucial. In comparing chromatography or other molecular biology techniques with spectroscopy techniques, the latter method often requires more complicated procedures and extensive analysis. Besides that, some analytical methods, such as DNA extraction, require sample preparation, which might take some time to extract the result. The chromatography method does provide accurate results, but the instrument is expensive and humongous, and the technique is destructive to the sample.

Figure 1: The flow of the food authentication process.

Among the wide range of emerging technological solutions in food analysis and authentication, spectroscopic techniques have increasingly garnered substantial and noteworthy attention from researchers and industry. This is primarily due to their ability to deliver rapid, non-invasive, and non-destructive measurements while requiring minimal sample preparation. Various spectroscopic approaches, including but not limited to near-infrared (NIR), mid-infrared (MIR), Fourier-transform infrared (FTIR), Raman, and ultraviolet-visible (UV-Vis) spectroscopy, have found expanding and widespread applications across a broad spectrum of food matrices. Nevertheless, despite their many advantages, the spectral data produced by these techniques are often highly complex and frequently characterised by overlapping signals, which pose significant challenges in interpretation and therefore necessitate sophisticated and advanced chemometric analysis methods to extract meaningful information accurately.

It is precisely at this critical juncture that chemometric, which involves the comprehensive, and rigorous application of advanced mathematical modelling approaches combined with sophisticated statistical methodologies, specifically intended for the extraction, interpretation, and modelling of meaningful patterns, underlying structures, and complex interrelationships inherent within high-dimensional spectroscopic data, assumes an indispensable role within the overarching analytical framework that supports contemporary spectroscopic approaches to food authentication. Many machine learning algorithms have become powerful tools for handling nonlinearities and large datasets. Researchers are now equipped with enhanced capabilities for achieving significantly improved accuracy, reliability, and robustness in classifying food products, quantifying specific components or contaminants, and predicting authenticity markers or adulteration events across various food matrices and production systems.

Based on previous works, there is a lack of comprehensive reviews that explore how spectroscopy and chemometric analysis can be combined with analytical methods to authenticate food as the reference method. This review addresses these limitations by critically examining recent advancements in food authentication, focusing on matters related to halal status, including adulteration, product origin, and quality. It is also designed with the primary objective of thoroughly exploring and evaluating current scholarly studies and scientific investigations that specifically focus on integrating spectroscopy techniques and chemometric methods for authentication related to food safety and the detection of adulteration, with references to halal and religious compliance where applicable. The review aims to assess the application of chemometric methods in conjunction with spectroscopy. Furthermore, it highlights and discusses the emerging trends, methodological innovations, and thematic directions that characterise the current state of research in this area. It further identifies and discusses challenges and future spectroscopy and food authentication research directions.

2. Methodology

This comprehensive review was meticulously undertaken to thoroughly examine and analyse the existing research on utilising various spectroscopy techniques in conjunction with chemometric analysis for food authentication. A clearly defined and methodically structured approach was employed to guarantee that the literature coverage was extensive, representative, objective, and free from bias.

2.1 Literature search strategy

A literature search was conducted to identify relevant studies, involving queries of several primary and reputable scientific databases, including Scopus, Web of Science, PubMed, and ScienceDirect. The search was limited to peer-reviewed articles published within the time frame spanning from 2020 to 2025. A predefined set of keywords and Boolean operators effectively refined and focused the search results. A total of 97 publications were identified based on publication year and relevant keywords; however, only 48 were selected for review due to their close relevance to the focus of this paper, which includes adulteration, protection of origin, and quality control.

The keywords included:

- ("food authentication" OR "halal" OR "food fraud" OR "food adulteration") AND
- ("spectroscopy" OR "NIR" OR "FTIR" OR "Raman" OR "UV-Vis" OR "Raman") AND
- ("chemometric" OR "PCA" OR "PLS-DA" OR "SVM" OR "LDA" OR "machine learning")

In addition to the database searches, the reference lists of all initially selected articles were carefully reviewed and manually screened to identify any additional studies that may have been relevant but were not captured through the database search alone.

2.2 Inclusion and exclusion criteria

The selection of inclusion and exclusion criteria used in this study is carefully defined in Table 1.

2.2.1 Inclusion criteria

Studies specifically involved using spectroscopy-based techniques, combined with chemometric methods, to authenticate food products. Research applying this combined spectroscopy and chemometric approach to a diverse range of food matrices, including but not limited to dairy products, edible oils, spices, and various processed food items. Investigations that utilised multivariate statistical models or machine learning algorithms for tasks such as classification of food types, quantification of components, or detection of adulteration within the food samples. Review articles were included as data sources because they provide background information and current updates on the topic.

Table 1: The inclusion and exclusion criteria for the literature search strategy

Criteria	Inclusion	Exclusion
Sample studied	Food	Non-food
Food authentication	Adulteration, origin, and quality control	Use not for food authentication
Method	Spectroscopy method (NIR, RAMAN, FTIR, UV)	Conventional methods, such as DNA or chromatography
Chemometric	Classification and regression	Dimension reduction

2.2.2 Exclusion criteria

Studies that did not include any chemometric analysis in their methodology were excluded from consideration, as well as research focusing on applications of spectroscopy techniques unrelated to food authentication or involving non-food-related subjects. Additionally, conference abstracts, book chapters, and other forms of literature that were not peer-reviewed were excluded from the study to maintain a high standard of scientific rigour and reliability. This review did not include a formal quality assessment of the included studies, such as evaluations based on sample size or methodological rigour. Future research should incorporate a standardised quality appraisal to enhance the reliability and validity of the conclusions.

3. Results and discussıon

3.1 Application of spectroscopy

3.1.1 Overview of spectroscopy method

Spectroscopy has been widely used to analyse the composition, adulteration, and quality of food authentication products. It is an analytical method that analyses the interaction between electromagnetic radiation and the sample studied. The different wavelengths of electromagnetic radiation emitted during the measurement will determine the method of spectroscopic measurement used. The advantages of spectroscopic measurement compared to other analytical tools include less labour-intensive and time-consuming methods and direct detection. This method can also identify and detect low levels of composition in analytes with minimal or no sample preparation. (de Freitas Oliveira *et al.*, 2025). The spectroscopic techniques commonly employed in food authentication include near-infrared (NIR), Fourier Transform Infrared (FTIR), ultraviolet (UV), and Raman spectroscopy. Each spectroscopic technique presents unique analytical strengths for detecting and characterising food composition and potential adulteration. The sample's physicochemical properties largely determine the method under investigation.

FTIR spectroscopy is a method that provides molecular fingerprinting of the sample by measuring the mid-infrared (IR) absorption band corresponding to a specific molecular bond and functional group. The wavelength range (refer to Table 2) of FTIR utilises a longer wavelength; thus, it will be more advantageous because more absorption bands can be investigated. The wavelength emission used in FTIR is less detrimental to the sample; thus, multiple analyses can be run on the same sample without introducing sample degradation or altering absorption. Several FTIR spectroscopy techniques include transmission, attenuated total reflectance, and photoacoustic spectroscopy. (Pasieczna-Patkowska *et al.*, 2025). The method of spectroscopy used is dependent on the sample studied and the objective of the analysis.

Given the lower molecular specificity of NIR, its application in detecting subtle adulterants such as lard may require enhanced chemometric modelling. By contrast, FTIR, with its ability to capture fundamental vibrations described above, provides more evident spectral fingerprints for such compounds. There are three modes of sampling in NIR spectroscopy: transmission, reflectance and transflectance, depending on the sample type. One of the advantages of NIR spectroscopy is its rapid measurement capability, but it requires a calibration method to be deployed in the food authentication process. UV spectroscopy is a method that measures the absorption of light by a sample in the UV range, from 200 nm to 400 nm. The electronic transition also occurs in UV spectroscopy, and it is primarily applied to samples containing molecules with functional groups that include conjugated double bonds, aromatic rings, or lone pairs of electrons. Compared to NIR, UV light has a lower penetration depth, which limits its applicability primarily to aqueous samples, liquids, and soft solids.

Raman spectroscopy is a method of measuring the scattering of laser light that occurs due to the excitation of molecular vibration, unlike the previous spectroscopy method based on absorption. There are two types of scattering: elastic (Rayleigh) and inelastic (Raman). In Raman scattering, the molecule is excited from its ground state to a higher state and then relaxes to another state. A minor portion of the scattered photons exchanges energy with the target molecule. The method of Raman spectroscopy depends on the change of the polarised molecule at the frequency at which scattered radiation occurs. This spectroscopy method is suitable for investigating molecular bonds, such as C-C, C=C, C-CH, and C-CH_3. (Kolašinac *et al.*, 2025). Raman spectroscopy also offers rapid analysis with high sensitivity, making it a practical analytical tool for food authentication (Li *et al.*, 2024). Table 2 shows the wavelength range for each spectroscopic method, along with the use and type of sample studied.

3.1.2 Example of spectroscopy application

NIR spectroscopy is suitable for rapid quality evaluation due to its portability for detecting adulteration and identifying food origin. The application of NIR spectroscopy in detecting the quality index of ginger to identify its origin is exemplified. (Chen *et al.*, 2024). In NIR spectra, the peak at 1205 nm was attributed to the second overtone of the C-H bond in ginger powder, and the peak near 1460 nm corresponded to a signal from C-H stretching, the second overtone of O-H, and the radical features of gingerols. UV-Visible (UV-Vis) spectroscopy is applied to determine sugar adulteration in Mediterranean honey and investigate the molecular information of a sugar and honey mixture. The absorptions in the range of 250 nm to 350 nm are related to glucose, fructose, amino acids, proteins, and phenolic compounds, as shown by Dimakopoulou-Papazoglou *et al.* (023). Additionally, UV spectra were measured and analysed to differentiate between species of Javanese turmeric

Table 2*:* The details of the FTIR, NIR, UV AND Raman spectroscopy methods

Technique	Wavelength	Used for	Sample Types	Sensitivity	Portability	Drawback
FTIR	2500–25,000 nm	Functional group, adulterant	Powders, solids, liquids	High due to a sharp and well-defined peak	Less portable due to the bulky instrument	Strong water absorption requires sample contact
NIR	780–2500 nm	Moisture, fat, protein, sugar	Grains, dairy, liquids	Moderate due to broad and overlapping peaks	Yes, because handheld instruments are available	Require calibration and are sensitive to sample texture
UV	200–400 nm	Coloured compounds, polyphenols	Clear liquids, beverages, and extracts	High due to a sharp peak	Yes, because miniature equipment is available	Limited sample and cannot identify structural components
Raman	400–1000 nm	Pigments, lipid or adulterant	Aqueous samples, liquids, soft solids	Highly sensitive using surface-enhanced Raman spectroscopy	Yes, if it is integrated with fibre probes	Fluorescence interference, and sometimes, the signal intensity is weak

Table 3*:* Examples of recent research using the spectroscopy method for food authentication

Title	Sample	Method of detection	Performance / Accuracy	Relevance to the halal sector
Authentication of Mentha arvensis essential oil using attenuated total reflectance-Fourier transform infrared spectrophotometry coupled with chemometric (Jayasekher *et al.*, 2024a)	Mentha arvensis essential oil	Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectrophotometry. The wavenumber range of 500-4000 cm-1 was used.	The ATR-FTIR used to authenticate Mentha arvensis Essential oils produced a prediction model of 100% accuracy.	Adulteration in essential oil may undermine transparency and consumer trust.
Moringa oleifera seed oils: Physico-chemical characterisation and their authentication using FTIR spectroscopy and chemometrics (Irnawati *et al.*, 2024)	Moringa oleifera seed oils	FTIR spectroscopy method that utilised the mid-infrared region between 4000-6000 cm^{-1}.	The coefficient determination result obtained was 0.9971 for quantifying the presence of oil adulterants.	Identifying oil adulteration is essential to avoid quality degradation and mislabeling.
Portable NIR spectrometer and chemometric tools for predicting quality attributes and adulteration levels in butteroil (da Silva Medeiros *et al.*, 2023a)	Butteroil	NIR spectroscopy using DLP NIRscan ranges from 900 to 1700.	The sensitivity in detecting adulterants obtained was more than 91.5%.	Adulteration of non-halal ingredients such as lard is not permissible in Islamic dietary law.
Simple analytical method using ultraviolet spectral dataset and chemometrics for the authentication of Indonesian ground roasted coffee with different botanical and geographical indications (Suhandy *et al.*, 2023)	coffee	A UV-visible spectrometer in the range 190 to 399 nm was used for the measurement.	The prediction model for sample authentication achieved 100% accuracy.	Geographical origin may affect halal claims, particularly about contaminants.
Adulteration detection of multi-species vegetable oils in camellia oil using Raman spectroscopy: Comparison of chemometric and deep learning methods (Wang *et al.*, 2025)	Camellia oil	Raman spectroscopy	A Raman spectrometer with a 785 nm laser was used to measure the oil samples. The deep learning algorithms deployed have achieved an R^2 of 0.999 and an RMSE of 0.9.	Adulteration detection to ensure product quality and safety for consumer consumption.

(Temulawak), which is used in medicine and supplements (Kusumadewi *et al.*, 2022). Raman spectra were used to analyse the chemical properties of cocoa butter, cupuassu butter, passion fruit oil, and sacha inchi oil and their blend with cocoa butter used in chocolate manufacturing (Balcázar-Zumaeta *et al.*, 2025). All these methods of spectroscopic measurement discussed provide minimal to no sample preparation, are non-destructive, and produce rapid results. Table 3 reviews a few previous experimental works conducted by researchers and food analysts in the food industry using different spectroscopy methods.

NIR spectroscopy and chemometrics have been used to differentiate among edible oils and oilseeds (Li *et al.*, 2020). NIR spectroscopy has also been used to discriminate between the spectra of extra-virgin olive oil and virgin olive oil, and the result obtained using Partial Least Squares (PLS) density modelling has a correct classification rate of 82.35% (Garrido-Cuevas *et al.*, 2024; Rodionova *et al.*, 2024). Isdhiyanti *et al.* (2024) have utilised fingerprints unique in the NIR spectral range to monitor the quality change of cooking oil. The resulting NIR spectral display peaks, originating from C-H, CH2, and CH3 bonds, appear at wavelengths of 1730 nm and 2350 nm due to stretching and deformation. The peroxide number and free fatty acid are the chemical contents analysed using NIR spectroscopy (Isdhiyanti *et al.*, 2024).

The application of spectroscopy in halal food authentication primarily focuses on detecting non-halal ingredients, such as pork and its derivatives, and verifying authenticity to prevent false claims regarding origin or composition. The review work done by Claude Mona Airin *et. al.* discussed the application of FTIR to determine non-halal ingredients in meat products. Based on the review, the limit of detection of the FTIR method to detect non-halal meat in the range 1 % to 5 % (w/w) *(Airin et al.*, 2025). Besides halal concerns in meat products, the substitute for pork fat, known as lard, has been adulterated with butter to reduce production costs. The use of NIR spectroscopy to detect the presence of lard in butter oil, as tabulated in Table 3, demonstrates the method's capability to differentiate between halal and non-halal ingredients in a mixture. The method of Raman spectroscopy has been utilised to detect lard in the butter, and the result of R^2 is 0.99 (Taylan *et al.*, 2020). This result indicates that the Raman method is more suitable than NIR for detecting lard in butter, particularly due to the lipid compounds listed in Table 2.

The assurance of product authenticity represents a fundamental aspect of food safety management, extending across all supply chain segments from raw material procurement to final consumer delivery. In the context of halal compliance, this requirement becomes even more critical, as it necessitates stringent oversight by producers, suppliers, retailers, and regulators to ensure that the integrity of halal status is preserved throughout the production and distribution processes. A few studies have been summarised in Table 3 to highlight the application of various spectroscopy methods in the context of halal authentication.

Jiajun Zan *et al.*'s current work combines the methods of NIR and Raman spectroscopy and performs spectral analysis to detect tea seed oil adulteration. (Zan *et al.*, 2024). The feature layer fusion strategy was used to enhance the comprehensiveness of information usage. The accuracy obtained after the analysis reached more than 90% for calibration and prediction datasets. Motahari and coworkers characterise edible and non-edible oils using spectroscopic methods, including Raman, FTIR, and UV-Vis spectroscopy. (Motahari *et al.*, 2023). The research employed a variety of spectroscopic methods to conduct a thorough investigation of the molecular fingerprint of the oil sample. The broad UV-Vis absorption peak observed around 370 nm signifies $\pi \rightarrow \pi^*$ transitions within the carbon double bonds of the oil. A 270–300 nm peak indicates $n \rightarrow \pi^*$ transitions from carbonyl groups (C=O). FTIR spectra exhibit peaks at specific wavelengths corresponding to molecular bonds, including C=O, C–O, -CH2, H–O–H, and C–OH. Raman peaks occur due to the stretching of molecular bonds, including C–H, CH2, CH3, and N–H.

UV-Vis and FTIR spectroscopy have been deployed by Cagri Cavdaroglu *et. al.* to detect adulteration using spirit vinegar and acetic acid. Although the method of data fusion from both methods did not improve classification results, the percentage of correct classification and sensitivity is more than 90% (Cavdaroglu & Ozen, 2022). A more accurate interpretation of spectra and correlation with the reference method requires chemometric analysis to extract information due to the low sensitivity and weak intensity of spectral data. (Motahari *et al.*, 2023). Specific spectra lack corresponding reference values, rendering them unlabelled data. In such instances, clustering algorithms can partition the spectra into subsets based on feature similarity or distance metrics. The multi-source data fusion technique was employed to integrate visible/NIR spectroscopy with machine vision data to predict the soluble solids content of oranges. The convolutional neural network model exhibited a 36.4% improvement in prediction RMSE. (Sun *et al.*, 2025). Data from three spectroscopic methods, NIR, mid-IR, and Raman, were combined to classify different milk types. The performance of prediction accuracy has increased from 85.71% to 95% (Mohammadi *et al.*, 2024).

3.2 Chemometric

Spectroscopic techniques, such as near-infrared (NIR), mid-infrared (MIR), Raman, and UV-Vis spectroscopy, generate detailed spectral fingerprints that reflect food samples' molecular composition and structure. However, these raw spectra are often complex and challenging to interpret due to overlapping peaks and background noise. Chemometric algorithms address this challenge by modelling the relationship between spectral features (independent variables) and reference values such as chemical concentrations or physical properties (dependent variables).

Chemometrics is a branch of science that relates measurements made on a chemical system or process to the system's state by applying mathematical or statistical methods (Kusumadewi *et al.*, 2022). Chemometrics is also a multivariate data analysis technique applied in spectroscopy. Currently, most researchers focus on data mining numerous spectral datasets. Chemometric algorithms implemented in spectroscopy analysis extract large amounts of hidden information from the spectral data. The recent advancements in the chemometric field have raised hope for overcoming the challenges in food authentication. The combination of chemometric techniques has helped extend the application of spectroscopy in many areas, such as halal authentication (Musfiroh *et al.*, 2025).

In this paper, the review of chemometric techniques is classified into classification and regression analysis. Classification analysis, also known as pattern recognition, uses information about the class membership of the samples and classifies new unknown samples in one of the known classes based on their measurement pattern. Regression is a

quantitative analysis that involves correlating the input variables (spectra) with the continuous value of the numerical output (target). The performance measures for classification and regression analysis differ. In classification, the algorithm's performance was evaluated based on accuracy, sensitivity, precision or specificity. Error-based matrices were used in regression analysis, including root mean square error (RMSE), mean absolute error (MAE), and mean squared error (MSE). R2, computed in regression, indicates how well the independent variables explain the variability of the target variable, with values closer to 1 showing better model fit.

3.2.1 Classification analysis

3.2.1.1 Principal component analysis (PCA)

One of the most employed techniques for classification analysis is principal component analysis (PCA). PCA is a technique used to classify two or more unknown groups. PCA is an unsupervised pattern recognition method with the simplest eigenvalue-based multivariate analysis. The PCA algorithm transforms the data and creates a new space based on the principal components, which can be used for the dimension reduction step. (Aslam *et al.*, 2024; Mohammadi *et al.*, 2024). The PCA algorithm decomposes the spectral data using either eigenvectors and eigenvalues or singular value decomposition (SVD). The eigenvectors and eigenvalues were calculated from the covariance matrix of the spectra, indicating the variables' variance relative to one another. The decomposition output produces principal components used as input to train the model. The optimal number of principal components depends on the model's performance. Rui Zhu *et al.*, thoroughly explained the details of the PCA method's process in their work on compressing spectral data (Zhu *et al.*, 2024).

Joanna Banas *et al.* carried out an investigation using PCA to characterise selected herb honeys, such as raspberry, lemon balm, rose, mint, black currant, instant coffee, pine, hawthorn, and nettle. (Banaś & Banaś, 2024). The first three principal components resulting from PCA are used to examine the natural pattern among samples and their clustering. The total variance in the data of the three PC was 97.6% variation. The first PC shows that the signals from all the fluorescent compounds in the herb honeys contribute nearly equally. These results suggest extracting and training the pro-health properties based on the relationship between individual polyphenols, pigments, vitamin B3, and vitamin B_9. The classification of Lampung robusta coffee based on fermentation using PCA algorithms has a cumulative percentage of variance of 98% based on two principal components. (Yulia & Suhandy, 2020).

3.2.1.2 Linear discriminant analysis (LDA)

The linear discriminant analysis (LDA) algorithm distinguishes samples based on class differences. The computation of the scatter matrix, both within and between classes, based on distance, is used to calculate eigenvectors and eigenvalues. The objective of the computation in LDA is to maximise variance between classes and minimise variance within classes. LDA, combined with the dimension reduction method, has demonstrated improvements in classification methods. LDA was used to discriminate peanut kernel samples based on their origin from different cities (Zhu *et al.*, 2024). Combining preprocessing techniques and an ensemble method with LDA has achieved 100% classification accuracy. The results have shown that the correct combination of chemometric processes applied to the dataset can produce a robust and reliable model. The combination of PCA and LDA is also used to solve the problem of high-dimensional data. The LDA algorithm was combined with PCA to differentiate various adulterants in Mentha arvensis essential oil, where the principal components derived from PCA were used to train the LDA model. The PCA-LDA model achieved 100% accuracy, indicating a highly effective performance. (Jayasekher *et al.*, 2024b). Besides that, LDA algorithms have been used as spectral dimension reduction to extract information. The extracted features or the linear discriminant vector were utilised as the input for the classification model. (Wu *et al.*, 2024).

3.2.1.3 K-nearest neighbour (KNN)

The k-nearest neighbour (KNN) algorithm calculates the K nearest neighbours using distance metrics such as Euclidean, Mahalanobis, or cosine distance to perform classification analysis. (Suyal & Goyal, 2022). The category with the most occurrences among the K closest data points determines the classification of a new data point. The application of KNN with different preprocessing methods achieved 95.2% accuracy for the test Raman spectra dataset of Pericarpium citri reticulatae (PCR) (Yang *et al.*, 2025).

NIR spectroscopy and the KNN algorithm were utilised to determine the quality of mei tea by classifying its grade (Wu *et al.*, 2024). The sample size and the parameter, K, set will determine the accuracy of the classification model. Wu and his coworker set the value of the parameter K to 1, 3, 5, 7, and 9. The highest accuracy was achieved with K values of 1 and 3, yielding an accuracy of 44% (Wu *et al.*, 2024). KNN has also been employed in a classification method to categorise peanut kernels using NIR spectra (Zhu *et al.*, 2024). The combination of maximum LDA to project the dataset and KNN enables improvement in classification accuracy from 62.96% to 70.99%. Based on previous works, it has been proven that selecting the optimal value of K is crucial for achieving the maximum accuracy.

3.2.1.4 Support vector machine (SVM)

The fundamental principle of the support vector machine (SVM) is that it finds the optimal hyperplane by dividing the dataset into different classes and maximising the margin of separation between these classes. The hyperplane was defined based on Equation 1, where w is the adjustable weight vector, x is the input vector, and b is the bias. (Mohammadi *et al.*, 2024; Yang *et al.*, 2025).

$$w^T x + b = 0 \qquad \text{Equation 1}$$

SVM algorithms were utilised to determine the optimal qualitative analysis model using the sample prediction accuracy to identify the adulterant in Tartary buckwheat samples mixed with whole wheat flour, oat flour, soybean flour, barley flour, and sorghum flour using NIR spectroscopy, and the accuracy reported was 100% (Wu *et al.*, 2024).

The SVM model achieved a sensitivity and specificity of 94.0% and 98.6% in authenticating tea samples based on their geographical origins. (Mohammadi *et al.*, 2024). The SVM algorithm's optimisation was tuned based on the parameters c (cost), epsilon, and gamma, in which optimisation can be performed using a genetic algorithm. (Mohammadi *et al.*, 2024). The output from the PCA, after dimension reduction, was used as input to an SVM using a radial basis function to

identify the presence of adulterant butteroil. (da Silva Medeiros *et al.*, 2023b). The SVM classification result has an accuracy of 98.46%, indicating that the model can identify pure samples. (da Silva Medeiros *et al.*, 2023b). SVM can solve nonlinear problems by employing a nonlinear kernel function to map input data into a high-dimensional feature space, wherein linear classification can be performed.

3.2.2 Regression analysis

3.2.2.1 Partial least squares (PLS)

Partial least squares (PLS) regression represents a multivariate regression method that uses the least squares algorithm to establish a relationship between variables. In PLS regression, the fundamental principle relies on latent variables, which are unobserved variables derived from the original predictors. The method decomposes the spectral data matrix, denoted as *X*, into a set of these latent variables or components. This decomposition process is carefully guided by the variation in the property values, represented as **y**, which are interesting in the analysis. The relationship between *X* and *Y* is governed by a functional relationship, ***f*,** as illustrated in Equation 2.

$$y = f(X) \qquad \text{Equation 2}$$

The co-variation between X and y is maximised to extract the variation in X directly correlated with y. Applying NIR can explain this by representing the spectra in the space of NIR wavelengths to show a linear correlation based on combinations of wavelengths, called factors, where the studied property is best described.

Balcázar-Zumaeta *et al.* employed PLS in the chemometric analysis, which was embedded with Raman spectroscopy, to quantify the concentrations of cupuassu butter, passion fruit oil, and sacha inchi oil blended with cocoa butter to make chocolate. (Balcázar-Zumaeta *et al.*, 2025). Three PLS models were developed for mixing cocoa butter with cupuassu butter, passion fruit oil, and sacha inchi oil, and the R^2 prediction obtained for each model was 0.749, 0.85, and 0.62. Although the results of some models are not above 0.80, with proper model tuning and optimisation, the model's performance can be improved.

3.2.2.2 Principal component regression (PCR)

Principal component regression (PCR) constitutes a multivariate regression methodology that integrates the frameworks of multiple linear regression (MLR) and principal component analysis (PCA) to address challenges inherent in high-dimensional spectral datasets. Spectroscopic data often exhibit substantial multicollinearity and dimensional redundancy, complicating conventional regression modelling. PCR circumvents these issues by applying PCA to the original set of correlated spectral variables, thereby projecting them onto a reduced-dimensional subspace defined by orthogonal principal components. These principal components, which are linear combinations of the original variables, retain the maximal variance structure of the data while eliminating inter-variable correlations. Subsequently, MLR is performed on this transformed set of uncorrelated components, facilitating more stable and interpretable regression modelling. This dimensionality reduction mitigates the adverse effects of multicollinearity and enhances model robustness and generalisation capacity in spectroscopic analysis. The number of principal components to be used in the PCR model is one of the parameters that must be optimised by varying the number of principal components and computing the prediction error. (Biancolillo *et al.*, 2020). A PCR model was developed using the FTIR spectrum to detect adulteration in Mentha arvensis essential oil. (Jayasekher *et al.*, 2024b). The correlation coefficient (R^2) and RMSE for prediction were 0.9953 and 0.01687, respectively. The results demonstrate that the PCR prediction model is robust, as evidenced by its high correlation and low error rate when applied to the prediction dataset.

3.2.2.3 Support vector regression (SVR)

Support vector regression (SVR) is a supervised machine learning algorithm that seeks to construct a function capable of approximating the underlying relationship between spectral features and their corresponding target values while incorporating a specified margin of tolerance, commonly called the "ε-insensitive zone." This ε-insensitive loss function enables the model to tolerate minor deviations between predicted and actual values, thereby focusing on capturing the general trend of the data rather than precisely fitting every observation. A notable advantage of SVR is its robustness when dealing with relatively small datasets, as it minimises a regularised loss function that effectively balances the trade-off between predictive accuracy and model complexity. This balance is crucial in preventing overfitting, especially when data availability is limited, which is often the case in many applied spectroscopy and photonics applications.

Moreover, SVR demonstrates flexibility in handling both linear and nonlinear regression problems by applying kernel functions, which enable the mapping of input data into higher-dimensional feature spaces where complex patterns may be more readily identified. Like its counterpart, Support Vector Machines (SVM), which is widely used for classification tasks, SVR relies on carefully tuning several key hyperparameters to optimise its performance. These hyperparameters include the choice of kernel type, the regularisation parameter (which controls the trade-off between the flatness of the function and the allowed deviations), and the epsilon parameter that defines the width of the ε-insensitive margin. Hyperparameter optimisation is a critical step in model development, and methods such as grid search are commonly employed to explore various parameter combinations to identify the optimal configuration that yields the best generalisation performance.

The SVR algorithm has been applied in food authentication to quantify adulterants in coriander powder using FTIR spectroscopy. The R^2 obtained for the validation was 0.8289, and the RMSE was 0.1113 (Goyal *et al.*, 2025). SVR algorithms trained to detect mycotoxins in food samples have achieved an accuracy of 0.995, indicating that they can be a valuable tool for regulatory compliance and food safety monitoring (Tarcan & Küplülü, 2024; Usman *et al.*, 2025). The prediction model developed based on SVR algorithms to determine fructose, glucose, and sucrose concentrations in high-fructose syrup has yielded R^2 values of 0.8491 for fructose, 0.7812 for glucose, and 0.8871 for sucrose. (Erinawati *et al.*, 2025)Based on the nonlinear SVR model, the developed model offers a rapid and robust approach, making it suitable for routine monitoring.

3.2.2.4 Artificial neural network (ANN)

Artificial neural networks (ANNs) constitute a widely adopted machine learning technique in chemometric analysis. It has demonstrated considerable reliability and effectiveness, particularly in performing regression tasks such as adulterant

quantification, compositional analysis, and estimating food product quality. This modelling approach is especially advantageous in the context of spectroscopy. This field frequently generates complex, high-dimensional, and inherently noisy datasets, often presenting significant challenges for conventional analytical methods. ANN's capacity to model nonlinear data structures enables it to capture intricate patterns and interactions within the data that simpler, linear models may overlook. Nevertheless, to ensure the development of a robust and generalisable model, careful tuning of the network's hyperparameters is crucial to overcome the risk of overfitting, wherein the model excessively adapts to the noise in the training data rather than capturing the authentic underlying relationships.

The flexibility of ANN allows its application in classification and regression analyses, depending mainly on selecting the activation function employed within the network architecture. Structurally, an ANN is composed of three fundamental layers: the input layer, which serves to receive and introduce the raw data into the network; one or more hidden layers, where complex transformations and feature extractions are performed; and the output layer, which delivers the final predictive or classification outcomes. Due to its interconnected structure, an ANN typically requires a larger dataset than classical algorithms. This requirement arises from the need to iteratively adjust and optimise the numerous connection weights between neurons during the training process, allowing the network to effectively learn and model the complex relationships between the input features and the corresponding output variables. The research to predict adulteration in coriander powder utilised FTIR spectra to train an ANN with an input layer of 64 neurons, a hidden layer of 32 neurons, and an output layer of 1. R^2 of validation data for the ANN model was 0.9351, and the root mean square error (RMSE) was 0.0753 (Goyal *et al.*, 2025). The ANN model's high performance is due to its ability to calculate nonlinear relationships and complex relations between features. A convolutional neural network (CNN) was also utilised to detect sugar alcohol adulteration in coconut water using FTIR spectroscopy (Thomas A. Teklemariam *et al.*, 2024). The accuracy obtained surpassed that of discriminant analysis and SVM. This demonstrates the capability of FTIR to detect alcohol in beverages, a critical requirement for ensuring compliance with Islamic dietary laws.

In addition, Table 4 shows that a few researchers utilised a regression algorithm to develop a predictive model for detecting adulteration or quality authenticity. Different types of regression algorithms, based on previous work, for example, support vector regression (SVR), PLS, and Gradient boosted regression (GBR), have achieved low error rates in the prediction model. As shown in Table 4, the support vector regression (SVR) application yields a low prediction error of less than 0.1 for nutrient prediction. However, SVR can also result in higher errors, with a maximum observed value of 3.78. These findings demonstrate that chemometric-based prediction models offer high accuracy and generally maintain a low risk of significant errors in quantifying food components, depending on the characteristics of the input spectra. The prediction model in chemometric analysis requires an optimisation process before being deployed to the instrument. More regression algorithms are available; thus, the chemometricians must try multiple algorithms before choosing the best model.

PLS, PCR and SVR are effective for small to medium-sized datasets due to their strong generalisation performance, but ANN require a large dataset to avoid model overfitting. In some applications, regression is combined with classification techniques to enhance food authentication. For instance, a classification model might first identify whether a food sample is halal or non-halal, while a regression model estimates the concentration of specific non-halal components. This hybrid approach increases the robustness and reliability of the authentication process. Overall, regression algorithms are indispensable in modern food spectroscopy, providing rapid, nondestructive, and accurate solutions for ensuring food authenticity, quality, and safety throughout various stages of the food supply chain.

Table 4: Different types of regression methods to assess food authenticity

Sample	Regression method	Root mean square error (RMSE)	Application	Industry implication
Potato plants (Abukmeil *et al.*, 2024)	SVR	< 0.1	Nutrient prediction (NPK) using Vis-NIR spectroscopy	Enhances precision agriculture through rapid nutrient assessment
Arabica coffee (Suhandy *et al.*, 2025)	PLS	2.01 %.	Detection of roasted soybean adulteration in Arabica coffee	Determine coffee quality control by identifying adulteration with cheaper ingredients
Honey (Boateng *et al.*, 2022)	GBR	2.183	Detection of syrup adulteration in honey	Ensures authenticity and protects consumer trust by detecting syrup adulteration
Extra virgin olive oil (Zaroual *et al.*, 2025)	SVR	3.78.	Adulteration quantification using emission spectra (excitation at 430 nm)	Aids in verifying purity and detecting economic fraud in premium oil products

Furthermore, regression models can be integrated into real-time monitoring systems, enabling continuous testing of food quality without the need for extensive sample preparation. This ability makes them ideal for high-throughput industrial applications. In more advanced systems, regression models may be combined with classification techniques to enhance food authentication's accuracy, such as distinguishing between halal and non-halal ingredients. Overall, regression algorithms play a crucial role in transforming spectral data into actionable insights, thereby ensuring the authenticity and safety of food.

4. Conclusion

Spectroscopy techniques such as FTIR, UV-Vis, NIR, and Raman have demonstrated strong potential in food authentication, with each method offering distinct advantages depending on the nature of the food matrix. For example, NIR and FTIR spectroscopy have efficiently quantified nutrients and detected adulterants due to their ability to capture complex molecular vibrations. With its high specificity, Raman spectroscopy has shown strengths in differentiating similar chemical compounds, making it suitable for origin verification and variety classification. When integrated with chemometric techniques, the predictive performance of these spectroscopic methods is significantly enhanced. For regression tasks such as nutrient quantification, SVR and PLS were among the most accurate models, with SVR achieving errors lower than 0.1 in some instances. However, model performance was also sensitive to the quality of spectral input, with occasional high errors indicating the need for robust preprocessing. For classification problems, methods such as PCA combined with LDA or classifiers like SVM have demonstrated high accuracy in distinguishing between authentic and adulterated samples and identifying the origin of food. The key contribution of this review lies in its focused examination of how spectroscopy and chemometric methods address not only general food authentication challenges but also specific religious requirements, such as halal verification.

However, despite these advancements, several critical challenges remain that limit the full deployment and standardisation of spectroscopy-based authentication systems. One primary concern is the lack of standardised protocols and calibration models across different instruments, which can affect the reproducibility and comparability of results. Data reproducibility and model transferability across different platforms and operators also remain challenging, especially for portable or handheld devices in field conditions. Methods, such as calibration transfer, should play a crucial role in ensuring the repeatability and reproducibility of data prediction across different instruments. Another significant issue is the limited availability of comprehensive spectral libraries and validated reference datasets, which are crucial for building robust predictive models. Future advancements in chemometric and spectroscopic instrumentation are expected to enhance these techniques' accuracy and usability and improve sensitivity and specificity. These techniques' usability promotes the evolution of artificial intelligence, real-time portable devices and transparent food authentication frameworks. In the context of halal food systems, these analytical tools support compliance with religious dietary laws by enabling the detection of non-halal adulterants such as pork derivatives without compromising the integrity of the sample. This technological approach not only reinforces trust and transparency within halal supply chains but also helps manufacturers and certifiers meet the increasing expectations of consumers for religiously permissible and ethically verified products. As advancements in portable devices and real-time spectral analysis continue, these methods are becoming increasingly accessible for on-site verification and ensuring halal integrity.

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Muslim-friendly tourism in non-Muslim majority destinations: A review of Bali Island

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Received:8/7/2025
Accepted:27/7/2025
Published:31/7/2025

Keywords:
Halal services; Bali; Muslim-friendly Tourism; Halal certification; Tourism challenges

Abstract

The global rise in Muslim tourists has prompted the international tourism industry to prioritise Muslim-friendly services and amenities. Bali, as a world-renowned tourist destination, faces a unique challenge in balancing its predominantly Hindu cultural identity with the growing expectations of Muslim travellers, particularly about religiously appropriate services. This study investigates the potential, challenges, and strategic approaches to implementing Muslim-friendly tourism in Bali. A narrative review methodology was employed, utilising secondary data from academic literature, industry reports, statistical sources, and documents highlighting current trends in Muslim-friendly tourism. The findings reveal that Bali offers supportive infrastructure, business interest, and several Muslim-friendly facilities, including prayer spaces, hotels, and halal food options. However, challenges persist, such as limited halal-certified establishments, local cultural resistance, and unclear regulatory frameworks. The study concludes that developing inclusive Muslim-friendly tourism in Bali requires a culturally adaptive approach, clear standards, and active stakeholder collaboration.

1. Introduction

The association of *Shari'ah* principles with tourism has given rise to several terminologies, including Islamic tourism, *Shari'ah* tourism, halal tourism, halal lifestyle, halal travel, Muslim-friendly tourism (MFT), halal tourist destinations, and religious tourism. These terms share a common foundation: the notion that Islamic teachings should guide tourism activities (Fitriani & Naamy, 2019). This tourism segment that caters to Muslim tourists has experienced rapid growth, prompting businesses such as hotels, restaurants, tour operators, and travel agencies to innovate and expand their presence (Aziz, 2018). In developing these destinations, it is necessary to consider all aspects holistically as an ecosystem (Sutono *et al.*, 2021). In addition, growing tourist awareness regarding health, safety, and security has become an important consideration for destination managers. In this context, efforts to promote this segment significantly encourage stakeholders to offer high-quality amenities, attractions, and accessible services that align with Islamic values (Abbas *et al.*, 2021; Ntounis *et al.*, 2022).

As reported by Prayer Times (2025), the global Muslim population is projected to reach approximately 2.04 billion, which is expected to lead to a proportional rise in demand for Islamic tourism. This segment has emerged as a fundamental part of the global tourism sector. The Global Muslim Travel Index (GMTI) 2024 reported a significant improvement in the accommodation of Muslim-friendly services, with the average destination score increasing by nearly 10%. This indicates that more destinations are actively striving to meet the needs of Muslim travellers. Indonesia, in particular, demonstrated a strong performance, securing a top two ranking along with Malaysia in the GMTI 2024 (see Table 1). This achievement reflects Indonesia's robust tourism infrastructure and ongoing efforts to enhance tourism facilities, highlighting its growing potential and competitiveness in the global Muslim travel market.

Countries with significant Muslim populations, such as Malaysia and Indonesia, tend to be preferred by global Muslim travellers seeking a comprehensive experience aligned with their faith. This may be explained by the fact that Muslims can feel more comfortable in an environment that adheres to Islamic law in diet, attire, and other traditions (Mohsin *et al.*, 2016). Indonesia has outlined a clear vision and mission for this tourism sector in response to this demand. The country aspires to position itself as a premier destination for Muslim travellers while fostering diversity and promoting sustainable tourism practices. Its mission includes market-oriented promotional strategies, establishing a competitive environment for Muslim-oriented tourism, and enhancing Indonesia's global competitiveness (Sutono *et al.*, 2019).

Bali, Indonesia's most iconic and internationally recognised tourist destination, offers an intriguing context for this evolution. It is predominantly a Hindu culture, and a strong secular tourism identity raises important questions about how Muslim-friendly tourism can be implemented in a way that is both respectful and inclusive. As such, Bali is a compelling case for exploring how Muslim-friendly tourism principles can be integrated into non-Muslim-majority settings without

Table 1: GMTI 2024 rankings

GMTI Rank	Change VS 2023	Destination	GMTI Scores
1	0	Indonesia	76
1	0	Malaysia	76
3	0	Saudi Arabia	74
4	+1	Turkiye	73
5	-1	United Arab Emirates (UAE)	72
6	0	Qatar	71
7	0	Iran	67
7	0	Jordan	67
9	+6	Brunei	66
9	+4	Oman	66
9	+2	Singapore	66

Source: Global Muslim Travel Index (GMTI) (2024)

compromising cultural authenticity. While Bali is already showing signs of adapting to the needs of Muslim travellers, a critical gap remains in understanding how to develop its Muslim-friendly tourism capacity systematically. This study builds upon that gap by reviewing relevant literature and emerging trends in Muslim-friendly tourism, focusing on the opportunities and challenges that arise in non-Muslim-majority environments.

1.1 Definition of halal tourism vs Muslim-friendly tourism

Tourism has become a global focus due to increasing demand from Muslim travellers seeking tourism experiences that reflect Islamic values. Two key terms frequently appear in this context: halal and Muslim-friendly tourism (MFT). Although they are often used interchangeably in policy and academic discourse, academic literature has drawn distinctions between the two based on levels of compliance with *Shari'ah* principles (Table 2).

Halal tourism is defined as tourism that accommodates the needs of Muslim travellers in its products and services, including food, accommodation, financial services, and gender-specific facilities, consistent with Islamic principles. Halal tourism typically involves strict adherence to Islamic law across all aspects of the tourism experience. (Rahman *et al.*, 2020). Muslim-friendly tourism, by comparison, adopts a more inclusive and adaptable model that is especially relevant in non-Muslim-majority destinations where full *Shari'ah* implementation may not be feasible. It focuses on providing essential religious facilities and services, such as halal food and prayer areas, without requiring full *Shari'ah* compliance in all tourism aspects. This approach allows destinations to accommodate Muslim tourists' basic needs while preserving their cultural identity and welcoming travellers of all backgrounds (Muslim & Harun, 2022). Muslim-friendly tourism reflects the evolving nature of global Muslim travel by enabling broader application across diverse contexts, particularly in multicultural and secular environments. It promotes an inclusive, safe, and respectful tourism ecosystem of Islamic values, offering Muslim travellers a meaningful experience without excluding others (Nugroho *et al.*, 2019).

In the case of Indonesia, the country has officially adopted the term halal tourism in its regulatory and promotional frameworks. The Ministry of Tourism (2012) defines halal tourism as tourism activities supported by facilities and services from the community, businesses, and government that align with Islamic values. According to Sugihartati *et al.* (2022), Indonesia's implementation of halal tourism follows two main approaches. The first is rooted in religious tourism, emphasising Indonesia's Islamic heritage, such as mosque visits, pilgrimages to religious leaders' graves, and halal culinary tours. The second approach is more pragmatic, treating halal tourism as an enhancement of general tourism by adding Muslim-specific services. This includes features such as prayer spaces, halal-certified food, and family-friendly amenities—elements that allow Muslim tourists to maintain their religious practices while engaging in various tourism types such as nature-based, cultural, and leisure.

While Indonesia continues to use the term halal tourism, this article adopts the term Muslim-Friendly Tourism (MFT) to better reflect the broader, more commonly accepted interpretation found in the literature and a more inclusive approach to serving Muslim travellers in non-Muslim-majority destinations, such as research by Rasyid *et al.* (2024), Suswanta *et al.* (2023), and Takhim *et al.* (2023). The MFT term is also aligned with the second approach in Indonesia's model, which emphasises practical religious accommodations within mainstream tourism infrastructure. It prioritises service provision over doctrinal enforcement and promotes inclusivity without requiring comprehensive *Shari'ah* compliance. Framing the Indonesian case within the MFT paradigm allows for more accurate comparative analysis. It situates Indonesia within a global trend toward flexible, culturally sensitive tourism that meets the diverse expectations of Muslim travellers.

1.2 Muslim friendly tourism in Indonesia

Indonesia has great potential for developing Muslim-friendly tourism at the global level, supported by its Muslim-majority population and the wealth of available natural resources. This tourism sector not only contributes to economic growth but also plays a role in creating various jobs. Nevertheless, strategic and operational challenges must be addressed to fully actualise this potential (Rahim *et al.*, 2024). Several key aspects should be considered to support the development of high-quality and competitive Muslim-friendly tourism. To achieve this, its tourism resources must be managed effectively and professionally. Additionally, community members and stakeholders should be supportive by fostering a positive

Table 2: The Differences between halal and Muslim-friendly

Aspects	Halal Tourism	Muslim-Friendly Tourism
Definition	Tourism that considers tourists' compliance with *Shari'ah* law involves strict halal nuances such as food and beverages, clothing, tourism activities, services, and others (Azam *et al.*, 2019; Jafari & Scott, 2014).	The term Muslim-friendly is lighter and narrower than halal. Muslim-friendly tourism caters to Muslim tourists' needs, is based on adherence to their religious beliefs, or implements the main elements of Islamic attributes in services and products (Ahmed & Akbaba, 2020; Battour *et al.*, 2014; CrescentRating, 2016; Junaidi, 2020).
Target Market	Primarily, Muslim-majority countries are the primary target audience seeking products and services that comply with *Shari'ah* law, which also creates many opportunities for both Muslim and non-Muslim countries (Boğan & Sarıışık, 2019a).	Muslim-friendly tourism, while targeting Muslim travellers, is commonly associated with destinations in non-Muslim-majority regions, such as Bali (Ahmed & Akbaba, 2020)
Services and Facilities	Includes prayer facilities, halal food and beverages, entertainment, gender-segregated facilities (pools, bathrooms), avoiding alcoholic beverages, halal finance, and pharmaceuticals (Jamal & El-Bassiouny, 2018).	It may include halal food options, prayer spaces, and some Muslim-friendly amenities, but it may also provide non-halal products and services or not strictly comply with *Shari'ah* (Ahmed & Akbaba, 2020).
Industry Application	A niche market, halal tourism includes halal hotels, halal transportation (halal airlines), food, entertainment, tour packages, and halal finance (Akyol & Kilinç, 2014).	Tourism services are more accommodating of some Muslim-friendly options without full halal certification or integration of the basic needs of Muslim travellers (Ahmed & Akbaba, 2020).

attitude towards the growth of Muslim-friendly tourism (Nugroho *et al.*, 2021).

LPPOM MUI (2023) has conducted several initiatives to develop Indonesia as a Muslim-friendly tourist destination. Table 3 summarises the establishment of institutions and the ratification of laws that form the foundation of the halal certification system in Indonesia. This robust and evolving halal certification framework is instrumental in enhancing Indonesia's credibility as a leading destination for Muslim-friendly tourism, assuring travellers of genuine adherence to Islamic principles.

Table 3: Historical Development of Halal Certification System

Year	Policy
1975	The Indonesian Council of Ulama (MUI) was formed.
1989	LPPOM MUI was formed, and halal certification was started.
2012	LPPOM MUI officially launched (Halal Assurance System 23000) and requires companies to implement it.
2014	Law No. 33 of 2014 concerning halal product assurance was passed.
2017	The Halal Product Assurance Agency (BPJPH) was formed.
2019	The obligation of halal certification by Law No. 33 of 2014 should have been implemented.

Currently, no law explicitly regulates halal or Muslim-friendly tourism in Indonesia. However, this segment in Indonesia is governed by various regulations and policies related to the tourism sector as a whole, as well as laws governing halal product guarantees. In addition, several regions in Indonesia have issued regional regulations (*peraturan daerah*, Perda) related to halal tourism. Moreover, to fulfil these necessities, although not as strong as a law, the National Sharia Council-Indonesian Ulema Council DSN-MUI (2016) issued a fatwa No.108/DSN-MUI/X2016, after considering that Indonesia needs guidelines for organising tourism based on *Shari'ah* principles. One of the provisions is as follows: "*Shari'ah Tourism Destinations are geographical areas located in one or more administrative areas in which there are tourist attractions, worship and public facilities, tourism facilities, accessibility, and communities that are interrelated and complement the realisation of tourism following shariah principles*." The study by Saviera *et al.* (2024) showed that the following regions have halal tourism regulations: Regulation Number 51 of 2015, which is from the Governor of West Nusa Tenggara; Regulation Number 1 of 2020, which is from the Province of West Sumatra; Regulation Number 19 of 2022, which the Governor of North Sumatra Province issued; and Regulation Number 6 of 2020, which is from Bandung Regency. The Government of South Sumatra Province also issued Regulation Number 9 of 2019 regarding halal tourism.

1.3 Bali as a Muslim-friendly tourism destination

Bali has become a leading domestic and international tourist destination (Ramadhani *et al.*, 2023). As a tourist destination, Bali tourism has a strong branding that emphasises natural

beauty, cultural diversity, ethnic arts, traditional Balinese artistic performances, and religious ceremonies, all of which make Bali visually striking to tourists (Pageh *et al.*, 2022; Utama *et al.*, 2023). According to the Central Statistics Agency (BPS) by Yustiani (2024), Bali had significant fluctuations in local and international visitor arrivals from 2020 to 2023. It shows the influence of several global and regional occurrences, including the COVID-19 pandemic and its subsequent recovery, on the tourism industry. Figure 1 shows Bali's tourism recovery from 2020 to 2023. International tourist visits rebounded from a notable decline in 2021 to exceed 5.2 million in 2023, while domestic tourism reached its peak of 11.6 million. This indicates Bali's critical role in revitalising Indonesia's tourism sector.

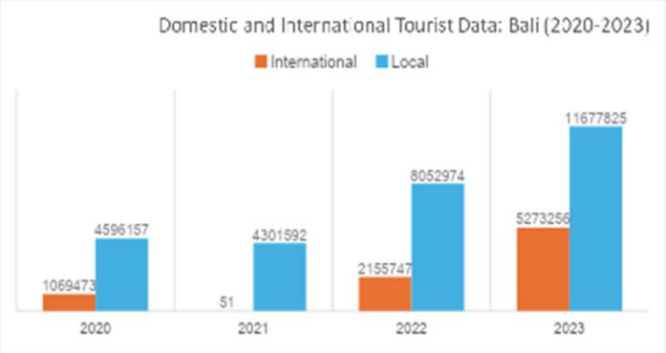

Figure 1: Domestic and international tourist data: Bali 2020-2023. Source : Yustiani (2024).

While Bali is predominantly Hindu and known for its unique cultural tourism identity, it increasingly attracts many Muslim tourists from domestic and international markets. Research indicates that Muslim-friendly services (MFT), such as halal dining options and prayer facilities, play a crucial role in enhancing the satisfaction and loyalty of Muslim travellers toward their destinations (Battour *et al.*, 2014). The study by Subagiyo and Syaichoni (2023) shows that the opportunities for halal culinary tourism in Bali are readily apparent; however, engaging with local producers and expanding the variety of halal menu offerings is essential. Despite Bali, Indonesia, being a major tourist destination that has gained increasing popularity among Muslim travellers, a comprehensive assessment of its halal facilities and food services is still necessary. This includes ensuring the availability of halal-certified food, providing facilities like prayer rooms and gender-separated restrooms, and serving meals prepared by halal principles (Setiawan & Pahlevi, 2023). Given the significant and expanding global Muslim travel market and Indonesia's top-tier ranking in the Global Muslim Travel Index, developing Muslim-friendly tourism (MFT) in Bali becomes a strategic imperative.

Therefore, understanding why Bali should embrace this requires a comprehensive review of existing literature and data to identify the potential benefits, challenges, and implications of integrating MFT services into Bali's tourism sector. This review will explore whether and how Muslim-friendly tourism can complement Bali's established tourism brand, significantly enhance visitor satisfaction, and contribute to the island's economic growth by diversifying its appeal without compromising its cherished cultural authenticity.

Accordingly, this study aims to fill this knowledge gap by analysing the current state of Muslim-friendly tourism (MFT) in Bali, while examining the potential, challenges, and strategies the growing Muslim community poses. The study will review current literature and data to discuss the potential of MFT initiatives to enhance Indonesia's economic development. This review aims to highlight the significance of strategic planning and stakeholder contribution to maximising the potential of Muslim-friendly tourism (MFT) in Bali by addressing the subsequent question: What are the potential challenges and appropriate strategies to support the development of Muslim-Friendly Tourism (MFT) in Bali?

2. Materials and methods

A narrative literature review approach provided background and context on developing Muslim-friendly tourism, particularly its potential in Bali. This method draws on secondary data from academic sources, industry reports, statistical data, and relevant documents that describe current trends in Muslim-friendly tourism (Halim & Aghwan, 2024). The literature was searched explicitly through academic databases including Scopus, ScienceDirect, and Google Scholar, prioritising studies published between 2014 and 2025 to capture the most recent developments in the field.

Narrative reviews, commonly used across the social sciences and humanities, are especially suited for topics where reality is subjective and dynamic. This approach enables researchers to describe the current state of knowledge on a subject and offer a subjective examination and critical analysis of the existing literature. It allows exploring under-researched areas, offering new insights, or presenting alternative perspectives on even well-established fields (Rumrill & Fitzgerald, 2001; Sukhera, 2022). In this article, a narrative review helps to effectively contextualise Muslim-friendly tourism's development and discuss its potential in Bali from a specific perspective.

Unlike systematic reviews that follow a rigid and replicable search protocol, this narrative review synthesises insights from selectively chosen studies based on their relevance to core themes in Muslim-friendly tourism (Demiris *et al.*, 2019). These themes include governance, policymaking, marketing strategies, and levels of public awareness that influence the attractiveness of Muslim-friendly tourism destinations. The review also incorporates illustrative case examples from destinations recognised for successful Muslim-friendly tourism initiatives to highlight effective practices that may be applicable in Bali's context. Additionally, it explores challenges such as varying levels of halal awareness and understanding among the local population. It emphasises the importance of collaboration with local communities and businesses in building a sustainable model that benefits all stakeholders.

3. Results and discussion

The following section outlines the key findings derived from secondary data, integrating them with insights from relevant literature. Figure 2 graphically illustrates the identified potentials, challenges, and corresponding strategies crucial for advancing the Muslim-friendly tourism sector**.**

3.1 Muslim-friendly tourism potential in Bali

The Islamic economic perspective on Muslim-friendly tourism is rooted in the principles of Islamic economics, which emphasise values such as justice, sharing, ethics, and equality in distributing wealth and resources. The halal food industry is an essential component of Muslim-friendly tourism, as halal

food must adhere to Islamic law in its production and distribution. This creates substantial business opportunities for halal food producers and contributes to the local economy (Basyariah, 2021; Pranika *et al.*, 2023). Bali can become a halal tourism destination, provided the government takes the initiative. Improving services for the Muslim tourist segment should be a priority. One way to achieve this is by developing the concept of organising Muslim-friendly tourism. Governments of countries with non-Muslim majority populations, such as Japan, Taiwan, Singapore, and Thailand, are keenly aware of the economic potential presented by the

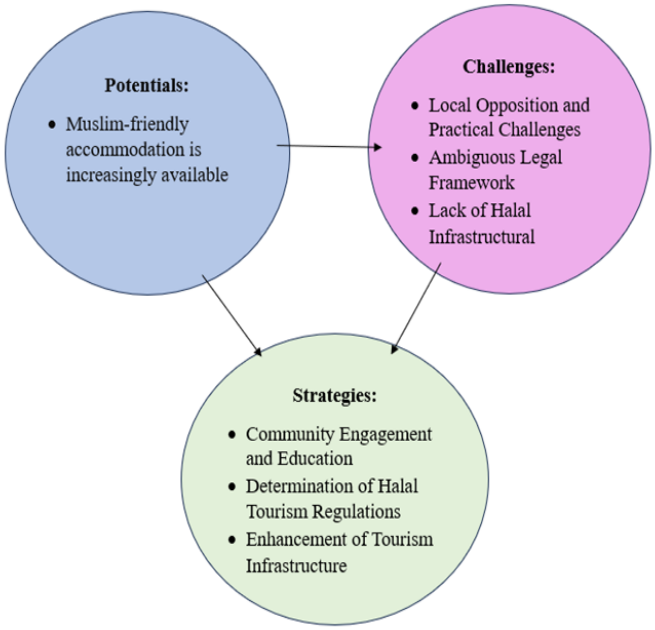

Figure 2: Muslim-friendly potentials, challenges, and strategies.

global movement of Muslim tourists, enabling them to develop Muslim-friendly tourism concepts (Napitupulu *et al.*, 2022). According to Sofyan (2021), chairman of the team for accelerated development of Halal tourism, several regions in Indonesia have already been planned and developed as Muslim-friendly tourism destinations. Figure 3 illustrates the top 10 destinations that are friendly to Muslims.

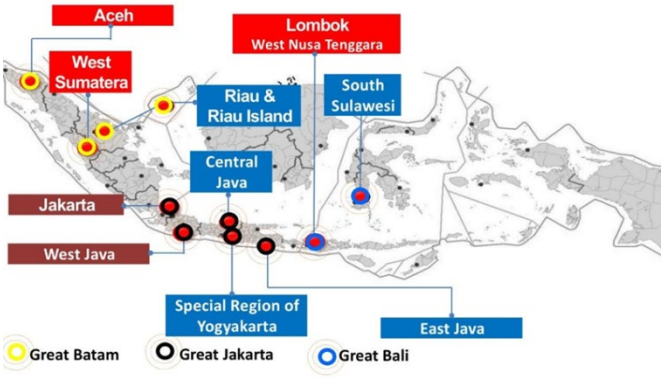

Figure 3: Top 10 Muslim-Friendly Destinations in Indonesia
Source: Ministry of Tourism and Creative Economy of the Republic of Indonesia (2019).

"Great Bali" is identified as a strategic area with significant tourism potential, including for Muslim visitors. However, this does not imply Bali is currently a fully Muslim-friendly destination. Instead, it highlights future potential and governmental development efforts. The drive towards Muslim-friendly tourism aligns with Islamic values, supported by 765 Islamic worship facilities in Bali, comprising 515 prayer rooms and 250 mosques (Annur, 2022). Research by Zamany and Wiliasih (2023) further revealed that the availability of halal food and drinks, prayer facilities, and suitable accommodation significantly influenced tourists' perceptions of Bali as a Muslim-friendly destination. Furthermore, while five hotels in Bali have adopted a Muslim-friendly concept, only Bayt Kaboki and Princess Keisha hotels operate with management that closely aligns with such standards. The remaining three: Rhadana Hotel, Alam KulKul Boutique Resort, and Grand Santhi Hotel, currently offer only basic Muslim-friendly facilities, focusing on general hospitality, good service, and attention to halal aspects rather than full Sharia compliance (Halim & Baroroh, 2021).

3.2 Muslim-friendly tourism challenges in Bali

As society becomes more aware of implementing Islamic law in everyday life, Muslim-friendly tourism presents solutions for Muslim tourists and significant growth opportunities in the global tourism market. On the other hand, it also faces several challenges that could hinder its development. Vargas-Sánchez and Moral-Moral (2020) revealed that the main concerns in the halal sector include several important aspects that need to be addressed to develop this industry well:

1) Ignorance is a major obstacle, and a lack of information about this market, its characteristics, and its potential is another significant obstacle. Understanding and appreciating what is unknown is impossible.
2) The lack of adequate infrastructure to meet the needs of Muslim tourists is also a significant concern. This includes the availability of halal-certified food and proper prayer facilities, which are especially important for Muslim tourists.
3) There are difficulties in serving Muslim and non-Muslim customers simultaneously due to their cultural differences. This challenge includes how to make both markets compatible in the same space, taking into account factors such as Islamophobia, intolerance, and cultural misunderstanding.

The literature also identifies the diversity of interpretations of Muslim obligations worldwide as one of the problems in certifying halal products or services. Similarly, in this context, some key challenges associated with Muslim-friendly tourism are also identified. These include local opposition and practical challenges, ambiguous legal frameworks, and a lack of halal infrastructure and accessibility.

3.2.1 Local opposition and practical challenges

Although Indonesia is a Muslim-majority nation, several provinces most notably Bali are religiously and culturally distinct. Bali is a Hindu-majority region with a strong international tourism identity rooted in cultural heritage, art, and spiritual practices. This presents both a challenge and an opportunity when integrating Muslim-friendly services. In such areas, smaller Muslim populations may face challenges in accommodating the specific needs of Muslim travellers. The

behaviour of Muslim tourists is complex because they are guided by Islamic rules and values, which influence nearly every aspect of life, including travel. This creates uncertainty in how tourism services should be provided and can lead to unexpected consumer behaviours such as continuing to travel, compromising certain needs, or even cancelling trips altogether (Olya & Al-ansi, 2018).

Against this backdrop, the national emphasis on developing "halal tourism" has been perceived by some as a hegemonic move, prompting concerns about preserving the unique cultural and religious identities of minority regions particularly in Bali, where Hinduism predominates (Makhasi & Rahimmadhi, 2020). The continued promotion of halal tourism has also sparked the emergence of identity politics in regions with non-Muslim majorities, where communities resist or oppose the perceived dominance of halal tourism initiatives planned for their territories.

In 2019, Sandiaga Uno (former Indonesian Tourism and Creative Economy Minister 2020–2024) faced public resistance in Bali following his statement promoting halal tourism (Musthofa *et al.*, 2023). The Governor of Bali publicly criticised the proposal, emphasising that political interests should not be allowed to politicize matters of halal and haram. Similarly, the Head of the Bali Tourism Office expressed concern that the implementation of "halal tourism" could undermine Bali's original tourism identity, which has long been associated with its unique cultural attractions. The governor further suggested that halal tourism initiatives be directed toward other underdeveloped sectors, in order to preserve Bali's authenticity.

This backlash largely stems from the conceptual ambiguity surrounding "halal tourism," which is often perceived as a rigid or imposing framework. This perception persists despite the government's practical implementation, which often aligns with the more flexible and inclusive "Muslim-friendly tourism" (MFT) model, even while the broader "halal" term is used for national branding. The disconnect between terminology and practical scope can intensify resistance and misunderstanding, as communities react to the perceived implications of "halal" rather than the more adaptable reality. Conversely, the term MFT may offer a pragmatic and less intrusive approach, enabling destinations to cater to the essential needs of Muslim travellers without compromising their core cultural identity.

For example, the Bali Tourism Board (BTB) has explicitly rejected branding Bali as a "halal tourism" destination, asserting that such a move could dilute its cultural authenticity and spiritual heritage (Sanctuaries, 2025). The BTB leadership has affirmed Bali's commitment to preserving its cultural identity, local wisdom, traditions, and artistic heritage rather than adapting to comprehensive halal tourism standards. It has refused halal certification for traditional Balinese products and services that do not align with halal principles. Nevertheless, Bali remains committed to offering Muslim-friendly services, demonstrating respect for Muslim tourists' needs without altering its distinct cultural identity. This strategic approach prioritises cultural preservation while fostering sustainable and inclusive tourism. (Yaqub, 2025). A similar pattern of rejection due to a lack of proper socialisation and understanding of halal policies was observed in North Toraja (Putra *et al.*, 2021). Zuhdi *et al.* (2023) highlight that limited awareness and misconceptions about halal principles and certification remain significant barriers to the broader acceptance of halal tourism in diverse regions. They emphasise the necessity of government initiatives to promote interfaith harmony actively.

Furthermore, varying levels of understanding about halal principles influence how Muslim consumers evaluate products and services. Those with limited awareness might view such offerings more positively without critical consideration. Conversely, individuals with a deeper understanding of halal requirements tend to assess these attributes more rigorously and may become sceptical, particularly if they doubt the service provider's intentions (Boğan & Sarıışık, 2019; Newman & Cain, 2014; Silver *et al.*, 2021).

Without proper understanding, heightened awareness can lead to resistance. Communities may perceive integrating Islamic values into public or commercial areas as culturally intrusive. These dynamics highlight the critical need for balanced community education to foster acceptance and understanding of Muslim-friendly tourism, mitigate potential social tensions, and prevent initiatives from being misunderstood or rejected by local communities.

3.2.2 Ambiguous legal framework

The regulatory framework for halal tourism in Indonesia remains underdeveloped and lacks comprehensive legal clarity (Effendi *et al.*, 2021). One of the most significant obstacles to the growth of halal tourism is the absence of a binding, unified legal structure that can serve as a definitive benchmark for business actors and tourists. In regions where Muslims are not the majority, such as Bali, this legal ambiguity leads to confusion among tourism entrepreneurs who are uncertain about how to implement halal tourism practices properly. The current situation reflects a broader issue: Indonesia still lacks a robust legal foundation capable of supporting the development of a halal tourism industry that provides both legal protection and assurance for Muslim travellers (Pastika & Khoirudin, 2025).

Indonesia lacks dedicated national laws or centralised government regulations addressing halal or Muslim-friendly tourism. Although Law Number 10 of 2009 on Tourism includes provisions that promote respect for religious norms, customs, and cultural values, particularly in Article 26, paragraph 1, these provisions are broad and do not provide actionable or technical guidance for implementing halal tourism standards. While religious norms are central to halal tourism practices, their legal interpretation within existing tourism legislation remains implicit rather than explicitly defined. Moreover, there is a lack of legal alignment with Law Number 33 of 2014 on Halal Product Assurance, which has the potential to serve as a complementary legal framework for supporting halal tourism initiatives (Susilawati, 2019).

The absence of precise regulatory enforcement mechanisms further undermines existing religious guidance. For instance, the fatwa issued by the Indonesian Ulema Council (MUI), No. 108/DSN-MUI/X/2016, outlines key principles for sharia-compliant tourism. This fatwa provides comprehensive guidelines for sectors such as hotels, spas, travel agencies, and tour operations. Although rooted in Islamic principles, the fatwa promotes inclusivity by aiming to deliver quality service to all tourists—Muslim and non-Muslim alike, regardless of ethnicity or cultural background. However, unless this fatwa is codified into law or formalised through ministerial regulations by the Ministry of Tourism, it lacks legal authority and enforceability. As such, current laws and religious decrees

remain fragmented and ineffective in creating a cohesive regulatory environment for halal tourism. This legal vacuum hampers the development of a transparent and standardised halal tourism model across Indonesia. Without formal government endorsement and integration of religious guidelines into binding policy, efforts to promote halal tourism will continue to face inconsistency, business uncertainty, and limited consumer trust, particularly in regions with diverse cultural and religious dynamics.

3.2.3 Lack of halal infrastructure and accessibility

The increasing prevalence of halal and Muslim-friendly tourism has led many tourist destinations to integrate halal food provisions to accommodate the demands of Muslim visitors (Perguna *et al.*, 2021). According to Suaidi *et al.* (2025), in the context of Bali, one of Indonesia's leading tourist destinations, fulfilling culinary needs by *Shari'ah* principles presents a strategic opportunity to attract more Muslim tourists, particularly from Southeast Asia and the Middle East. On the other hand, without adequate halal infrastructures, Bali risks losing this potential market segment. By strengthening the halal food infrastructure and ecosystem, it can expand its market reach and increase its competitiveness in the global tourism industry.

Bali, often known as the Island of a Thousand Temples, boasts an impressive 4,755 Hindu temples, and strong religious ceremonies heavily influence the lives of its people, contributing to the uniqueness of their culture (Annur, 2022). While this rich Hindu heritage is central to Bali's identity, it is also home to a Muslim population, with approximately 434,941 individuals identifying as Muslim, accounting for 9.63% of the total population, according to Darmawan (2023). The main issue encountered is the deficiency of halal infrastructure, characterised by the lack of halal auditors, insufficient raw material distribution facilities, and slow halal certification procedures. In this situation, halal auditors are crucial, as stated in Articles 39-45 of PP No. 39 of 2021, which stipulates that BPJPH and the Halal Inspection Agency must conduct the halal audit, verification, and certification processes. The limited number of halal auditors in Bali results in a delayed certification procedure, negatively impacting businesses seeking halal certification due to longer processing times and higher expenses (Suaidi *et al.*, 2025). Zuhdi *et al.* (2023) highlight the necessity of government initiatives to enhance Muslim-friendly infrastructure, including providing halal food, prayer spaces, appropriate ablution facilities, and actively promoting interfaith harmony.

3.3 Muslim-friendly tourism strategies in Bali

The Muslim-friendly tourism strategy is designed to meet the basic needs of Muslim tourists, particularly in religious aspects, without requiring full compliance with strict *Shari'ah* standards, as in the concept of halal tourism. Non-Muslim countries or destinations generally apply this strategy to attract global Muslim tourists. The main goal of this strategy is to provide comfort and a sense of security for Muslim tourists during their travels, although the services offered are still limited. This approach is flexible and more inclusive, allowing non-Muslim destinations to participate in the growing Muslim tourism market without having to build a complete *Shari'ah* infrastructure system. The following are some strategies related to Muslim-friendly tourism.

3.3.1 Community engagement and education

Education is needed to achieve public awareness about halal. Halal awareness is closely related to knowledge, understanding, and the level of religiosity of the community; thus, relevant parties require more intense socialisation to provide understanding and awareness of the halal lifestyle for the community, especially concerning the consumption of halal products. Similarly, socialisation efforts should target MSME entrepreneurs, particularly those involved in the halal industry, including goods and services (Fathoni & Syahputri, 2020).

The integration of community engagement in the development process is crucial. Involving the local community ensures the project's sustainability and brings rich and authentic local cultural elements to the tourist experience. By gaining support from the local community, Muslim-friendly tourism projects have a greater chance of enduring and thriving (Hidayatullah, 2023). Active participation by residents contributes to effective destination management and promotes cultural harmony, bridging the needs of tourists and the local community's values.

In Taiwan, halal institutions, the local Muslim community, and the Taiwanese government all greatly influence the growth of Muslim-friendly tourism. Through public diplomacy, the government utilises its soft power to promote Taiwan as a Muslim-friendly destination. Nonetheless, the local Muslim community actively supports Muslim-friendly tourism and businesses by organising educational seminars, introducing halal products during events, and disseminating information about Muslim-friendly tourism and industries through social media (Mahendra & Surwandono, 2021).

The development of the Muslim-friendly tourism industry must be carried out with a comprehensive approach. To encourage the tourism sector, the development of the creative economy must involve close collaboration between various stakeholders, including the government and regulators, workers, tourism business actors, local communities, religious figures, the private sector, educational institutions, academics, and Muslim media and influencers.

3.3.2 Development of halal tourism policies and regulations

More detailed regulations are needed to outline the fundamental aspects of Muslim-friendly tourism, including its definition, scope, and implementation. Regulations specifically regulating halal facilities and tourism services and guiding tourism business actors who want to implement *Shari'ah* principles are essential. According to Ramadhani (2021), the positive impacts of halal tourism have been widely felt in Indonesia, particularly in the economic and employment sectors. Regulations related to halal tourism can be established in the Governor's Regulation or Regional Regulation, such as the Regional Regulation of West Nusa Tenggara Province Number 2 of 2016 concerning Halal Tourism in Lombok, NTB; however, they cannot be applied comprehensively, as they solely pertain to Lombok, NTB. In this case, the Ministry of Tourism must act swiftly to establish such regulations, as any delay in their formulation could confuse stakeholders involved in halal tourism when conducting their business due to the lack of clear guidelines to follow (Rasyid, 2018).

In a previous study, Santoso *et al.* (2020) identified destination development policy as the primary key to halal tourism policy. Human resources for halal tourism management, grouped into

three categories, support these policies: 1) Human resources for making and implementing halal tourism policies; 2) Human resources for workers in the halal tourism sector; and 3) Human resources for driving the improvement of the quality of halal tourism nationally.

3.3.3 Enhancement of tourism infrastructure

According to *Al-Muwafaqat fi Usul al-Ahkam*, the seminal work by Imam Asy-Syatibi, initially published in 1884 and later reprinted by *Dar al-Ma'rifah* in 1996, tourism can be viewed as an activity that is susceptible to misuse if not guided by proper ethical and legal frameworks. Table 4 illustrates the paradigm in tourism development based on *Maqasid Shari'ah*, which can be classified as one aspect of needs. The levels of *Maqasid Shari'ah* based on benefits are divided into three categories, namely *Daruriyyat* (necessity), *Hajiyyat* (complement), and *Tahsiniyyat* (embellishments).

By grounding MFT in this classification, tourism initiatives can be harmonised with Islamic jurisprudence (*fiqh*) and universal principles of well-being, contributing to a balanced and ethical tourism experience. MFT facilitates Muslim travellers in fulfilling religious obligations and reinforces principles of inclusivity, sustainability, and respect for cultural diversity. This makes MFT a strategic model for integrating tourism's religious, social, and environmental dimensions. To operationalise MFT in regions like Bali, where Muslims are a minority, there is an urgent need to enhance the capacity and competency of halal auditors through structured, accredited training programs led by both governmental and academic institutions. The availability of trained professionals is vital to accelerating halal certification processes, particularly for micro, small, and medium enterprises (MSMEs) that often face bureaucratic and financial hurdles (Suhartini *et al.*, 2024).

Additionally, a study by Aliffia and Komaladewi (2021) revealed that the most significant attribute based on Muslim preferences for halal-friendly destinations in non-Muslim tourist destinations is the accessibility of information concerning halal options at the tourist area, along with the standard of halal food and beverages and access to prayer facilities. In this context, digital infrastructure is an important enabler that bridges the information gap and provides convenience for Muslim tourists in planning their trips. Digital platforms, also known as digital infrastructure innovation, play a significant role in MFT development. The development of mobile apps could enhance the quality and accessibility of services and information for Muslim travellers. The app containsinformation on halal restaurants, mosques, prayer timings, and other Muslim-friendly facilities and helps travellers navigate new destinations (Baran & Karaca, 2023). Travel agents and tourism marketers need to consider and improve the availability of information on halal tourism attributes to become Muslim-friendly destinations. Japan has started to develop halal food and places of worship in big cities and public places through the application "Halal Navi" (Aji *et al.*, 2020).

The study by Aliffia and Komaladewi (2021) showed Muslim travellers prioritise five indicators while visiting non-Muslim tourist destinations. These indicators include the following: halal food and beverages offered in tourist locations must be clean, safe, and hygienic; the availability of halal food options at attractions; halal food providers in tourist sites are accredited with halal certification; the clear display of halal certification logos by restaurants; and tourist information centres provide halal service information.These indicators are essential in building trust, enhancing the visitor experience, and promoting MFT as a viable and inclusive tourism model.

Table 4: Classification of *Maqasid Shari'ah* Objectives

1. Category	2. Definition by Syaharani and Fahmi (2024)	3. Example Objectives in Tourism
4. Ad-Daruriyyat	5. These fundamental needs are essential for preserving life, religion, and basic human well-being.	• Providing places of worship at tourist destinations; • Halal food and beverages; • Security; • Healthcare
6. Al-Hajiyyat	7. The needs that are not urgent promote comfort and convenience but may lead to difficulties without threatening basic life.	• Supporting services such as prayer time applications; • *Qibla* direction at the hotel; • Easy and safe transportation; • Provision of Islamic educational tour packages
8. At-Tahsiniyyat	9. The complementary needs that aim to beautify and perfect human life according to Islamic ethics.	• Hygiene • Cleanliness • Aesthetic appeal of the destination

4. Conclusion

This article reviews the potential for developing Muslim-friendly tourism (MFT) in Bali by examining the interplay between religious sensitivity, socio-cultural dynamics, and tourism governance. Bali offers an attractive environment with well-developed infrastructure and rich cultural experiences such as religious ceremonies, traditional dances, and intricate carvings. However, implementing MFT principles faces challenges from identity politics, religious diversity, and fragmented policies. This review contributes to the existing literature by arguing that religious tourism can be thoughtfully adapted to the context of a non-Muslim majority region while preserving local traditions and promoting social harmony.

The practical implications emphasise the need for focused public policies integrating inclusivity with cultural preservation, particularly through collaborative frameworks involving local stakeholders, Muslim communities, and regulatory authorities. For example, implementing halal certification programs, educational seminars, training hospitality professionals to provide welcoming service that accommodates dietary and religious needs, ensuring environments and facilities align with Islamic principles, and promoting interfaith tourism initiatives can increase acceptance while respecting Bali's distinct cultural identity.

Future studies should explore case studies related to implementing MFT in destinations with a non-Muslim majority population to evaluate their long-term socio-economic and cultural impacts. Comparative policy analysis between Indonesia and other multicultural tourism destinations, such as Thailand, Japan, and Singapore, may provide significant insights into appropriate and effective strategies for implementing MFT in these regions while maintaining cultural integrity.

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Halal assurance beyond science: A perspective on socioeconomic factors and consumer trust in food authentication

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Received:30/04/2025
Accepted:22/07/2025
Published:31/07/2025

Keywords:
Halal assurance, Food authentication, Consumer trust, Religious compliance, Socioeconomic factors

Abstract

Halal assurance within the global food system has traditionally relied on scientific verification methods such as chromatographic, spectroscopic, genomic and immunological analyses to authenticate and determine product compliance with Islamic dietary laws. While these methods remain critical and essential for detecting non-compliant contaminants, this article argues that scientific validation alone is insufficient to foster consumer confidence and trust in halal certification. Drawing on an interdisciplinary synthesis of food science, analytical chemistry, sociology, economics, and religious studies, this article explores how socioeconomic and cultural factors, including education, income, religious literacy, cultural identity, and institutional credibility, influence consumer perceptions and acceptance of halal-certified products. The analysis also reveals that these sociocultural dimensions are significant in legitimising halal governance frameworks and sustaining public trust. This article recommends advancing halal literacy, enhancing transparency in certification processes, adopting participatory and inclusive governance models and utilising digital traceability tools to strengthen the integrity and inclusivity of halal certification systems. Hence, by expanding halal assurance beyond laboratory-based validation, this study calls for a more holistic, socially attuned and equitable approach to halal authentication that reflects the complexity of contemporary worldwide markets and the diverse expectations of Muslim consumers.

1. Introduction

The contemporary discourse on halal assurance has undergone a significant paradigm shift, moving beyond purely scientific verification methodologies toward an integrated understanding encompassing complex socioeconomic dimensions. Meanwhile, the analytical authentication methods are fundamental to halal authentication for certification, particularly for detecting pork, boar, swine, their derivatives, or ethanol content, as they provide objective, reproducible and scientifically validated evidence to ensure compliance with halal standards and prevent cross-contamination or intentional adulteration in food and pharmaceutical products. However, these scientifically-approach methods represent only one aspect of a complex ecosystem influenced by cultural values, economic interests and evolving customer expectations (Lubis *et al.*, 2016). As such, the assurance of halal integrity cannot rely solely on laboratory analyses but must also consider the sociocultural and ethical underpinnings of the trust. Consumer trust, particularly, should be anchored not in anecdotal legitimacy, but in verified knowledge (*'ilm*), trustworthiness (*amanah*) and credibility (*thiqah*), which are the foundational values in Islamic epistemology. This expanded perspective recognises that halal food systems exist within broader networks of social relations, economic structures and trust mechanisms that fundamentally influence how *halal* integrity is understood, maintained and negotiated in global marketplaces (Othman & Md Nawi, 2025; Ng *et al.*, 2022).

An exclusively scientific approach to halal authentication has limitations, especially considering the sociological dimensions of consumer trust formation. Scientific testing can verify the absence of forbidden (*haram*) ingredients; however, it cannot adequately address the socially constructed nature of authenticity that emerges through community endorsement, authority recognition and lived experience. Muslim consumers often navigate halal choices through complex webs of social capital, trusted relationships, and community knowledge parallel to formal certification mechanisms. These dynamics create rich cultural landscapes where halal assurance is continuously negotiated through interpersonal connections rather than solely through laboratory analysis (Amid, 2024; Sani *et al.*, 2023). Nevertheless, it is equally crucial to recognise that halal authenticity cannot rest on social construction alone. It must be firmly rooted in *shari'ah*-compliant evidence drawn from Islamic jurisprudence and verified methodologies rather than perception or communal consensus. This dual emphasis ensures that Muslim consumers' sociocultural realities and the

Islamic law's foundational principles are upheld in the halal assurance ecosystem.

The economic dimensions of halal certification further complicate authentication practices, creating tension between profit motives and integrity toward the religion (Bux *et al.*, 2022). As the global halal market expands into a multi-trillion-dollar industry, halal certification has evolved from a religious service into a significant commercial enterprise associated with pressures and incentives. This commodification process raises critical questions about accessibility, power dynamics and whether economically marginalised communities can meaningfully participate in formal halal authentication systems (Mohd Fauzi *et al.*, 2020). Therefore, the political economy of halal certification requires inquiry alongside scientific methodologies to understand how economic factors shape authentication practices and outcomes. Moreover, contemporary scholars increasingly emphasise how halal authentication practices reflect broader societal values regarding transparency, ethical consumption and food sovereignty. This evolving discourse acknowledges that halal assurance exists within complex global networks where power differentials between producers, certifiers and consumers create uneven landscapes of knowledge and authority. While economic growth has expanded halal certification into a global enterprise, this need not come at the expense of religious integrity. Economic profit and *Shari'ah* compliance must coexist through transparency, accountability and trust principles. Upholding *shari'ah*-based standards ensures consistency, inclusivity and integrity across the global halal ecosystem, anchoring halal certification practices through Islamic law while responding to contemporary market realities. (Islam *et al.*, 2023).

This article aims to explore the dimensions of halal assurance that extend beyond the scientific authentication methods, emphasising the crucial role of socioeconomic factors and consumer trust in the halal food ecosystem. While stringent regulatory frameworks and the availability of sophisticated laboratory techniques are critical pillars for ensuring the integrity of halal certification, they alone are insufficient to fully secure consumer confidence, particularly in a diverse and globalised market (Yuswan *et al.*, 2020). This article also explores how education, income, cultural background, religious knowledge and institutional credibility influence consumer perceptions and acceptance of halal-certified products. Notably, it is important to distinguish that while these socioeconomic variables are relevant for understanding consumer behaviour and market engagement, they should not be incorporated into the formal criteria for halal assurance. The determination of halal status must remain rooted in clear and objective rulings derived from Islamic jurisprudence (*Shari'ah*), which are universally applicable and not subject to sociocultural variation. Introducing context-dependent factors into the halal certification process risks compromising the standardisation and theological integrity of halal. By synthesising findings from various interdisciplinary studies of food science, sociology, economics and religious studies, this article offers a comprehensive understanding of the multifaceted factors influencing consumers in halal authentication, reaffirming that *Shari'ah* compliance remains the non-negotiable foundation of halal certification. The scope of this article includes a discussion of the limitations of current scientific approaches. These sociocultural dynamics impact halal food assurance and strategic recommendations for enhancing the integrity and credibility of halal certification systems in both local and international contexts.

2. Literature review

2.1 Overview of scientific methods and sociocultural challenges in halal authentication

The scientific authentication of halal products represents a complex intersection of religious requirements and analytical methodologies, establishing objective verification frameworks within a domain traditionally governed by religious authority. Furthermore, contemporary halal certification bodies increasingly establish sophisticated laboratory techniques to detect prohibited substances with remarkable sensitivity, creating standardised verification protocols that operate across diverse production contexts. High-Performance Liquid Chromatography (HPLC) has emerged as a valuable analytical tool in halal verification, enabling technicians or operators to separate, identify and quantify components within complex food matrices. This chromatographic approach quantifies various food additives and contaminants, which are critical in processed foods for ensuring product safety and regulatory compliance. The sensitivity of modern HPLC systems enables detection at parts-per-million levels, guaranteeing unintentional consumption of prohibited substances that might be present in trace amounts yet still violate religious requirements. Complementing these chromatographic approaches, the Gas Chromatography Mass Spectrometry (GC-MS) techniques offer powerful capabilities for identifying volatile compounds, proving especially valuable in detecting porcine-derived additives and other non-*halal* components that may be incorporated into complex food formulation (Rohman & Windarsih, 2020).

DNA-based authentication methodologies have revolutionised halal verification practices, enabling species identification with unprecedented precision. The Polymerase Chain Reaction (PCR) techniques allow certification laboratories to amplify and detect species-specific genetic markers, particularly those indicating porcine contamination in meat products, gelatine-containing foods and pharmaceutical formulations. The remarkable sensitivity of real-time PCR enables the detection of porcine DNA at concentrations below 0.1%, addressing concerns about cross-contamination in shared production facilities where halal and non-halal products might be processed. These genomic approaches have proven particularly valuable in complex supply chains where visual inspection and traditional verification methods prove inadequate for detecting adulterations or substitutions. Immunological techniques such as Enzyme-Linked Immunosorbent Assay (ELISA) offer complementary capabilities by targeting specific proteins characteristic of prohibited species, providing rapid screening tools that can be employed in field settings where sophisticated laboratory infrastructure might be unavailable (Aprilia *et al.*, 2022; El Sheikha *et al.*, 2017).

The scientific aspects of halal authentication extend beyond laboratory analysis to encompass standardised production protocols that govern the manufacturing process. Organisations such as the Standards and Metrology Institute for Islamic Countries (SMIIC) and the Malaysian Standards Department, as well as the Malaysian Standard (MS1500), have developed comprehensive guidelines that codify religious requirements into technical specifications applicable across industrial settings (Azam & Abdullah, 2021; Ahmad *et al.*, 2018). These standards address critical control points

throughout production, including animal welfare considerations, stunning parameters, slaughter techniques, blood drainage requirements and cross-contamination prevention measures. Certification bodies such as the Department of Islamic Development Malaysia (JAKIM) implement these standards through systematic audit protocols that combine on-site inspections, documentation reviews, and periodic laboratory testing to verify ongoing compliance. The development of these standardised frameworks represents a significant achievement in translating religious principles into operational parameters that can be consistently applied and objectively verified across diverse production contexts.

In the meantime, traceability systems represent another crucial scientific dimension of contemporary halal authentication frameworks, enabling verification of product provenance and processing history throughout complex global supply chains. Digital traceability solutions incorporating blockchain technology have emerged as particularly promising approaches to maintaining halal integrity across multiple production stages and geographic boundaries. These systems create immutable digital records documenting compliance at each production phase, addressing authentication challenges when products traverse numerous jurisdictions with varying halal standards and certification requirements. Traceability mechanisms can confirm that all production inputs, including processing aids, packaging materials, and cleaning agents, meet halal standards and mitigate concerns regarding concealed non-compliance that may arise at upstream supply chain stages. This addresses concerns regarding hidden or inadvertent non-compliance at upstream supply chain stages. Furthermore, advanced traceability systems progressively integrate quick testing methods, facilitating real-time verification at essential control points. The establishment of multifaceted authentication methods integrates documentary proof with analytical methods to deliver through halal certification (Abd Rahman *et al.*, 2017).

The halal assurance system is a structured framework designed to ensure that food and other consumer products comply with *Shari'ah* at every stage of the supply chain. It comprises a set of operational components, including traceability mechanisms, critical control points, standard operating procedures and compliance audits, whereby each is aligned with the core objective of maintaining halal integrity from farm to fork. Most certification bodies necessarily operationalise specific Islamic legal schools (*madhhabs*) of *Hanafi*, *Maliki*, *Shafie* and *Hanbali* or interpretative frameworks, creating standardised protocols such as ingredient analysis, slaughter procedures, manufacturing practices and transportation oversight, that may not accommodate the full diversity of legitimate religious perspectives on halal requirements (Hamizar *et al.*, 2024). This standardisation process frequently emphasises aspects of halal that are amenable to quantification and objective verification while downplaying equally important dimensions that resist such measurement. While presenting as neutral technical systems, the resulting certification frameworks often embed specific cultural interpretations and religious judgments within seemingly objective scientific methodologies. This dynamic becomes particularly problematic in global markets where diverse Muslim communities may hold varying interpretations of halal requirements yet encounter standardised certification systems that inadequately reflect their specific religious understandings. The political economy of halal certification further complicates this landscape, as the interplay of economic interests and political power enables dominant market actors to disproportionately influence the interpretations of halal requirements formally encoded in verification standards (Noordin *et al.*, 2014).

Most fundamentally, scientific approaches to halal verification inadequately address the sociological dimensions of trust formation that ultimately determine consumer acceptance of halal claims. While grounded in technical accuracy and scientific rigour, laboratory certification derives its ultimate legitimacy not solely from these attributes but from the complex social processes through which religious authority is constructed, recognised and maintained within communities (Van der Spiegel *et al.*, 2012). Ethnographic research consistently demonstrates that Muslim consumers often prioritise personal relationships, community endorsements, and recognised religious authority over technical certifications when making halal consumption decisions. Scientific verification systems that fail to engage meaningfully with these social dimensions of trust frequently find their certifications carrying limited practical authority despite technical rigour. This social dimension becomes particularly evident in diaspora contexts where Muslim communities negotiate halal consumption within non-Muslim majority societies, often developing elaborate trust networks and verification practices parallel to formal certification systems. These community-based authentication approaches reveal how halal verification fundamentally operates as a social process embedded within specific cultural contexts rather than merely as a technical procedure isolated in laboratory settings.

2.2 Socioeconomic factors influencing halal perception

The halal perception among consumers extends far beyond the boundaries of scientific validation and is significantly influenced by various socioeconomic factors. These include the education level, income, occupation, religious adherence, cultural background and access to halal-certified products, all of which shape consumer attitudes and trust toward halal authentication. For example, individuals with higher socioeconomic levels in educational attainment, income levels, social class, and occupation tend to understand halal certification standards better. They are more critical of labelling and source verification (Bonne & Verbeke, 2008). Education often enhances the ability to question and interpret complex labelling or certification claims, leading to an increasing inquiry into the halal logo and a stronger demand for a transparent traceability system. Additionally, education enables individuals to better comprehend the nuances between halal certification bodies, especially in regions where multiple and sometimes conflicting halal authorities exist.

Moreover, it is noted that income level also plays a crucial role in halal consumption behaviour. Following Awan *et al.* (2015), higher-income consumers may prioritise health, hygiene, and religious values and be more willing to pay premium prices for authenticated halal products. Conversely, lower-income groups might rely more on price and accessibility, potentially compromising their halal preference if such products are unaffordable or unavailable. Occupational status can similarly influence halal perception, especially among urban professionals frequently exposed to diverse food systems and global halal markets. These individuals may develop heightened sensitivity to halal integrity due to frequent exposure to high levels, international trade and a broader

worldwide context (Lever & Miele, 2012).

Besides that, religious commitment and cultural environment strongly shape halal consciousness. In predominantly Muslim societies, halal is often culturally embedded, resulting in automatic trust in local food systems. However, in non-Muslim or multicultural settings, consumers may exhibit scepticism about the authenticity of halal claims, prompting reliance on formal certifications and third-party assurance (Lada *et al.*, 2009). For example, cultural context mediates this behaviour; in Muslim-majority countries such as Malaysia, Indonesia or Saudi Arabia, halal is embedded in national policy, and public trust in local halal governance is relatively high. Conversely, in secular or non-Muslim-majority countries, Muslim minorities may display increased scepticism and seek multiple layers of assurance, including endorsement from international halal bodies, personal inquiries or community networks to verify halal compliance. This often leads to localised halal trust systems, where social and communal endorsement play an equal or greater role than formal education (Wilkins *et al.*, 2019).

The socioeconomic factors also play a central role in understanding consumer trust and perceptions regarding halal authentication. These factors do not act in isolation but interact dynamically with education level, income, occupation, religious adherence, cultural background, and access to halal-certified products. Therefore, a comprehensive halal assurance strategy must go beyond scientific verification methods to integrate socioeconomic insights, ensure equitable access to information, and reinforce institutional credibility. Tailoring halal governance frameworks and communication strategies to reflect the socioeconomic diversity of consumers can significantly enhance trust, compliance and the integrity of the global halal food system.

2.3 Consumer perception in halal food authentication and halal certification body

Consumer trust plays a vital role in the effectiveness and credibility of food authentication systems, particularly within the context of halal assurance, where religious, ethical and cultural considerations intersect with scientific validation. In the halal assurance system, consumer trust is an outcome, not a criterion of rigorous *Shari'ah* compliance, technical verification and consistent certification by recognised authorities. Trust is earned through transparency, integrity and adherence to established standards, not merely through perception or cultural sentiment. Trust is not solely built upon the technical accuracy of food testing methods such as FTIR spectroscopy, DNA analysis, and chromatography, but also upon the perceived integrity, transparency, and reliability of the institutions and certification bodies responsible for the halal governance (Kua, 2022). However, trust is multidimensional, encompassing confidence in the regulatory framework, belief in the consistency of certification standards, and assurance in the enforcement mechanisms behind halal labels. When consumers perceived food authentication processes to be transparent, standardised and endorsed by credible religious authorities, their willingness to accept halal labels increased significantly (Aziz & Chok, 2013).

However, in contexts with a lack of centralised regulation, inconsistencies among certification bodies or incidences of fraud, such as mislabelling non-halal ingredients, consumer trust can erode rapidly, even if advanced scientific methods are employed. Furthermore, the globalisation of food supply chains has made halal authentication more complex and transnational, requiring consumers to trust not just local authorities, but also international halal certifiers and multinational manufacturers. In such scenarios, trust is often contingent upon perceived institutional legitimacy, historical performance and alignment with religious values (Tieman, 2011). Studies have shown that Muslim consumers tend to rely on both formal (certification logos, government agencies) and informal (religious community, social media reviews, word-of-mouth) trust mechanisms to validate halal status, especially in non-Muslim-majority countries where halal governance is fragmented or voluntary (Golnaz *et al.*, 2010).

Moreover, it is noteworthy that technological tools such as blockchain, QR code traceability, and halal mobile apps are emerging as facilitators of consumer trust by offering greater transparency and access to supply chain information (Zailani *et al.*, 2015). The effectiveness of these technologies is influenced by socioeconomic factors, including digital literacy, education and income, which determine the extent to which consumers can access and understand authentication data. In conclusion, fostering and sustaining consumer trust in food authenticity demands more than stringent laboratory analysis; it requires a holistic, multi-stakeholder strategy incorporating religious legitimacy, institutional transparency, effective communication and cultural sensitivity. Ensuring the reliability of halal food authentication systems is a socio-technical challenge that integrates research, regulation and public perception.

2.4 Significance of religious devotion and wisdom

Religious devotion and wisdom are fundamental drivers influencing consumer perceptions, decisions and trust in halal food authentication. For Muslim consumers, halal consumption is not merely a dietary preference, but a religious obligation grounded in Islamic jurisprudence (*Shari'ah*). Therefore, the degree of a consumer's religious devotion, defined by the extent to which Islamic teachings are internalised and practices, profoundly affects the vigilance with which they assess the halal status of food products (Mukhtar & Butt, 2012; Lada *et al.*, 2009). Highly committed Muslim individuals are more likely to seek certified halal products, question ambiguous ingredients, avoid cross-contaminated foods and engage in active verification of halal claims. A spiritual imperative often influences their decisions to ensure that what they consume is both halal (permissible) and *toyyib* (wholesome), aligning dietary choices with their broader religious and ethical values.

Religious knowledge further reinforces this devotion by equipping Muslim consumers with the ability to interpret labels, understand certification processes and critically evaluate the credibility of certifying bodies. According to Bonne and Verbeke (2008), Muslim consumers with a thorough understanding of Islamic dietary laws are more likely to distinguish between superficial halal claims and verified halal certifications endorsed by religious authorities. This knowledge allows them to navigate complex food systems, particularly in multicultural and multi-certification environments, such as Western or secular countries, where halal regulations are less centralised. In such contexts, knowledge protects against misinformation and fraud, reducing reliance on mere packaging symbols or unverified marketing claims. Nevertheless, halal education, whether formal or informal, can influence consumer behaviour across generations. Younger Muslim consumers who received halal

education are more likely to maintain halal observance in adulthood, especially when such knowledge is complemented by modern awareness tools, such as mobile halal applications, community-based learning or engagement with halal influencers and religious scholars (Ramli *et al.*, 2023). Importantly, halal education also plays a mediating role in resolving ambiguity when facing uncertain or borderline products, such as emulsifiers, enzymes, and flavouring. Consumers often follow fatwas, local religious authorities, or halal certification guidelines to guide their decisions. This behaviour demonstrates that trust in halal food is not formed solely through institutional labelling, but through a dynamic interplay between internal religious consciousness and external validation mechanisms (Idris, 2025; Riofita & Iqbal, 2022).

Religious devotion and knowledge of halal education significantly shape how halal authentication is perceived and acted upon. These factors affect both the cognitive (knowledge-based) and affective (faith-based) dimensions of consumer trust, reinforcing the need for halal certification systems to align with scientific rigour and theological clarity and accessibility. Strengthening Islamic and halal education among consumers while ensuring that certification processes remain transparent, standardised and religiously grounded can enhance consumer confidence and fortify the integrity of the halal food ecosystem.

2.5 Credibility of halal certification bodies and authorities

The credibility of halal certification bodies plays a crucial role in establishing consumer trust in halal-certified food products. Although scientific tools are essential in verifying ingredients and processes, consumers ultimately rely on halal certification marks as the visible assurance that a product complies with Islamic dietary laws. In this context, the trustworthiness of the halal certifying body becomes a proxy for the integrity of the entire halal food authentication process. In countries like Malaysia, Indonesia and Singapore, centralised government-endorsed institutions such as JAKIM (Department of Islamic Development Malaysia), BPJPH (Halal Product Assurance Organising Agency) and MUIS (Islamic Religious Council of Singapore) are recognised as authoritative and competent, mainly because of their alignment with both *Shari'ah* principles and regulatory oversight mechanisms (Arsil *et al.*, 2018). Their involvement lends legitimacy to halal claims domestically and in international trade, where their logos are accepted in global markets due to high compliance standards and international cooperation.

On the other hand, the halal certification framework in non-Muslim-majority nations is frequently decentralised and characterised by an abundance of private certifiers with differing degrees of competence and religious legitimacy. This abundance of private halal certifiers has resulted in considerable confusion among customers who may lack familiarity with the varying standards, logos and methods employed by these halal certifying organisations. Aniqoh & Hanastiana's (2020) research shows that many European Muslim consumers struggle to differentiate between trustworthy and questionable halal certification marks, particularly without a central regulatory authority. This fragmentation undermines the perceived credibility of the halal assurance system and opens the door to fraud, mislabelling or inconsistent auditing practices, ultimately eroding consumer confidence. A significant factor contributing to the credibility of halal certification bodies is their transparency and governance structure. Credible halal certification authorities typically publish clear certification procedures, publicly disclose their auditing practices and include qualified *Shari'ah* scholars in their decision-making process.

Talib *et al.* (2015) emphasise that consumers are likelier to trust halal certification bodies that practice transparent decision-making and involve Islamic jurists to oversee *fatwa* processes and religious rulings. On the other hand, halal certification agencies that operate behind closed doors or do not maintain religious accountability often face scepticism from both consumers and manufacturers. The perceived opacity of such agencies can be interpreted as a sign of weak institutional integrity, especially considering past scandals involving fraudulent or expired halal certification (Asa, 2019). Moreover, the ability of a certification body to operate within a globalised supply chain has become a key component of its credibility. As halal-certified products are increasingly traded across borders, consumers expect certifiers to maintain consistent standards, even when dealing with international suppliers and manufacturers. Mutual recognition agreements (MRAs) between halal certification authorities, especially those based on internationally recognised standards such as MS1500:2019 or OIC/SMIIC, help to build consumer trust by ensuring that halal compliance is maintained throughout the global supply chain (Latif, 2020).

Without such agreements, consumers may view foreign halal certifications with suspicion, particularly if the certifying body is unknown or not endorsed by a local religious authority. Therefore, cross-border credibility and cooperation among halal certification authorities are crucial for strengthening international trust. In addition to technical competence and regulatory reach, the ethical reputation of certification bodies significantly influences consumer perception. Halal certification bodies perceived as profit-driven, politically compromised or lacking moral integrity are often distrusted, even if their procedures appear scientifically sound. This is due to halal assurance, which is not only about compliance but also about moral legitimacy. Consumers expect halal certifiers to act according to Islamic ethical standards, encompassing honesty, accountability, and concern for the *ummah* (Muslim community). Certification bodies that demonstrate social responsibility, engage with religious scholars and respond swiftly to public concerns are more likely to retain consumer trust during times of controversy or crisis (Che Azmi *et al.*, 2020).

Notably, the credibility of halal certification bodies and authorities is a multidimensional construct encompassing regulatory competence, religious legitimacy, global consistency and ethical behaviour. While science can determine the physical presence or absence of non-halal substances, the institutional reputation of halal certifying bodies conveys the assurance of religious compliance. As consumers become more informed and the halal market becomes more competitive, the ability of halal certification bodies to build and maintain trust through transparent, accountable and religiously grounded practices becomes increasingly vital. Without credible and competent certifiers, the halal authentication system risks being undermined, especially in multicultural and cross-border contexts where faith and global food trends shape consumer expectations.

2.6 Challenges in integrating socioeconomic dimensions into halal assurance

Integrating socioeconomic dimensions into halal assurance presents a significant challenge, as most current systems prioritise scientific and technical criteria while underestimating the influence of social, economic and cultural factors on consumer trust and compliance. Halal assurance is a scientific process and a social construct reflecting religious values, financial accessibility and community dynamics. A recent article published by Marzuki *et al.* (2021) has highlighted the growing disconnect between the highly regulated, standardised frameworks of halal certification and the diverse socioeconomic realities of Muslim consumers across various regions. The rigid application of halal standards often overlooks marginalised communities who may adhere to halal principles but lack access to certified products or information due to economic and geographical limitations.

Economic inequality is a significant impediment to equitable halal assurance. In many developing countries, halal-certified products are often priced higher due to certification costs, specialised logistics and regulatory compliance. The result renders them less attainable for low-income consumers, with price frequently taking precedence over certification status, particularly when halal-certified alternatives are scarce or considerably more costly (Muhamed *et al.*, 2019). Moreover, small-scale producers, particularly from informal or rural sectors, face steep entry barriers to obtaining halal certification, including high application fees, audit costs and language barriers. In addition to restricting their access to markets, this also keeps regional halal practices from being officially acknowledged within the certification ecosystem, exacerbating socioeconomic inequality in the halal supply chain (Basir *et al.*, 2018).

Correspondingly, the urban-rural disparity adds another layer of complexity whereby urban populations generally benefit from well-regulated retail networks, increased availability of certified halal products and digital tools able to verify authenticity. Rural communities, on the other hand, often depend on informal markets and traditional practices where halal assurance is assumed but not documented or certified. This reliance on trust and local knowledge can lead to inconsistency in halal compliance and expose consumers to risks, especially as supply chains become more complex (Latiff *et al.*, 2020). Context-sensitive halal assurance models that include mobile auditing units, community-based certification, or tiered certification schemes for rural micro-enterprises are needed to bridge this gap. Moreover, the lack of adaptability within certification systems to accommodate cultural and socioeconomic diversity further hinders integration. Many halal standards are standardised at national or international levels without meaningful engagement from diverse stakeholders such as indigenous Muslim communities, women entrepreneurs or informal vendors. These diverse stakeholders may operate according to Islamic principles but are excluded from formal certification due to bureaucratic rigidity or limited institutional support. As Sari *et al.* (2024) highlighted, halal certification bodies must broaden their scope to include community-led standards and grassroots input, ensuring that certification aligns with religious principles and social equity.

2.7 Opportunities and recommendations for strengthening consumer trust

Consumer trust is essential to the success of any halal assurance system. In an increasingly complex and globalised food supply chain, halal consumers demand transparency, accountability and religious integrity in product authentication. Opportunities for strengthening trust go beyond scientific testing and regulatory enforcement as they foster social inclusion, enhance awareness and create transparent systems that resonate with the values and expectations of diverse consumer groups. As halal becomes a global market force, certification authorities and stakeholders must respond to these evolving expectations with innovative strategies that address technical compliance and socioeconomic dimensions (Hashim *et al.*, 2022).

One key opportunity lies in enhancing halal literacy among consumers. These consumers are more likely to trust halal products when they understand the certification process, recognise official logos, and distinguish between authentic and false claims. Moreover, educational campaigns using digital platforms, religious institutions and community-based organisations can help bridge the knowledge gap, especially among low-income or less-educated groups (Norazmi & Kamaruddin, 2019). Schools, universities and mosques can act as conduits for spreading awareness of halal standards, empowering consumers to make informed choices and reducing susceptibility to misinformation or fraud. Next, adopting digital technologies presents another promising pathway because the technologies allow consumers to trace a product's halal status from farm to fork, enhancing transparency in supply chains (Harsanto *et al.*, 2024). For instance, blockchain-enabled platforms can store immutable records of slaughtering processes, ingredients sourcing and certification history, addressing common consumer concerns over authenticity and tampering. Governments and halal authorities should invest in and subsidise the development of such technologies, particularly for use in rural and underserved areas.

Building inclusive and tiered certification systems ensures equitable access to halal assurance. Many small businesses and home-based producers follow halal practices but are excluded from certification due to bureaucratic and financial barriers. Developing simplified, localised certification models such as the community-based or regional endorsements can help integrate these producers into the formal system without compromising religious compliance (Ratnasari *et al.*, 2019). This approach not only expands the certified halal ecosystem but also increases consumer trust in grassroots food providers who are often already trusted informally by their communities. Meanwhile, transparency and credibility of certification bodies play a pivotal role in trust-building, where conflicts of interest, inconsistent enforcement and lack of public engagement can erode confidence in certifiers. Encountering this, certification bodies should improve their governance structures, publish audit outcomes and engage religious scholars and consumer representatives in standard-setting processes (Nusran *et al.*, 2023). Transparency in decision-making and grievance mechanisms will ensure accountability and reassure consumers that certification is rigorous and impartial. Publicly accessible databases of certified products and businesses can further enhance confidence in halal assurance systems.

Besides, strengthening cross-border cooperation and harmonisation of halal standards is another area of opportunity. The fragmentation of halal certification where different countries or agencies apply differing standards confuses consumers and weakens trust in imported products. Regional or global standardisation efforts, led by organisations such the Standards and Metrology Institute for Islamic Countries (SMIIIC), can harmonise expectations and simplify recognition of halal-certified goods across markets (Abdullah & Abdul Razak, 2020). Such efforts must be balanced with respect for local cultural and jurisprudential differences while maintaining a shared minimum standard to uphold credibility. Finally, engaging the wider halal ecosystem including media, religious leaders, youth influencers and civil society is essential to cultivate the culture of integrity and vigilance. Community-based monitoring systems, consumer feedback platforms and whistleblower protections can enable public participation in halal oversight, thereby democratising the assurance process (Antara *et al*., 2016). Certification authorities must treat consumers not only as end-users but as active stakeholders in maintaining halal integrity. Trust is not built solely through labels and logos, but through transparency, participation and alignment with sincerely held religious and social values.

In conclusion, strengthening consumer trust in halal food authentication requires a multi-pronged approach that blends technological innovation, inclusive governance, education and community engagement. By moving beyond a purely technical paradigm and embracing the socioeconomic realities of diverse consumer groups, halal authorities and stakeholders can build a resilient, equitable and trustworthy assurance system. These efforts must be continuous, adaptable and rooted in a shared commitment to religious principles, consumer protection and public accountability.

3. Conclusion

This article reaffirms that while scientific validation is foundational to halal assurance, it is not the sole determinant of consumer trust or acceptance. Notably, socioeconomic variables such as education, income, occupation, religious commitment and cultural context play critical roles in shaping how consumers perceive and engage with halal-certified products. The credibility of halal certification bodies, the accessibility of halal-certified products and the visibility of ethical governance further affect public confidence in the halal ecosystem. To ensure sustainable trust in halal authentication, stakeholders must embrace a socio-technical approach that combines rigorous scientific standards with religious legitimacy, transparent communication and inclusive practices that accommodate marginalised communities. Strengthening halal literacy, enabling digital transparency tools and harmonising international certification standards are vital to building a resilient and trustworthy hala*l* system. Ultimately, the halal assurance must evolve into a multidimensional framework that not only complies with *Shari'ah* law but also reflects Muslim consumers' lived realities and moral expectations across varying socioeconomic backgrounds.

4. Acknowledgement

The authors would like to express their sincere gratitude to the Innovation Centre in Agritechnology for Advanced Bioprocessing (ICA), Universiti Teknologi Malaysia (UTM), Pagoh Campus, for the encouragement and support in initiating and developing this article on halal-related research.

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HALALSPHERE
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Halal science as an emerging academic field: Examining its academic and epistemological foundation

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Received:25/7/2025
Accepted:30/7/2025
Published:31/7/2025

Keywords:
Halal science, Academic discipline, Islamic science, Halal curriculum, *Tawhidic* epistemology

Abstract

Halal science refers to the use of scientific and technological principles in halal research, production, and innovation, and is becoming crucial to the global halal industry, yet its definition, scope, and scholarly foundations remain vague. This review evaluates whether halal science meets accepted hallmarks of an academic discipline by analysing peer-reviewed studies, educational texts, and authoritative reports. Evidence shows a rising presence in universities and research, hinting at disciplinary status. However, gaps persist: no standardised frameworks, limited institutional backing, and weak integration of religious and scientific paradigms. To mature, halal science must clarify its interdisciplinary nature, build stronger theoretical models, and gain wider academic recognition. The information gathered pointed towards its emergence as an academic discipline. A clearer disciplinary profile is vital for designing structured curricula and producing skilled professionals who can sustain the halal industry's expanding needs.

1. Introduction

The sustainability of the global halal industry, a rapidly expanding sector with a projected market value reaching trillions of dollars annually, fundamentally relies on a comprehensive halal ecosystem. This intricate ecosystem inherently encompasses diverse disciplines, ranging from the foundational principles of *Shari'ah* (Islamic law) to crucial aspects of modern management and cutting-edge scientific innovation. The strategic integration of science and technology, in particular, has proven instrumental in enhancing the development of halal products, ensuring the unwavering integrity of halal certification processes, and driving innovation to find ethical and permissible alternatives to *haram* (unlawful according to Islamic law) or *shubhah* (doubtful) ingredients. As consumer demand for transparent and verifiable halal products continues to surge worldwide, the role of scientific rigour in upholding halal standards has become paramount, making a clear conceptualisation of 'Halal Science' increasingly urgent.

Despite its demonstrable practical relevance and widespread application within the industry, the term 'Halal Science' largely remains a loosely defined concept within academic discourse. It is often broadly employed to encompass various applied scientific methods within halal-related fields, yet it frequently lacks the precise theoretical grounding and clear methodological boundaries characteristic of established academic disciplines. This absence of a formalised scholarly definition creates a significant conceptual void, leading to limited in-depth scholarly discussion on its true scope, foundational framework, and specific epistemological underpinnings (Hashim *et al.*, 2022). Such conceptual ambiguity not only impedes its maturation into a recognised academic discipline but also poses a substantial challenge to the systematic development of specialised human capital and tailored curricula essential for the sustained growth and integrity of the halal industry.

Recognition and formalisation of a field as an academic discipline are not merely semantic exercises but critical for systematically generating, disseminating, and applying knowledge. A well-defined discipline provides a structured framework for research methodologies, fosters specialised communities of scholars, establishes standardised curricula, and ensures the quality and credibility of its outputs (Trench & Bucchi, 2010; Krishnan, 2009). Without such a clear academic identity, 'Halal Science' risks fragmentation, inconsistent development, and a struggle for global academic acceptance, despite its profound societal and economic impact.

Consequently, this review is designed to address these definitional and foundational gaps. This study aims to examine the established characteristics that typically define an academic discipline and then critically evaluate the extent to which 'Halal Science' currently fulfills these criteria. By undertaking this analysis, this review seeks to contribute to a clearer conceptualisation and academic legitimisation of Halal Science. This thereby fostering a more structured approach to its research, education, and professional development.

2. Methodology

This article adopts a narrative review approach to explore the emergence of halal science as an academic discipline. Given halal science's complex, interdisciplinary, and evolving nature, the narrative review methodology was chosen for its flexibility and interpretive depth. As Sukhera (2022) outlined, narrative reviews are particularly suited for topics that require critical reflection, contextual sensitivity, and the integration of diverse sources of knowledge. Unlike systematic reviews, which focus on exhaustive coverage and rigid inclusion criteria, narrative reviews allow for thoughtful synthesis and thematic exploration. These characteristics make them ideal for conceptual fields like halal science.

The review began with a clear justification for the chosen approach and a defined scope of inquiry. It explored whether halal science fulfils the characteristics typically used to determine an academic discipline. These characteristics, drawn from Trench & Bucchi (2010) and Krishnan (2009), include a bounded field of study, shared terms and concepts, theoretical grounding, international reach, academic programs, scholarly publishing, and organised scholarly communities.

Sources were gathered using targeted keyword searches such as "halal science," "academic discipline," "Islamic science," and "*tawhidic* epistemology." Materials included peer-reviewed articles, academic program descriptions, institutional policy documents (such as the MQA Program Standard), and official records from research centres and scholarly journals focusing on halal-related topics. The selection of sources was guided by relevance to the thematic focus of the article, rather than exhaustive coverage, in line with saturation logic often applied in narrative reviews. Emphasis was placed on conceptual relevance and institutional significance rather than methodological uniformity.

An analytical framework was applied to map the reviewed literature against the discipline-defining characteristics. Each characteristic was then assessed and discussed based on the presence or absence of supporting evidence. The findings were synthesised into a tabular format (Table 1), which guided the interpretive discussion presented in the body of the article.

This approach also incorporated reflexivity, acknowledging the authors' positionality and interpretation in synthesising a diverse and sometimes ambiguous body of literature. While subjective judgment is inherent in narrative reviews, transparency in reasoning and alignment with established frameworks help ensure academic rigour and relevance. By combining empirical data, policy structures, and epistemological debates, this review provides a holistic understanding of halal science's current and potential status as a recognised academic field.

3. Defining halal science

Despite its use in the halal industry, the term halal science did not emerge in scholarly work in empirical pure or applied science related to halal research conducted between 1996 and 2020 (Hashim *et al.*, 2022). However, definitions of halal science, albeit scarce, do exist in scholarly literature that attempt to decipher the term and its concept. The earliest definition, proposed by researchers at Universiti Putra Malaysia's Halal Product Research Institute (HPRI), describes halal science as the application of scientific approaches to support matters governed by shari'ah (Islamic law) principles (Mat Hashim *et al.*, n.d.). Another researcher defined halal science as a multidisciplinary scientific framework rooted in halal concepts (Ahmad *et al.*, 2011). Similarly, Akademi Sains Malaysia (2019) and Azman & Ben (2017) described halal science as the systematic study of natural phenomena related to halal practices through observation and experimentation.

In contrast, some scholars challenge the validity of halal science as an independent discipline. Tariqur Rahman (2021) contends that halal science is limited in its ability to produce new scientific knowledge because it is rooted in Islamic scriptures rather than empirical hypothesis testing. This raises questions about whether it can be considered a scientific and academic discipline. In a more recent work, Hashim *et al.* (2023) listed the various definitions and concepts of halal science proposed by researchers. However, it is observed that the definitions and concepts have similar keywords or fall into the same broad scope of 'science and technology' and 'science approach', suggesting a potentially unified understanding of the term 'halal science'.

4. Evaluating halal science as an academic discipline

There are no universally accepted criteria for defining an academic discipline. However, Trench & Bucchi (2010) suggest that a discipline should exhibit at least some of the following characteristics, i) a bounded field of study, ii) shared interests, terms, and concepts, iii) significant presence in higher education teaching and research, iv) international reach, v) specialist scholarly publishing, vi) organized communities or networks of scholars, and vii) a theoretical foundation supporting empirical research. While emerging disciplines may not satisfy all these criteria, the more characteristics they fulfil, the more established they become (Krishnan, 2009). The term halal science has been used in the nomenclature of academic programs, the names of research centres or institutions and halal-related journals, suggesting that the term is aligned with the recognition of being an academic discipline (Hashim *et al.*, 2021). This section attempts to expand the evaluation of halal science based on these characteristics to determine its disciplinary recognition further. Table 1 shows the mapping of the characteristics and the justification of halal science as an academic discipline.

The increased number of specialist scholarly publications related to halal research is evident from the list below, which has 28 titles in total. Indonesia led the list with 18 titles (Table 2). These journals serve as a platform to disseminate research in halal studies, including halal science. However, the quality, frequency, and indexing of these journals are beyond thescope of this work. Other journals that publish halal-related research in Malaysia include the Journal of Fatwa Management and Research and the Malaysian Journal of Shariah and Law.

5. Methodological and epistemological foundations of halal science

Halal science shares similarities with other scientific disciplines such as biomedical and food sciences, particularly in its reliance on empirical research, laboratory testing, and technological advancements. Like food science, it involves the study of ingredients, processing methods, and safety assessments to ensure compliance with halal standards. Similarly, its connection to biomedical sciences is evident in areas like halal pharmaceuticals and nutraceuticals. However, halal science's integration of religious principles sets halal science apart, requiring scholars to balance scientific methodologies with Islamic jurisprudence (*fiqh*). Unlike conventional sciences that operate purely on empirical

Table 1. Evaluation of halal science as an academic discipline

Characteristics	Discussion/Justification	Meet the requirement?
A bounded field of study	The existence of program standards and frameworks to guide curricula development: The Malaysian Qualification Agency (MQA) Program Standard for Halal Studies (2021) outlines the knowledge required for halal studies. This is generally categorised into halal standard core courses (for all fields of study) and specific core courses for management and applied science (Malaysia Qualification Agency, 2021). The Department of Skills Development oversees the National Skill Certificate (Sijil Kemahiran Malaysia, SKM) under the Ministry of Human Resources. 2021 the department introduced the Halal Industry Occupational Framework, outlining job structures, descriptions, and skill demands. These insights were integrated into the revised National Occupational Skills Standard (NOSS) Registry (May 2023), which lists NOSSs approved by the National Skill Development Council to guide industries and training providers.	Partial (Emerging but limited scholarly discourse)
Shared interests, terms, and concepts,	Much interest in the concept and practice of 'halal science'. However, there are various understandings of the terms (including definitions) and concepts (Hashim et al, 2023)	Partial (high interest but lack of standard terms with an ambiguous concept)
Significant presence in higher education teaching, research and services to the industry	The increasing use of the term 'halal science' in academic institutions and research initiatives suggests its emergence as a distinct field. For instance: Several universities offer academic programs incorporating 'halal science' in their titles, such as the *Master of Science in Halal Industry Science* (INHART, IIUM) and the *Master of Science in Halal Products Science* (UPM). Halal science centres, such as the *Halal Science Centre at Chulalongkorn University, Thailand*, and *the Halal Science Centre at IPB University, Indonesia, conduct scientific research on halal-related issues and provide services* to the halal industry. The *Journal of Halal Science and Research* (Universitas Ahmad Dahlan, Indonesia) and the *Journal of Halal Science and Technology* (UNISSA, Brunei) are dedicated to publishing research on halal-related scientific topics (Hashim *et al.*, 2024)	Yes
International reach	International presence and reach of the field can be seen in several scenarios as below: At the certificate and diploma level, the Osaka University International Certificate Program in Halal Science, Technology, and Innovation (OUICP-HaSTI) offers a structured curriculum covering halal science and technology, catering to international students seeking a professional understanding of halal practices. The Malaysian National Education Code (NEC-2020) under the purview of the Ministry of Higher Education (MoHE) follows the International Standard Classification of Education (ISCED) Fields of Education and Training 2013 (ISCED-F 2013) produced by the United Nations Educational, Scientific and Cultural Organisation (UNESCO). This suggests that the curricula developed in the country are aligned with international standards. In the NEC-2020, halal management was	Partial (present but limited)

	recognised as one of the components of NEC0414 Management and Administration. However, there is no specific mention of halal science (Hashim *et al.*, 2023)	
Specialist scholarly publishing	Increasing number of homegrown journals, especially in Malaysia, Indonesia and Brunei. However, the journals are not indexed in internationally renowned scientific abstract and databases (see Table 2 for further details).	Partial (emerging)
Organised communities or networks of scholars	Examples include Halal Development Corporation (HDC) Malaysia Community of Practice (COP) and Konsortium Institut Halal Malaysia (KIHIM) (*Malaysian Halal Institute Consortium*), which provides a platform for the Halal centres/institutes to carry out concerted efforts in halal research and education (currently inactive). There is also an active landscape of activities surrounding scientific conferences, congresses, seminars and halal science workshops organised by various entities. (Hashim *et al.*, 2024)	Partial (Present but limited)
A theoretical foundation supporting empirical research	Said & Hanapi (2019) argue that the philosophy of halal science is fundamentally Islamic, emphasising three key elements: *Tauhid* (Absolute Oneness of Allah) as the central pillar *Wahyu* (Divine revelation) is the primary source of knowledge *Khilafah* (human stewardship) in managing halal-related scientific advancements This framework differentiates halal science from conventional science, which relies exclusively on empirical data. In halal science, empirical research is subordinate to Islamic revelation. This distinction raises epistemological challenges, particularly in integrating halal science into conventional academic structures.	Partial (emerging)

Table 2: Halal-related journal

Journal	Date of first issue	Country
Journal of Halal Product and Research (JHPR)	21 November 2018	Indonesia
Indonesian Journal of Halal Studies (IJHS)	11 December 2018	
Indonesian Journal of Halal Research (IJHAR)	28 February 2019	
Journal of Industrial Engineering and Halal Industries (JIEHIS)	1 June 2020	
Nusantara Halal Journal	June 2020	
Halal Research Journal (HRJ)	18 February 2021	
International Journal of Halal System and Sustainability	1 January 2021	
International Journal of Mathla'ul Anwar of Halal Issues (IJMA)	1 March 2021	
Ar Rehlah Journal of Islamic Tourism, Halal Food, Islamic Travelling, and Creative Economy	1 May 2021	
Journal of Halal Research, Policy, and Industry (JHRPI)	31 July 2022	
Journal of Halal Industry Studies	7 May 2022	
The Journal of Business and Halal Industry	24 October 2023	
Halal Ecosystem Research Journal (HERJ)	1 April 2024	
Journal of Halal Sciences	25 March 2024	
Halal Studies and Society (HaSS)	31 January 2024	
Halal International Journal	3 July 2024	
JHR: Journal of Halal Review	25 January 2025	
The Journal of Shariah Economics and Halal Industry (JOSEHI)	January 2025	
Journal of Halal Industry and Services	24 November 2018	Malaysia
The Malaysian Journal of Halal Research (MJHR)	June 2019	
International Journal of Halal Research	1 December 2019	
The International Journal of Halal Ecosystem and Management Practices (IJHEMP)	12 December 2021	
Halalsphere	31 July 2022	

Journal of Halal Science and Technology (JHST)	June 2022	Brunei
The Halal Journal Human, Health and Halal Metrics (HHHM)	February 2019 November 2020	Iran
AP Journal of Halal Lifestyle (APJHLS)	30 June 2023	Türkiye
Journal of Halal Science, Industry, and Business (JHASIB)	31 May 2023	Thailand
Journal for Halal Quality and Certification	May 2023	Europe

evidence, halal science must also consider ethical, spiritual, and theological dimensions, making it a multidisciplinary and highly contextual field.

Islamic and tawhidic (absolute monotheism) epistemology plays a crucial role in shaping the framework of halal science, particularly through key concepts like *tawhid* (the absolute oneness of God), *wahyu* (divine revelation), and *khilafah* (human stewardship) (Said & Hanapi, 2018). The philosophy of halal science has been described to be composed of four elements, i) *wahyu* as the primary reference, *tawhid* is the core of the Islamic science (which is the umbrella for halal science), iii) humankind and nature are only creatures, and iv) Islamic science cannot be influenced by non-metaphysical presuppositions of modern science (Said & Hanapi, 2018).

Methodologically, halal science incorporates elements from both positivist and interpretivist paradigms—positivist in its use of scientific experimentation and verification, and interpretivist in its need to interpret religious texts and cultural contexts. This dual approach allows halal science to evolve as a scientific discipline and a field deeply rooted in Islamic knowledge. This is not new or impossible to comprehend and implement because the Golden Age of Islamic Science, which lasted from the 8th to 13th centuries of the common era, left a lasting legacy of the success of the dual approach.

6. Challenges and limitations in the development of halal science

The development of halal science faces significant challenges, particularly in standardising its curricula across different educational institutions. Given the diverse interpretations of halal regulations in various countries and Islamic schools of thought, creating a universally accepted curriculum is difficult. Some regions emphasise traditional religious teachings, while others incorporate modern scientific approaches such as food technology, biotechnology, and forensic analysis. The lack of standardisation can lead to inconsistencies in training, qualifications, and expertise among halal science professionals, ultimately affecting the credibility and reliability of halal certification processes worldwide.

Another major limitation is the ethical concerns and religious sensitivities in integrating scientific research with Islamic principles. Some scientific methods, such as research on controversial topics like pre-slaughter animal stunning methods or lab-grown meat, must be approached with caution to avoid conflicts with religious authorities and public perception. Scholars who are well-versed in Islamic jurisprudence and modern science must ensure that halal science progresses while respecting religious boundaries.

Securing funding, gaining publication opportunities, and achieving global academic recognition also present significant obstacles for halal science researchers. Many funding bodies prioritise mainstream scientific research over niche fields like halal science, making it difficult for researchers to secure grants. Furthermore, publishing halal-related studies in high-impact scientific journals can be challenging due to the field's interdisciplinary nature, which combines religious, ethical, and scientific perspectives. The limited global recognition of halal science as an academic discipline further hinders collaboration, research advancement, and the establishment of dedicated institutions, slowing down its development.

7. The future of halal science: Pathways for academic recognition

To strengthen halal science as a recognised academic discipline, institutions must develop comprehensive and standardised curricula that integrate Islamic principles and scientific methodologies. While this may include establishing dedicated halal science departments and offering specialised degrees, careful consideration of the graduates' future career paths must be in place. The industry-specific needs for halal science must be scrutinised to ensure graduates are well equipped to contribute to the sector once graduated (Tukiran *et al.*, 2025).

An alternative perspective can be explored to pave the way for recognising halal science as an academic field. One of the potential ways is to foster interdisciplinary curriculum research that bridges fields like food science, biotechnology, pharmacology, and Islamic studies with a focus on halal. While interdisciplinary research is common, interdisciplinary curriculum is less prevalent. However, this mode of programming is possible. For instance, based on the Malaysian Qualification Agency (MQA) Program Standard for Halal Studies (2021), it is possible to establish a 'major-minor' undergraduate program where the main body of knowledge is a well-established academic discipline (for instance, major biotechnology) and halal science as a minor. This ensures fair graduate employability as they can venture to work in established fields while having a value-added knowledge in halal science. A double major program is also possible, where the bachelor's program offers two disciplines. At a higher level (Master's and PhD), a specialised degree in halal science is commendable as this will nurture halal talents in the scope of research, development and innovation towards generating new knowledge and providing solutions to the halal industry.

Additionally, universities should encourage academic discourse by hosting conferences, workshops, and research symposia focused on halal science. Several examples can be quoted, including the International Halal Science and Technology Conference (IHSATEC) in 2024, the International Halal Science Conference (IHASC) in 2023, the Virtual Halal Science Conference (ViHASC) in 2021 and the International Halal Congress 2024 in Türkiye

(https://inthalalcongress.org/). Promoting scholarly publications and establishing high-impact journals dedicated to halal research will also enhance the credibility and visibility of the field, attracting more students and professionals.

Policy and regulatory support are crucial for institutionalising halal science in higher education. Governments and academic bodies should continue working together to develop an effective curriculum structure for halal science programs, ensuring consistency and quality in education and research. Policymakers can also allocate funding for halal-related studies, support the development of research centres, and provide incentives for universities to incorporate halal science into their curricula. Furthermore, regulatory frameworks should facilitate collaboration between religious scholars, scientists, and industry experts to ensure that halal standards remain scientifically sound and religiously compliant.

International collaborations and interdisciplinary research can also significantly advance halal science on a global scale. Partnerships between universities, research institutions, and industry stakeholders from different countries can foster knowledge exchange and technological advancements in halal certification, food safety, and pharmaceutical developments. Additionally, interdisciplinary approaches combining fields such as artificial intelligence, blockchain technology, and biomedical research can lead to innovative halal verification and traceability solutions. Strengthening global networks and cooperation will ultimately contribute to halal science's widespread recognition and credibility as an essential academic and scientific discipline.

Notwithstanding the above strategies, the main effort should be to develop a clear concept and framework (body of knowledge) of halal science to ensure its wide and sustainable applicability.

8. Conclusion

This review affirms that Halal Science, when evaluated against the established characteristics of an academic discipline, is an emerging and increasingly important field within the broader halal ecosystem. Although its foundations are still developing, particularly its distinct epistemological framework that combines scientific methodology with Islamic principles, its expanding presence in higher education, research institutions, and scholarly publications reflects ongoing progress toward academic recognition.

The importance of Halal Science extends beyond the academic sphere. It plays a critical role in maintaining the integrity, authenticity, and global trust underpinning the halal industry, representing a multi-trillion-dollar sector. Halal Science supports key areas such as food safety, pharmaceutical development, and ethical consumer practices by ensuring compliance with scientific standards and *Shariah* principles.

To strengthen its academic standing, several areas require focused attention. First, there is a clear need for the standardisation of curricula and the establishment of a comprehensive body of knowledge that integrates scientific and Islamic foundations. Second, fostering interdisciplinary collaboration and encouraging contributions to high-impact academic journals will enhance its visibility and credibility. Third, sustained policy and regulatory support and international cooperation will be essential to ensure the field's continued growth. These efforts will also help develop a skilled professional workforce capable of supporting the long-term sustainability of the global halal industry.

9. Acknowledgement

The authors thank the International Institute for Halal Research and Training (INHART), IIUM, for the support and facilities in completing this work. The authors would also like to thank Ms. Habiba Khatun Shiha for her technical assistance in this work.

10. Authors' contribution

Conceptualization, Y.Z.H-Y.H.; methodology, A.N.A.; formal analysis, N.K.; investigation, N.K. and N.S.; data curation, N.K.; writing—original draft preparation, N.S., Y.Z.H-Y.H.; writing—review and editing, H.M.S.; supervision, Y.Z.H-Y.H.; project administration, N.K. All authors have read and agreed to the published version of the manuscript.

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