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Research Article

BIODEGRADABLE SMART PACKAGING MATERIALS IN *HALAL* FOOD LOGISTICS: A REVIEW OF ENGINEERING INNOVATIONS

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Abstract
The integrity of the *halal* food supply chain is paramount, yet it faces significant challenges from potential cross-contamination and environmental concerns associated with conventional packaging. This review examines the critical engineering innovations at this intersection, focusing on materials and systems that ensure both *halal* compliance and ecological responsibility. The objective is to identify key technologies, assess their compatibility with *halal* principles, and highlight their potential to improve supply chain integrity and sustainability. A systematic literature review was conducted using major scientific databases, including Scopus, Web of Science, and Google Scholar. The selected literature was analyzed to identify material compositions, sensor mechanisms, and their functional applications in maintaining *halal* integrity. The review identifies several promising innovations, including the development of biopolymer-based films (e.g., PLA, starch, chitosan) integrated with pH-sensitive and microbial spoilage indicators. These smart systems can provide real-time monitoring of food freshness and detect potential non-*halal* contaminants, such as ethanol or porcine derivatives, without direct contact. The findings show a strong trend towards non-invasive sensor technologies that align with the principles of tayyib (wholesome and pure). Engineering innovations in biodegradable smart packaging offer a robust solution for enhancing the security and sustainability of *halal* food logistics.

Keywords: Biodegradable Materials, Engineering Innovation, Food Integrity

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INTRODUCTION

The global *halal* food market has expanded into a multi-trillion-dollar industry, driven by a growing Muslim population and increasing demand from non-Muslim consumers for products perceived as safe, clean, and ethical. Central to this industry is the concept of *halalan tayyiban*, a holistic principle mandated by Islamic scripture that requires food to be not only permissible (*halal*) but also wholesome, pure, and of high quality (*tayyib*). Maintaining the integrity of this standard throughout the complex global supply chain from farm to fork is a paramount challenge, requiring unwavering assurance against cross-contamination, spoilage, and fraudulent activities (Kofidis, 2024; C. Li dkk., 2024). This assurance forms the bedrock of consumer trust, which is the most valuable asset in the *halal* market.

Contemporary food logistics, however, faces a dual crisis that directly impacts the *halal* sector. The first is the pervasive environmental burden of conventional food packaging, which is predominantly made from non-renewable, petroleum-based plastics. These materials contribute significantly to landfill waste, ocean pollution, and carbon emissions, creating an ecological footprint that is increasingly at odds with the Islamic principle of stewardship (*khalifah*) over the Earth (Reddy & Kumar, 2024; Zhao dkk., 2024). The second crisis involves the inherent limitations of this traditional packaging, which acts as a passive, opaque barrier, offering no transparency into the product's condition or its handling history after it has been sealed.

In response to these challenges, two powerful streams of technological innovation have emerged within materials science and engineering. The first is the development of biodegradable materials, derived from renewable resources like starch, cellulose, and polylactic acid (PLA), which offer a sustainable alternative to conventional plastics. The second is the advent of smart packaging systems, which integrate intelligent sensors and indicators directly into the packaging to provide real-time information about the product's freshness, safety, and environment (Chen dkk., 2024; Z. Li dkk., 2024). The convergence of these two fields presents a transformative opportunity to engineer a new generation of packaging that is both ecologically responsible and capable of actively monitoring and safeguarding *halal* integrity.

A significant and persistent problem within the modern *halal* food supply chain is its vulnerability to integrity breaches that are undetectable by conventional means. The journey of a product involves numerous touchpoints, including processing, storage, and transportation, where the risk of contact with non-*halal* substances (*najis*), such as porcine derivatives or alcohol, is a constant concern. Furthermore, deviations from prescribed conditions, such as temperature abuse, can compromise the *tayyib* aspect of the food, leading to spoilage and potential health risks (Chen dkk., 2024; Liu dkk., 2024). Traditional “dumb” packaging provides no mechanism to monitor for these specific threats, leaving consumers and regulators reliant on costly, time-consuming, and often retroactive certification and testing processes.

This logistical challenge is compounded by a pressing environmental and ethical dilemma. The *halal* industry, like the broader food sector, is a major consumer of single-use plastic packaging. The accumulation of this non-biodegradable waste poses a severe threat to ecosystems worldwide. This reality creates a fundamental conflict for the industry, as the pursuit of food safety and preservation through conventional means directly contributes to environmental degradation (Guo dkk., 2024; Rodrıguez dkk., 2024). This misalignment undermines the holistic nature of *halalan tayyiban*, which implicitly includes care for the environment from which the food is sourced.

The specific problem this review addresses is the fragmented and unsynthesized state of knowledge at the intersection of biodegradable materials, smart sensor technology, and the unique requirements of *halal* food logistics (Guo dkk., 2024; Liu dkk., 2024). While innovations are rapidly occurring in smart and sustainable packaging, there is a lack of a consolidated academic framework that critically evaluates these technologies through the specific lens of *halal* assurance. The engineering challenge is not just to make packaging "smart" or "green," but to engineer it to be "*halal*-smart" and "*halal*-green," a nuanced objective that has not been systematically explored in the existing scientific literature.

The principal objective of this review is to systematically map, analyze, and synthesize the current landscape of engineering innovations in biodegradable smart packaging materials that are directly applicable to enhancing the integrity and sustainability of the *halal* food supply chain (Mishra dkk., 2024; Xu dkk., 2024). This research aims to bridge the gap between materials science advancements and the practical, theological, and logistical demands of the global *halal* industry. The goal is to construct a coherent body of knowledge that can serve as a foundational reference for future research, development, and industrial implementation.

To fulfill this primary aim, the study pursues several specific sub-objectives. The first is to identify and categorize the key biodegradable polymers and smart sensor technologies that demonstrate potential for food packaging applications. The second objective is to conduct a critical assessment of the compatibility of these technologies with core *halal* principles, examining factors such as the origin of raw materials for bioplastics and the chemical mechanisms of sensors (Wu dkk., 2024; Zheng dkk., 2024). A third objective is to evaluate the functional capacity of these smart systems to detect specific threats to *halal* integrity, including the presence of prohibited substances like ethanol and the onset of microbial spoilage that would render a product non-*tayyib*.

The ultimate intended outcome of this research is the creation of a comprehensive technological roadmap. This roadmap will highlight the most promising and mature technologies, identify current limitations and challenges, and chart clear directions for future scientific inquiry. By providing this structured overview, this review seeks to accelerate the transition from conceptual possibilities to tangible, commercially viable packaging solutions that can build a more transparent, trustworthy, secure, and environmentally sustainable *halal* food ecosystem for the 21st century.

The existing body of scientific literature on smart packaging is extensive, with numerous reviews covering innovations in freshness indicators, time-temperature indicators, and biosensors (Dayarathna dkk., 2024; Panwariya & Dwivedi, 2024). However, this research is predominantly focused on general food safety and quality concerns, such as detecting generic microbial growth, pH changes, or volatile compounds associated with spoilage. The specific and highly sensitive detection of contaminants that are critical for *halal* verificationsuch as trace amounts of porcine gelatin or ethanol produced during fermentationis rarely the central focus of these broad reviews.

Simultaneously, the field of biodegradable packaging has matured significantly, with a wealth of research dedicated to improving the mechanical properties, barrier performance, and degradation kinetics of biopolymers (Wang dkk., 2024; Zhai & Luo, 2024). The primary driver of this research has been sustainability and the replacement of fossil-fuel-based plastics. While the integration of functional additives is a growing area, the specific incorporation of intelligent sensor systems designed to meet the stringent requirements of a religio-ethical framework like *halal* is a nascent and not yet systematically reviewed field of inquiry.

A clear and critical gap therefore exists at the confluence of these distinct but related research domains. There is a notable absence of a comprehensive review that synthesizes the engineering innovations in both biodegradable materials and smart sensors through the specific, demanding lens of *halal* food logistics. While individual studies may describe a particular biopolymer or a novel sensor, there is no work that consolidates these disparate findings to provide a holistic overview of the state-of-the-art in "*Halal*-Compliant Biodegradable Smart Packaging (Wu dkk., 2024; Yazgan dkk., 2024)." This review directly addresses this lacuna by creating a scholarly bridge between advanced materials engineering and applied religious dietary law.

The novelty of this review is rooted in its unique interdisciplinary synthesis. It is the first scholarly work to systematically connect and evaluate cutting-edge developments in materials science and sensor engineering with the complex theological, ethical, and logistical requirements of the global *halal* industry (Lei dkk., 2024; Z. Li dkk., 2024). The originality of this paper lies in its framing of technological innovation within the *halalan tayyiban* paradigm, thereby assessing materials and systems not only on their technical performance but also on their alignment with a holistic religio-ethical framework. This approach establishes a new and specific sub-field of inquiry.

This research is justified by its significant academic contribution. It will provide a foundational reference text for researchers across multiple disciplines, including food science, materials engineering, analytical chemistry, and supply chain management (Hu dkk., 2024). By identifying the state-of-the-art, pinpointing technological challenges, and outlining specific research questionssuch as the development of highly selective, non-invasive sensors for *halal*-critical analytesthis review will catalyze and guide future scientific investigation in a field of growing importance. It moves the conversation from general possibilities to specific, targeted research and development needs.

The broader societal and industrial justification for this work is compelling. The global *halal* market is a cornerstone of the economy for billions of people, and its integrity is a matter of deep consumer trust and faith. This research is critically important because it addresses an urgent need for verifiable technologies that can secure this trust in an increasingly complex global supply chain (Rodrıguez dkk., 2024; Singh dkk., 2024). By focusing on biodegradable solutions, it simultaneously aligns this massive industry with pressing global sustainability mandates, offering a pathway to an economic model that is verifiably ethical, transparent, and environmentally responsible.

RESEARCH METHOD

Research Design

This study utilizes a systematic literature review as its core research design. This methodology was deliberately chosen for its rigorous and replicable approach to synthesizing existing research in a comprehensive and unbiased manner. A systematic review is particularly well-suited for the objectives of this paper, which aim to map the current state of a rapidly evolving and interdisciplinary field (Geng dkk., 2024; Hu dkk., 2024). The design provides a structured framework for identifying, appraising, and integrating all relevant published evidence to answer specific research questions concerning engineering innovations in biodegradable smart packaging for *halal* logistics. The approach ensures a transparent and exhaustive survey of the literature, forming a reliable foundation for analysis and the identification of knowledge gaps.

Research Target/Subject

The population for this review comprises the entire body of scholarly literature pertaining to biodegradable polymers, smart packaging technologies, and food supply chain integrity. The sample consists of a curated selection of academic works drawn from this population, based on a precisely defined set of inclusion and exclusion criteria. Inclusion was limited to peer-reviewed journal articles, conference papers, and review papers published in English between January 2015 and the present day, a timeframe chosen to capture the most recent and relevant technological advancements (Geng dkk., 2024; Xun dkk., 2024). Excluded from the sample were non-peer-reviewed sources such as patents, dissertations, books, and industry reports to maintain a high standard of scientific validity and rigor.

Research Procedure

The review procedure was systematically conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological transparency and completeness. The process began with the execution of the defined search query across the selected databases. In the second stage, all retrieved titles and abstracts were screened for relevance against the inclusion criteria by two independent reviewers to minimize bias. Any disagreements were resolved through discussion. The third stage involved a full-text review of the shortlisted articles to confirm their eligibility. Finally, a structured data extraction form was used to systematically collect relevant information from the final sample of articles, including material types, sensor mechanisms, detected analytes, and documented applications relevant to *halal* logistics, which then formed the basis for the synthesis and analysis presented in this paper.

Instruments, and Data Collection Techniques

The primary instruments for data collection were major electronic scientific databases renowned for their comprehensive coverage of engineering, materials science, and food science literature. The databases searched included Scopus, Web of Science, and Google Scholar. A structured search strategy was developed using a combination of keywords and Boolean operators. The core search terms included: (“biodegradable packaging” OR “biopolymers”) AND (“smart packaging” OR “intelligent sensors” OR “active packaging”) AND (“*halal*” OR “*halal* logistics” OR “food integrity”). Reference management software, specifically Zotero, was employed as an instrument to collate, de-duplicate, and manage the retrieved bibliographic records throughout the review process.

RESULTS AND DISCUSSION

The systematic review of the literature yielded 78 pertinent studies that met the inclusion criteria. These studies form the basis of the analysis, providing secondary data on the development and application of biodegradable and smart packaging technologies. The data extracted focuses on material composition, sensor mechanisms, target analytes for detection, and documented relevance to food integrity. A significant portion of the research originates from materials science and food engineering journals, with a growing but still limited number of studies explicitly addressing *halal* logistics.

The synthesized data from the selected literature is categorized and summarized below. The table highlights the most prominent biodegradable materials and smart sensor types, detailing their mechanisms and specific applications relevant to maintaining *halal* and *tayyib* integrity in the food supply chain.

Table 1: Synthesis of Innovations in Biodegradable Smart Packaging for *Halal* Applications

Category	Technology/Material	Mechanism/Principle	*Halal*/Tayyib Application Example
Biodegradable Films	Polylactic Acid (PLA)	Fermentation of corn starch/sugarcane	Base material for sensors; non-animal origin
	Starch-Based Bioplastics	Gelatinization of plant starches	*Halal*-certified gelatin alternative
	Chitosan	Deacetylation of chitin (from shellfish)	Antimicrobial properties; source requires review
Smart Sensors	pH-Sensitive Dyes	Colorimetric change due to pH shift	Detects spoilage from microbial growth
	Gas Indicators (O_2, CO_2)	Chemical reaction with target gas	Monitors package atmosphere integrity
	Time-Temperature Indicators	Temperature-dependent chemical reaction	Verifies cold chain integrity
	Biosensors	Antigen-antibody or enzyme-substrate binding	Specific detection of porcine DNA/proteins

The data clearly indicates a strong research emphasis on plant-derived biopolymers such as Polylactic Acid (PLA) and various starches. These materials are frequently highlighted due to their certifiable non-animal origin, which simplifies *halal* compliance. Their development is primarily driven by sustainability goals, but their role as a neutral, safe substrate for smart sensors is a recurring theme. Chitosan, while noted for its excellent antimicrobial properties, presents a point of contention within *halal* jurisprudence due to its typical origin from shellfish, necessitating careful source verification.

The sensor technologies identified are predominantly non-invasive and colorimetric, designed for easy visual interpretation by stakeholders throughout the supply chain. pH-sensitive dyes, often derived from natural pigments like anthocyanins, are the most commonly cited smart technology. They function by changing color in response to volatile amines or carbonic acid produced during microbial decay, providing a clear visual cue of compromised food quality (*tayyib*). This aligns well with the need for simple, low-cost indicators that do not require complex equipment to read.

The literature reveals a significant focus on technologies for monitoring the cold chain and detecting general spoilage. Time-Temperature Indicators (TTIs) are frequently discussed as a mature technology capable of providing a visual, cumulative record of a product's exposure to temperature fluctuations. These indicators are engineered to undergo an irreversible color change when a specific temperature threshold is breached for a defined duration, directly addressing a critical control point in *halal* meat and dairy logistics.

Gas-indicating sensors represent another well-documented category. These systems are designed to detect changes in the headspace gas composition within a package, such as a decrease in oxygen or an increase in carbon dioxide. This data is critical for products packaged in a modified atmosphere (MAP), which is common for extending the shelf life of fresh *halal* meats. A failure in the package seal, leading to a change in gas composition, is immediately flagged by the sensor, indicating a potential compromise in product quality and safety.

From the prevalence of research on spoilage and temperature indicators, it can be inferred that the current primary focus of smart packaging innovation is on preserving the *tayyib* (wholesome) aspect of *halal* food. The engineering efforts are concentrated on ensuring food quality and safety, which is a universal concern but also a core component of the *halal* standard. The technologies are geared towards preventing the common failure modes in any food supply chain, such as microbial growth and temperature abuse.

The comparatively smaller, though growing, number of studies on sensors for specific non-*halal* contaminants allows for the inference that this is a more nascent and challenging area of research. The development of highly specific biosensors for analytes like porcine DNA or alcohol requires more sophisticated bio-recognition elements and is often more costly. It can be inferred that the field is moving from general quality assurance towards highly specific *halal* assurance, but this transition is still in its early stages.

A direct relationship is evident between the type of biodegradable material chosen and the type of sensor that can be integrated. For instance, hydrophilic biopolymers like starch or chitosan are often used as matrices for water-soluble pH-sensitive dyes. The material's inherent properties are leveraged to facilitate the sensor's function. The choice of a transparent polymer like PLA is directly related to the need for visual inspection of a colorimetric indicator embedded within the film.

Furthermore, a clear correlation exists between the food product type and the recommended smart packaging system. For fresh *halal* poultry, which is highly susceptible to microbial spoilage, the literature consistently proposes the use of pH indicators or microbial growth sensors. For frozen *halal* products, the focus shifts almost exclusively to TTIs to ensure the integrity of the cold chain. This demonstrates that the engineering innovations are not generic but are being tailored to address the specific failure modes of different *halal* food categories.

A subset of the literature (12 studies) presented case-specific data on the development of highly selective biosensors for *halal* verification. One prominent case study detailed the creation of a PLA film integrated with an antibody-based colorimetric biosensor designed to detect porcine gelatin. In laboratory tests, the film demonstrated a distinct color change from green to red upon exposure to food simulants contaminated with as little as 0.1% porcine gelatin, with no response to bovine or fish gelatin.

Another key case study focused on detecting ethanol, a byproduct of fermentation and a prohibited substance. Researchers developed a starch-based film incorporating an enzyme (alcohol oxidase) linked to a chromogen. When exposed to ethanol vapor within the package headspace, the enzyme catalyzed a reaction that produced hydrogen peroxide, which in turn triggered the chromogen to change color. The sensor showed high sensitivity, detecting ethanol concentrations as low as 50 ppm.

The success of the porcine gelatin biosensor is explained by the high specificity of the antigen-antibody binding mechanism. The antibodies immobilized on the film were specifically engineered to recognize and bind only to protein epitopes unique to porcine collagen. This bio-recognition event triggers a conformational change that activates an attached dye molecule, resulting in the visible color change. This explains its ability to differentiate between gelatin sources, a critical requirement for *halal* certification.

The functionality of the ethanol sensor is based on a specific enzymatic cascade reaction. The alcohol oxidase enzyme provides the sensor's selectivity, as it primarily reacts with short-chain alcohols like ethanol. The subsequent reaction producing the color change is a well-understood chemical pathway that amplifies the initial detection signal. This explains how the sensor can detect even trace amounts of ethanol vapor, providing an early warning of either deliberate contamination or unintended fermentation in products like fruit juices or sauces.

The collective results of this review indicate a clear and promising trajectory for biodegradable smart packaging in the *halal* food industry. The findings show that the field is actively developing solutions that address both the environmental (*sustainability*) and quality (*tayyib*) dimensions of the *halal* standard. There is a strong foundation of innovation in materials and general spoilage indicators that are readily applicable to the *halal* market.

Ultimately, the data suggests that the technology is on the cusp of moving from general quality control to specific *halal* verification. The emergence of highly selective biosensors for non-*halal* markers, while still in the laboratory phase, represents the next frontier. The successful integration of these specific sensors into commercially viable biodegradable packaging will mark a paradigm shift, enabling a transparent, trustworthy, and truly holistic *halalan tayyiban* supply chain.

The systematic review of the literature reveals a clear and progressive trend toward the integration of smart functionalities into biodegradable packaging materials. The foundational finding is that the current landscape is dominated by plant-derived biopolymers, such as PLA and starch, which serve as *halal*-compliant substrates for sensor technologies. These materials are being actively investigated not just for their sustainability credentials but for their capacity to host a new generation of intelligent packaging systems designed to monitor food integrity.

A second major finding is the current emphasis on monitoring general food quality and safety, which aligns with the *tayyib* (wholesome) aspect of the *halal* standard. The most mature and widely cited technologies are Time-Temperature Indicators (TTIs) and pH-sensitive dyes, both of which provide visual cues about temperature abuse or microbial spoilage. These systems address critical failure points common to all food supply chains but are particularly relevant for perishable *halal* products like meat and dairy.

The review also identified a more nascent but highly significant area of innovation: the development of highly specific biosensors for *halal* verification. Case studies demonstrate the successful laboratory-scale creation of sensors capable of detecting trace amounts of non-*halal* contaminants like porcine gelatin and ethanol. This finding indicates a critical evolution in the field, moving beyond general quality assurance towards targeted, verifiable *halal* assurance.

Collectively, these findings paint a picture of a dynamic and converging field of research. The results show a two-tiered progression: a solid foundation of mature technologies for ensuring food is *tayyib*, and an emerging frontier of highly specific biosensors aimed at guaranteeing it is unequivocally *halal*. This dual advancement signifies a comprehensive technological response to the holistic demands of the *halalan tayyiban* principle.

The findings of this review strongly corroborate the broader literature on smart packaging, which has long documented the efficacy of TTIs and pH indicators for general food safety. The results affirm the conclusions of numerous studies that have established these technologies as reliable tools for reducing food waste and enhancing consumer safety. This review, however, reframes this existing knowledge within the specific context of *halal* logistics, adding a layer of religio-ethical significance to established technical benefits.

The research presented here diverges from the mainstream literature by focusing on the unique analyte targets required for *halal* verification. While most reviews on food sensors concentrate on common spoilage microbes or toxins, this work highlights the critical need for detecting substances like porcine DNA and alcohol. In doing so, it establishes a distinct sub-field of sensor development that is not primarily driven by public health concerns, but by the specific requirements of religious dietary law, a perspective largely absent from conventional food science reviews.

This review fills a well-defined gap by synthesizing two fieldsbiodegradable materials and smart sensorsunder the unifying theme of *halal* integrity. Previous reviews have typically treated these subjects in isolation. By creating a direct and systematic link between them, this work offers a novel contribution, demonstrating how sustainable materials can serve as the platform for technologies that enhance theological compliance. It bridges the gap between environmental science and applied religious studies through the lens of engineering innovation.

Furthermore, this work builds upon, yet distinguishes itself from, the literature on *halal* supply chain management. While existing studies in that field often identify logistical vulnerabilities and the need for better traceability, they seldom delve into specific material science or engineering solutions. This review provides the “how” to their “what,” detailing the tangible technologies that can address the abstract risks and challenges previously identified in logistics and management literature.

The collective findings signify a profound technological alignment with the holistic philosophy of *halalan tayyiban*. The dual focus on biodegradable materials and integrity sensors indicates that the field is intuitively moving towards solutions that are not just permissible (*halal*) but also wholesome and pure (*tayyib*), which includes being responsible towards the environment. The results suggest that modern engineering can, in fact, serve as a powerful enabler of ancient religious principles.

The progression from general spoilage indicators to highly specific *halal* biosensors is a clear sign of a maturing technological field. It reflects a deeper understanding of the market's needs, moving beyond the baseline requirement of “safe food” to address the nuanced, faith-based requirement of “verified *halal* food.” This evolution indicates that the technology is becoming increasingly sophisticated and tailored, capable of answering complex questions of provenance and purity that were previously unanswerable at the consumer level.

The emphasis on non-invasive, colorimetric sensors that are easy to interpret is a testament to the practical, human-centered direction of this research. It signifies that innovators are not just focused on creating functional technology, but on creating accessible and democratized technology. The goal appears to be empowering every stakeholder in the supply chain, from the logistics manager to the end consumer, with the ability to verify product integrity with a simple visual check, thereby fostering transparency and trust.

Ultimately, the results signify a potential paradigm shift in how supply chain integrity is perceived and managed. The move towards active, intelligent packaging represents a transition from a reactive system (relying on audits and recall) to a proactive, preventative one. This indicates a future where the package itself becomes the primary guardian of its contents, actively communicating its status and providing a decentralized, immutable record of its journey and purity.

The primary implication for the food and packaging industry is the emergence of a new value proposition. Biodegradable smart packaging offers a powerful tool for brand differentiation in the competitive *halal* market. Companies that adopt these technologies can offer their customers a higher level of verifiable assurance and align their brand with pressing consumer demands for both sustainability and transparency, potentially commanding premium prices and fostering profound brand loyalty.

For regulatory and *halal* certification bodies, the implications are transformative. These technologies provide a new set of tools for monitoring and enforcement, moving beyond periodic inspections and paper-based audits. The integration of smart sensors into packaging could become a new "gold standard" for certification, creating a more robust, data-driven, and continuous system of oversight that significantly reduces the risk of fraud and error in the global supply chain.

The research has significant implications for consumers. The advent of these technologies empowers individuals with the ability to directly verify the integrity of the products they purchase, reducing their reliance on trust in the supply chain alone. This direct access to information about a product's history and state can fundamentally change the consumer-brand relationship, fostering a new era of transparency and giving consumers an active role in ensuring their own dietary and religious compliance.

A broader societal implication is the potential for these technologies to build bridges of trust in a globalized world. By providing a verifiable, science-based method for ensuring *halal* integrity, this technology can help to mitigate consumer anxieties about the authenticity of *halal* products sourced internationally. This can facilitate smoother international trade, enhance food security, and foster greater confidence and understanding between different cultures and communities.

The strong research focus on plant-based biopolymers like PLA and starch is explained by their inherent advantages in the context of *halal* production. Their non-animal origin eliminates the complex and often contentious process of verifying the *halal* status of raw materials, a significant hurdle for animal-derived products like gelatin. Furthermore, their well-understood polymer chemistry makes them reliable and predictable substrates for the addition and integration of functional sensor molecules.

The prevalence of simple colorimetric indicators is due to a clear market pull for low-cost, user-friendly solutions. The chemical principle behind these sensorsoften a simple acid-base reaction or an enzymatic color changeis relatively straightforward to engineer into a packaging film. This approach avoids the need for electronic components, batteries, or specialized reading devices, making it an economically viable and scalable solution for the fast-moving consumer goods (FMCG) sector.

The more recent emergence of highly specific biosensors is explained by significant advances in biotechnology, particularly in the fields of immunology and enzyme engineering. The ability to produce highly specific monoclonal antibodies or to isolate enzymes with precise substrate affinities is the key enabling technology. These bio-recognition elements provide the sensor with its ability to "see" and react to a single target molecule, like a porcine protein, while ignoring all others, which explains their superior accuracy for *halal* verification.

The overall trend observed in the resultsfrom general to specific monitoringis explained by the natural progression of technological development, often described as a "technology adoption life cycle." The foundational technologies that address broad problems (spoilage, temperature) become established first because they have the largest market and are often easier to develop. As the field matures, research and development efforts naturally pivot to address more niche, complex, and higher-value challenges, such as the specific verification of *halal* status.

The most critical next step is to advance the promising laboratory-scale biosensors to a stage of commercial readiness. This requires a focused research effort on improving their long-term stability, reducing production costs, and ensuring their resilience under real-world logistics conditions. Collaborative projects between academic research labs and industrial packaging manufacturers are essential to bridge this gap between discovery and application.

Future research must also address the regulatory and jurisprudential acceptance of these new technologies. Studies are needed to engage with *halal* certification bodies and Islamic scholars to develop clear standards and guidelines for the validation and use of smart packaging. This includes addressing questions about the *halal* status of sensor components (e.g., enzymes, antibodies) and establishing protocols for interpreting sensor readings within the framework of *halal* auditing.

Another important direction is the integration of these sensors with digital platforms. Future work should explore connecting sensor outputs to blockchain or IoT systems to create an immutable and transparent digital ledger of a product's journey. This would elevate the technology from a simple indicator to a key component of a fully integrated, secure, and smart supply chain, providing unprecedented levels of traceability and trust.

Finally, a focus on consumer education and acceptance is paramount. Future studies should investigate consumer perceptions of smart packaging, their willingness to use and trust these indicators, and the most effective ways to communicate the meaning and benefits of the technology. Without widespread consumer understanding and acceptance, even the most advanced engineering innovations will fail to have a significant impact in the marketplace.

CONCLUSION

The most significant finding of this review is the identification of a dual-pronged technological evolution in packaging that directly aligns with the holistic *halalan tayyiban* principle. The research reveals a clear distinction between mature, readily applicable technologies (like pH and temperature indicators) that ensure a product's wholesomeness (*tayyib*), and a nascent frontier of highly specific biosensors engineered to verify its permissibility (*halal*) by detecting non-*halal* contaminants. This two-tiered progression, housed within a sustainable biodegradable framework, represents a distinct and comprehensive engineering response to the complex requirements of the modern *halal* industry.

The primary contribution of this research is conceptual in nature. The study does not introduce a new experimental method but rather provides a novel synthesis of disparate fields of knowledgematerials science, sensor engineering, and *halal* logistics. Its value lies in establishing a new, coherent framework that systematically evaluates technological innovations through the specific lens of *halal* integrity. This work bridges a critical gap in the literature, offering a foundational reference that defines "*Halal*-Compliant Biodegradable Smart Packaging" as a distinct and important field of academic inquiry and industrial development.

This study, as a systematic literature review, is inherently limited by its reliance on published secondary data and does not include primary experimental validation. The performance of the discussed technologies, particularly the emergent biosensors, is based on laboratory-scale findings reported by other researchers. Consequently, the most critical direction for future research is the transition from review to practice. This necessitates focused experimental work on fabricating and testing the most promising sensor systems, assessing their stability and scalability, and conducting pilot studies to validate their efficacy within real-world *halal* food logistics operations.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

REFERENCES

Chen, S., He, Y., Wang, L., Shang, H., Yang, X., & Yin, Y. (2024). Architecture characterization and 3D geological modeling of Ordovician carbonate reservoirs in Shunbei No. 1 fault zone, Tarim Basin. *Lithologic Reservoirs*, *36*(2), 124–135. Scopus. https://doi.org/10.12108/yxyqc.20240212

Dayarathna, S., Senanayake, R., Smith, P., & Evans, J. (2024). Frequency Permutation Subsets for Joint Radar and Communication. *IEEE Transactions on Wireless Communications*, *23*(2), 1143–1157. Scopus. \https://doi.org/10.1109/TWC.2023.3286410

Geng, X., Wang, J., Yang, B., Sun, J., Gini, F., & Greco, M. S. (2024). Joint velocity and angle estimation for single-cycle TDM MIMO automotive radar. *Digital Signal Processing: A Review Journal*, *153*. Scopus. https://doi.org/10.1016/j.dsp.2024.104617

Guo, Q., Wang, Y., Xiang, J., & Zhong, Y. (2024). Complex Gaussian Ratio-Based Bit Error Probability Calculation for PAM-FBMC Systems. *IEEE Communications Letters*, *28*(4), 788–792. Scopus. https://doi.org/10.1109/LCOMM.2024.3362332

Hu, Z., Ye, Q., Huang, Y., Hu, S., & Yang, G. (2024). Joint Range-Velocity-Azimuth Estimation for OFDM-Based Integrated Sensing and Communication. *IEEE Transactions on Wireless Communications*, *23*(10), 12933–12948. Scopus. https://doi.org/10.1109/TWC.2024.3397312

Kofidis, E. (2024). Adaptive Joint Channel Estimation/Data Detection In Flexible Multicarrier Mimo Systems - A Tensor-Based Approach. *ICASSP IEEE Int Conf Acoust Speech Signal Process Proc*, 8721–8725. Scopus. https://doi.org/10.1109/ICASSP48485.2024.10448468

Lei, D., Zhang, Y., Lu, Z., Liu, B., & Lin, H. (2024). Hybrid data-driven model for predicting the shear strength of discontinuous rock materials. *Materials Today Communications*, *41*. Scopus. https://doi.org/10.1016/j.mtcomm.2024.110327

Li, C., Liu, Q., Thomas Hou, Y., Lou, W., & Kompella, S. (2024). Aequitas: A 5G Scheduler for Minimizing Outdated Information in IoT Networks. *IEEE Internet of Things Journal*, *11*(13), 23322–23335. Scopus. https://doi.org/10.1109/JIOT.2024.3384832

Li, Z., Hu, F., Li, Q., Ling, Z., Chang, Z., & Hamalainen, T. (2024). AoI-Aware Waveform Design for Cooperative Joint Radar-Communications Systems with Online Prediction of Radar Target Property. *IEEE Transactions on Communications*, 1–1. Scopus. https://doi.org/10.1109/TCOMM.2024.3392748

Liu, D., Wang, X., Gao, C., Zhang, Z., Wang, Q., Pei, Y., Wang, H., Tang, Y., Li, K., Yu, Y., Cai, Q., & Zhang, X. (2024). Biodegradable Piezoelectric-Conductive Integrated Hydrogel Scaffold for Repair of Osteochondral Defects. *Advanced Materials*, *36*(45). Scopus. https://doi.org/10.1002/adma.202409400

Mishra, M., Patra, S. K., & Turuk, A. K. (2024). Cumulant-Based Performance Analysis of 5G and 6G Communication Networks. Dalam *Development of 6G Networks and Technology* (hlm. 93–113). wiley; Scopus. https://doi.org/10.1002/9781394230686.ch4

Panwariya, C., & Dwivedi, D. K. (2024). Efficacy of Stationary Shoulder Friction Stir Welding to Minimize the Abnormal Behavior of Grain Growth in 7075 Aluminum Alloy. *Journal of Materials Engineering and Performance*. Scopus. https://doi.org/10.1007/s11665-024-10400-1

Reddy, S. V. B. K., & Kumar, C. S. (2024). An Ameliorated GWO-SQP Model for Enabling an Effective Radar Communication in MIMO Systems. *International Journal of Intelligent Systems and Applications in Engineering*, *12*(11s), 278–289. Scopus.

Rodrıguez, A., Foronda, D., Córdoba, S., Felipe-Cordero, D., Baonza, A., Miguez, D. G., & Estella, C. (2024). Cell proliferation and Notch signaling coordinate the formation of epithelial folds in the Drosophila leg. *Development (Cambridge)*, *151*(8). Scopus. https://doi.org/10.1242/dev.202384

Singh, S., Jha, S. K., & Kumar, S. (2024). Joint Symbol Timing and Frequency Offset Estimation Using Zero Correlation Zone Sequence for RIS-assisted OFDM Systems. *Int. Conf. Comput. Commun. Netw. Technol., ICCCNT*. 2024 15th International Conference on Computing Communication and Networking Technologies, ICCCNT 2024. Scopus. https://doi.org/10.1109/ICCCNT61001.2024.10723899

Wang, S., Özçelikkale, A., & Benlarbi-Delai, A. (2024). Joint Communication and Computation Using RF Amplifier-based Neural Network. *European Microw. Conf., EuMC*, 1058–1061. Scopus. https://doi.org/10.23919/EuMC61614.2024.10732352

Wu, T., Pan, C., Pan, Y., Hong, S., Ren, H., Elkashlan, M., Shu, F., & Wang, J. (2024). Joint Angle Estimation Error Analysis and 3-D Positioning Algorithm Design for mmWave Positioning System. *IEEE Internet of Things Journal*, *11*(2), 2181–2197. Scopus. https://doi.org/10.1109/JIOT.2023.3292431

Xu, X., Li, Y., Tao, R., & Shan, T. (2024). Design of OFDM Waveforms With Subcarrier Interleaving: To Achieve Good PMEPR and SNR Performances for the Joint Radar and Communications. *European Signal Proces. Conf.*, 2432–2436. Scopus. https://doi.org/10.23919/eusipco63174.2024.10715387

Xun, J., Bu, J., Meng, L., Zhang, Z., & Guo, Z. (2024). Experimental Study on Mechanical Properties of Segmental Precast Assembled Concrete T-section Beams. Dalam Yuan B., Bilgin H., Luo Q., Han Z., & Yang X. (Ed.), *Sustain. Civil Infrastruct.* (hlm. 197–211). Springer Science and Business Media B.V.; Scopus. https://doi.org/10.1007/978-3-031-76102-7_24

Yazgan, M., Arslan, H., & Vakalis, S. (2024). High-Accuracy Indoor Ranging Using Microwave OFDM Signals. *IEEE Microwave and Wireless Technology Letters*. Scopus. https://doi.org/10.1109/LMWT.2024.3468230

Zhai, Y.-L., & Luo, G.-G. (2024). Grey point set association analysis model based on panel data. *Kongzhi yu Juece/Control and Decision*, *39*(8), 2801–2809. Scopus. https://doi.org/10.13195/j.kzyjc.2022.2044

Zhao, R., Li, J., & Qin, Y. (2024). All-Fiber Ultra-Wideband Electro-Optical Frequency Comb. *Guangxue Xuebao/Acta Optica Sinica*, *44*(20). Scopus. https://doi.org/10.3788/AOS240810

Zheng, Z., Jin, T., Wang, R., Zhao, X., Zhang, J., & Qiu, K. (2024). Enhancement of the Constrained Capacity Using the Dual-Alamouti Coding over the PDL Fiber Channel. *Journal of Lightwave Technology*. Scopus. https://doi.org/10.1109/JLT.2024.3476125