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DIGITALIZATION IN FOOD PROCESSING SMES IN INDONESIA: ENHANCING SAFETY, TRACEABILITY, AND CONSUMER TRUST

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Abstract

Digitalization has emerged as a transformative force in food quality control, offering new opportunities to enhance safety, traceability, and consumer trust. While large-scale food industries in developed countries have increasingly adopted technologies such as Internet of Things (IoT), artificial intelligence (AI), blockchain, and smart packaging, small and medium enterprises (SMEs) in developing economies face unique challenges in implementation. This review explores the current landscape of digital adoption in Indonesian food SMEs, highlighting both the potential benefits and the barriers to integration. This review was conducted as a structured literature analysis. Articles were retrieved from Scopus, Web of Science, and Google Scholar databases, covering the period 2018–2026. A total of 85 peer-reviewed articles were included after applying inclusion criteria (focus on food SMEs, digitalization technologies, AI in food technology, Blockchain, IoT, smart packaging, and food safety/traceability in food technology). Key opportunities include the use of low-cost sensor technologies for monitoring product quality, mobile-based applications for traceability, and cloud-driven platforms for quality assurance. However, constraints such as limited financial resources, digital literacy gaps, infrastructure disparities, and regulatory alignment remain significant obstacles. The findings emphasize the need for collaborative efforts among policymakers, academia, and industry stakeholders to ensure that digitalization not only strengthens food safety and quality management but also supports sustainability and competitiveness in the global market.

Keywords: Digitalization, Food Safety, Indonesia, SMEs, Traceability

1. Introductions

Small and medium enterprises (SMEs) in the food sector play a pivotal role in Indonesia's national food system, contributing substantially to employment, local economic resilience, and food security (Aprilia et al., 2025; Kartika & Rokhim, 2025; Wahab et al., 2024). According to the Ministry of Industry, SMEs account for more than 90% of food-related businesses in Indonesia

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and are responsible for sustaining the growth of the food and beverage sector, which recorded an annual increase of 5.82% in 2024 (Ramdhan et al., 2026). These enterprises are crucial in ensuring the availability of diverse food products, particularly traditional and regionally specific items, thereby supporting both domestic consumption and cultural heritage. However, Indonesian food SMEs often face structural challenges, including limited access to capital, reliance on manual processes, and uneven infrastructure development, which constrain efficiency and scalability (Kistiani et al., 2026; Purnomo et al., 2024). Comparatively, SMEs in other developing regions such as Africa and Latin America also serve as the backbone of agrifood supply chains, yet their integration into modern value chains has been more advanced through the establishment of agrifood clusters and stronger linkages with formal markets (Yáñez et al., 2026). This contrast highlights both the similarities in resource constraints and the differences in institutional support, suggesting that Indonesia’s food SMEs, while strategically positioned, require accelerated digital adoption and regulatory alignment to enhance competitiveness and consumer trust in the global market (Kartika, 2025; Purnomo et al., 2024).

Ensuring food quality and safety remains a critical challenge for small and medium enterprises (SMEs) in Indonesia’s food sector. Despite their dominant role in supplying diverse food products, SMEs often operate with limited resources, relying on manual processes and traditional practices that hinder compliance with international standards such as ISO 22000 and HACCP. Studies highlight that Indonesian SMEs face high levels of postharvest losses, with inefficiencies in drying and storage contributing to product deterioration and microbial contamination (Fauziana et al., 2023; Syikilili et al., 2026)). Limited access to affordable testing facilities and digital monitoring tools further exacerbates risks, resulting in inconsistent product quality and reduced consumer trust (BPOM RI, 2023). Similar challenges are observed in other developing regions, where SMEs struggle with inadequate infrastructure, weak enforcement of food safety regulations, and low adoption of traceability systems (Tang et al., 2024). However, while Latin American SMEs have increasingly integrated into agrifood clusters that facilitate shared quality control resources, Indonesian SMEs remain fragmented, with quality assurance largely dependent on individual enterprise capacity (Dibbern & Romani, 2025). This structural gap underscores the urgent need for scalable, low-cost digital solutions to strengthen food safety and quality management among SMEs in Indonesia, aligning them with global best practices while addressing local constraints.

The persistent challenges of food quality and safety among Indonesian SMEs underscore the urgency of adopting digital technologies as a strategic solution. Traditional manual practices, limited access to laboratory testing, and fragmented quality assurance systems have resulted in inefficiencies and inconsistent compliance with international standards (BPOM RI, 2023; Fauziana et al., 2023). Digitalization offers a pathway to overcome these barriers by enabling real-time monitoring, predictive analytics, and traceability across the food supply chain. Low-cost Internet of Things (IoT) sensors can provide continuous data on temperature and humidity, reducing risks of microbial contamination, while mobile-based applications facilitate affordable traceability systems accessible even to micro-scale enterprises (Alkhateeb et al., 2022; Liakos et al., 2018). Moreover, blockchain technology has been increasingly recognized for its ability to enhance transparency and consumer trust in food safety management, particularly in contexts where regulatory enforcement is uneven (Alkhateeb et al., 2022). Compared to SMEs in Latin America, which have begun integrating digital tools within agrifood clusters to collectively

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manage quality control, Indonesian SMEs remain at an early stage of digital adoption (Dibbern & Romani, 2025). This gap highlights the critical need for scalable, context-specific digital solutions that align with national standards such as SNI and international frameworks like ISO 22000, ensuring that SMEs can strengthen food safety practices while remaining competitive in the global market.

2. Methods

This review was conducted using a structured literature search to ensure methodological rigor. Relevant articles were retrieved from international databases including Scopus, Web of Science, and Google Scholar, covering the period 2018–2026 to capture recent advances in digitalization of food SMEs. The initial search yielded 142 publications, which were screened based on inclusion criteria: peer-reviewed status, focus on food processing SMEs, and discussion of digital technologies related to safety, traceability, or consumer trust. After applying exclusion criteria (non-English sources, non-peer-reviewed reports, and studies outside the food sector), a total of 85 articles were included in the final synthesis. This systematic approach allowed for the integration of global trends with national case studies, ensuring that the review provides both breadth and contextual relevance to the Indonesian food SME sector.

3. Discussions

3.1. Blockchain as a Strategic Enabler for SME Traceability

The implementation of end-to-end traceability is increasingly mandated by global regulatory frameworks, yet it remains fragmented for SMEs due to a lack of technical expertise and financial resources (Pham et al., 2026). To address these barriers, research suggests a unified blockchain-enabled services framework that abstracts complex functionalities, including data recording and rule enforcement, into reusable services accessible via web APIs. For SMEs, this service-oriented approach shifts the technological burden from the individual enterprise to a modular infrastructure, facilitating interoperability without requiring the replacement of legacy systems (Pham et al., 2026). In Indonesia, where sectors like fish and rice processing are vital, such decentralized architectures can solve the "information asymmetry" that often characterizes traditional supply chains (Ismail et al., 2023; Peng et al., 2022).

3.2. Enhancing Food Safety through IoT-Blockchain Integration

Food processing SMEs can significantly enhance safety by integrating blockchain with the Internet of Things (IoT), transitioning from a reactive "detect-and-fix" model to a proactive "predict-and-prevent" ecosystem. IoT-enabled sensors (monitoring temperature, humidity, and spoilage gases) provide real-time data that is securely registered on an immutable ledger (S Ismail et al., 2023; Kaur et al., 2022). This Cyber-Physical System (H-CPS) enables the automation of quality checks via smart contracts, which can automatically trigger alerts or "lock" contaminated batches based on predefined thresholds like pH levels or TVB-N markers (Djafar et al., 2026). This study identifies three dominant research clusters-physicochemical sensing for spoilage detection, bioactive materials for functional protection, and digital supply chain integration via RFID and blockchain-while also noting persistent commercialization barriers such as nanomaterial safety concerns, high sensor costs, and fragmented regulations.

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Such systems are particularly critical for temperature-sensitive products where maintaining the cold chain is essential for preventing foodborne illnesses (Ismail et al., 2023; Oh et al., 2025). IoT-based temperature sensors play a pivotal role in maintaining the integrity of the cold chain, which is essential for ensuring food safety in perishable products such as meat, seafood, dairy, and fresh produce. By continuously monitoring and transmitting real-time temperature data across storage and distribution stages, these sensors enable early detection of deviations that could compromise product quality or foster microbial growth. Integrated with cloud platforms and blockchain systems, IoT sensors enhance traceability by providing transparent records of temperature compliance throughout the supply chain, thereby strengthening regulatory adherence and consumer trust. Moreover, automated alerts and predictive analytics derived from sensor data allow SMEs to respond proactively to potential risks, reducing food loss and safeguarding public health. This digitalization of cold chain management exemplifies how smart technologies can transform traditional food handling practices into resilient, data-driven systems aligned with global food safety standards.

3.3. Bridging the "Trust Gap" and Consumer Engagement

Blockchain adoption in food SMEs is increasingly framed as a strategic solution to bridge the “trust gap” between producers and consumers by embedding transparency, accountability, and verifiability into the supply chain. Through immutable digital ledgers, blockchain ensures that every transaction and product attribute from origin and harvest date to certification status—is securely recorded and resistant to tampering—from origin and harvest date to certification status (Alkhateeb et al., 2022; Djafar et al., 2026). When paired with consumer-facing technologies such as QR codes or NFC tags, this system enables the creation of a “digital material passport” that allows buyers to instantly verify provenance, authenticity, and compliance with standards like Organic, Halal, or PDO. Such transparency directly combats fraudulent practices and “green-washing,” while simultaneously fostering consumer confidence in product integrity. Moreover, empirical evidence suggests that consumers are increasingly willing to pay a premium for food products backed by verifiable third-party certification, positioning blockchain not only as a technological safeguard but also as a market differentiator. This gives SMEs a dual function: enhancing regulatory compliance and strengthening consumer engagement. Consequently, blockchain adoption becomes a crucial step toward building trust, ensuring food safety, and securing competitiveness in both domestic and global markets (Dos_Santos et al., 2021; S Ismail et al., 2023).

3.4. Operational Resilience and Compliance Standards

To achieve standardized digitalization, SMEs could adopt models based on Critical Tracking Events (CTEs) and Key Data Elements (KDEs). These frameworks ensure that every change of custody or product transformation is recorded systematically, supporting rapid and targeted product recalls (Bhatlawande et al., 2024; Dos_Santos et al., 2021; Pham et al., 2026). Furthermore, the use of private or permissioned blockchains (e.g., Hyperledger Fabric) is recommended for SMEs to protect sensitive business data while maintaining high transaction throughput and data integrity (Vitaskos et al., 2024).

In the Indonesian context, adherence to BPOM (Badan Pengawas Obat dan Makanan) regulations for novel food contact substances is a critical safeguard to ensure that the integration

of digital sensors into packaging systems remains compliant with national safety standards. As highlighted by Djafar et al. (2026), although Smart Packaging 4.0 technology offers significant potential to enhance food safety and traceability, its commercialization is often hindered by regulatory concerns regarding material migration and risks to consumer health. BPOM's regulatory framework provides a structured mechanism to evaluate and approve new sensor-embedded materials, aligning them with international safety benchmarks while maintaining local relevance. This regulatory oversight not only mitigates risks associated with nanomaterial migration (e.g., ZnO, TiO₂) but also ensures that SMEs adopting digital packaging innovations can do so responsibly, thereby reinforcing consumer trust and supporting the broader agenda of food safety modernization in Indonesia (Djafar et al., 2026).

Despite the benefits, several challenges persist for SMEs (Ismail et al., 2023; Kaur et al., 2022; Peng et al., 2022; Tang et al., 2024):

1. Scalability and Latency: Traditional blockchain networks may struggle with the high volume of data generated by thousands of IoT devices, requiring off-chain storage solutions or hybrid models,
2. Data Quality: Blockchain makes sure that data is correct when it is recorded. But it cannot check that the information is correct when it is put in. This is called the "garbage in, garbage out" problem,
3. Resource Constraints: The energy demands and setup costs for blockchain nodes can be prohibitive, necessitating the exploration of Blockchain-as-a-Service (BaaS) to reduce entry costs,
4. Scalability and Cost: Transitioning from pilot projects to industrial-scale implementation remains expensive due to high sensor production and infrastructure setup costs,
5. Energy Demands: Maintaining a network of battery-powered sensors is challenging; future sustainability depends on energy harvesting technologies that draw power from environmental factors like motion or temperature changes,
6. Data Security: The expansion of connected devices increases the "attack surface" for cyber-physical threats, necessitating robust encryption to prevent data manipulation in safety records.

For Indonesian SMEs, the transition toward Smart Packaging 4.0 and blockchain-integrated supply chains represents a vital step in ensuring food security and building a resilient, transparent industry that aligns with international standards.

3.5. The Evolution Toward Smart Packaging 4.0

In the framework of Smart Packaging 4.0, the IoT serves as the essential "nervous system" that transitions food packaging from a passive physical barrier into an interactive cyber-physical interface. For Small and Medium Enterprises (SMEs), IoT integration involves embedding physical objects with sensors, actuators, and communication modules to enable continuous data acquisition throughout the supply chain. This connectivity provides a dynamic data stream regarding critical environmental parameters, moving beyond simple location tracking to provide comprehensive insights into product integrity and shelf-life status (Bhatlawande et al., 2024; Dakhia et al., 2025; Djafar et al., 2026).

This technological evolution is categorized into three phases: the foundation of modified atmosphere packaging (Phase I), the development of biodegradable sensor-embedded materials (Phase II), and the current (Phase III), which involves the convergence of AI, blockchain, and predictive analytics (Djafar et al., 2026).

Smart packaging is generally divided into two complementary systems: active and intelligent packaging (Bhatlawande et al., 2024; Kusuma et al., 2023).

- **Active Packaging:** This system involves the intentional incorporation of substances that interact with the food or its internal environment to extend shelf life. Key applications include oxygen scavengers to slow oxidation, ethylene scavengers to delay fruit ripening, and the release of antimicrobial agents such as garlic extract or essential oils to inhibit microbial growth (Dirpan et al., 2022).
- **Intelligent Packaging:** This system focuses on monitoring and communicating the condition of the food. Technologies such as Time-Temperature Indicators (TTIs), Radio Frequency Identification (RFID), and Near Field Communication (NFC) provide stakeholders with real-time data on freshness, temperature history, and logistics.

A primary trend in recent research is the replacement of petroleum-based plastics with biogenic and sustainable polymers to address environmental concerns. Natural biopolymers like chitosan, cellulose, starch, and alginate are increasingly utilized as matrices for smart systems. Nanotechnology plays a crucial role in enhancing these materials; bio-nanocomposites incorporating ZnO or TiO₂ nanoparticles provide structural reinforcement, UV shielding, and antimicrobial properties while maintaining biodegradability (Bhatlawande et al., 2024; Chaudhary et al., 2022; Djafar et al., 2026).

Furthermore, bacterial cellulose (e.g., from *Acetobacter xylinum*) has emerged as a superior carrier for sensors due to its nanofibrillar structure and high water-holding capacity. Studies have shown that bacterial cellulose-based films using Bromothymol Blue (BTB) can effectively signal beef spoilage through visible color shifts from orange to dark green as volatile alkaline compounds accumulate (Dirpan et al., 2022; Kusuma et al., 2023).

3.6. IoT implementation in food processing

A tangible benefit of IoT for food processing SMEs is the optimization of inventory management through a shift from First-In-First-Out (FIFO) to First-Expired-First-Out (FEFO) strategies. Traditional FIFO models rely on static expiration dates which do not account for actual storage fluctuations; conversely, IoT-enabled monitoring utilizes Time-Temperature Indicators (TTIs) and gas sensors to rank items based on their actual dynamic freshness (Djafar et al., 2026; Kusuma et al., 2023). This approach is critical in reducing the estimated 30% of global food waste typically lost during the distribution and retail phases.

While IoT offers transformative potential, SMEs often face barriers such as limited bandwidth and high latency in remote areas. Recent advancements emphasize the use of Edge and Fog computing to mitigate these issues (Dakhia et al., 2025; Taguta et al., 2026):

- **Localized Processing:** Using edge devices allows SMEs to perform initial data preprocessing locally, reducing the volume of data that must be transmitted over unstable networks,

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- **Fault Tolerance:** Localized monitoring ensures that critical safety alerts remain active even during temporary communication failures, which is vital for transport in closed metal containers or rural processing sites.

The perception layer of IoT systems in food processing utilizes diverse sensors to monitor variables that directly impact food safety (Oh et al., 2025; Bhatlawande et al., 2024; Djafar et al., 2026; Kusuma et al., 2023; Müller, 2026):

- **Environmental Sensors:** High-precision sensors for temperature and humidity (e.g., DHT11 or finger-sized sensor tags) are deployed inside containers to maintain the cold chain and prevent microbial growth during distribution,
- **Gas and Spoilage Sensors:** Advanced systems integrate sensors for CO₂, ethylene (C₂H₄), and volatile organic compounds (VOCs) to detect early stages of biochemical spoilage or premature ripening,
- **Chemical Indicators:** IoT-enabled packaging often incorporates pH-sensitive sensors and colorimetric indicators (e.g., using bacterial cellulose matrices) that detect the accumulation of Total Volatile Basic Nitrogen (TVB-N) in meat and seafood products.

Table 1. Challenges in digitalization in Food SMEs

Category	Brief Description	Impact on Digitalization
Technological and Infrastructure Limitations	Restricted access to reliable internet, digital devices, and system connectivity, particularly in non-urban areas.	Hinders the implementation of IoT, cloud-based quality control, and traceability systems.
Financial and Investment Constraints	Limited capital and perceived high costs of digital tools such as sensors, software, and data platforms.	Delays technology adoption and compliance with quality certification standards.
Digital Literacy and Human Resources	Insufficient technical skills among SME operators to effectively use and maintain digital systems.	Leads to data entry errors and underutilization of digital platforms.
Regulatory and Standardization Issues	Misalignment between national regulations (SNI, BPOM) and international standards (ISO, HACCP).	Creates confusion and inconsistency in implementing digital quality systems.
Data Security and Privacy Concerns	Fear of data breaches and misuse of production or transaction information.	Reduces trust and willingness to adopt digital platforms.
Fragmented Supply Chain Connectivity	Weak coordination among producers, distributors, and retailers within the food supply chain.	Limits integration of traceability and blockchain-based systems.

Despite the structural challenges faced by Indonesian food SMEs, the potential for digitalization to transform quality control and safety practices is considerable (Table 1). Affordable IoT-based monitoring devices, mobile applications for traceability, and cloud-driven

platforms offer scalable solutions that can be tailored to the resource constraints of SMEs (Liakos et al., 2018). Government initiatives such as *Making Indonesia 4.0* and the digitalization programs of the Ministry of Cooperatives and SMEs have begun to provide frameworks for integrating SMEs into broader digital ecosystems, although implementation remains uneven (Kemenkop, 2022; Kemenperin, 2021). Strategic adoption pathways include phased integration of low-cost digital tools, capacity-building programs to improve digital literacy among SME operators, and collaborative models where SMEs share access to digital infrastructure through cooperatives or agrifood clusters. Comparative evidence from Latin America demonstrates that collective adoption of digital technologies within SME networks can reduce costs and enhance compliance with food safety standards (Tang et al., 2024). For Indonesia, aligning these strategies with national standards such as SNI and international frameworks like ISO 22000 will be essential to ensure that digitalization not only strengthens food safety and consumer trust but also enhances competitiveness in regional and global markets.

3.7. Global digitalization Trends in Food Quality Control

Digitalization has become a cornerstone of modern food quality control, with global industries increasingly adopting advanced technologies to ensure safety, traceability, and consumer trust. The Internet of Things (IoT) enables real-time monitoring of critical parameters such as temperature, humidity, and microbial contamination, reducing risks across supply chains (Liakos et al., 2018). Artificial intelligence (AI) and machine learning models are widely applied to predict shelf-life, detect anomalies, and optimize logistics, while AI-driven packaging systems provide freshness indicators and contamination alerts (Madhu, 2025). Blockchain technology has gained prominence in Europe and North America, offering transparent and immutable records that strengthen compliance and authenticity in food safety management. Smart packaging innovations, including biodegradable polymers, nanomaterial-enhanced substrates, and embedded biosensors, are increasingly integrated with IoT and blockchain platforms to enable real-time data sharing and consumer engagement (Duong et al., 2024). Collectively, these technologies illustrate a global shift toward integrated, data-driven systems that enhance both efficiency and trust in food quality assurance.

The global food sector is undergoing a profound transformation driven by Industry 4.0, moving from traditional, labor-intensive methods toward data-driven food computing. This interdisciplinary field fuses data science, AI, and food science to address critical challenges such as food insecurity, environmental sustainability, and supply chain inefficiencies. AI serves as the analytical core of this evolution, processing vast datasets from Internet of Things (IoT) sensors to enable a transition from reactive "detect-and-fix" models to proactive "predict-and-prevent" strategies (Müller, 2026; Taguta et al., 2026). AI has revolutionized quality assessment through non-destructive sensing and automated inspection, including pathogen and spoilage detection. Convolutional Neural Networks (CNNs) have achieved up to 100% accuracy in distinguishing wholesome meat from spoiled samples, preventing cross-contamination in the supply chain (Amani & Sarkodie, 2022). The study developed an automated approach to mitigate contamination risks in the meat supply chain by applying deep learning techniques. Specifically, the authors trained a Deep Convolutional Neural Network (DCNN) optimized with a particle swarm optimization (PSO) algorithm to classify wholesome versus spoiled meat samples. Using a dataset of nearly 1,900 images, the model achieved 100% accuracy, precision, recall, and F1-

score, outperforming previous studies. This demonstrates that integrating AI-based image classification into supply chain management can significantly reduce human error, improve food safety, extend shelf life, and minimize economic and environmental losses associated with meat spoilage. Similar model evaluated fish freshness and detect microbiological hazards (Ismail et al., 2023; Müller, 2026).

Metagenomic Screening Uses: Explainable AI (XAI) is utilized to analyze microbial shotgun metagenomics data in milk production, identifying anomalous compositions that indicate fraud or antibiotic abuse that traditional statistical methods fail to detect (Beck et al., 2024). The study explores the use of microbial shotgun metagenomics data combined with statistical and artificial intelligence approaches as an untargeted screening tool in food production, using raw milk as a model system. Baseline data and anomalous milk samples (from outside farms and antibiotic-treated cows) and compared them using classical ecological metrics such as alpha/beta diversity, clustering, and contrastive PCA. These traditional methods failed to clearly separate anomalous from baseline samples. In contrast, explainable AI successfully classified anomalous versus baseline milk samples and identified microbial drivers associated with antibiotic use, even with relatively small datasets. Data validation using publicly available 16S rRNA milk microbiome data, where explainable AI differentiated milk by storage methods, processing stages, and seasons. Overall, AI-based anomaly detection applied to metagenomic data holds strong potential for food safety, fraud detection, and quality control in dairy supply chains. AI also provides the analytical depth necessary to optimize the movement of perishable goods:

- **Dynamic Inventory Management:** By processing time-series data from sensors, AI enables the shift from First-In-First-Out (FIFO) to First-Expired-First-Out (FEFO) inventory strategies, which is critical for reducing the 30% of global food waste typically lost during distribution,
- **Cold Chain Monitoring:** Long Short-Term Memory (LSTM) networks predict temperature deviations in refrigerated vehicles, allowing for dynamic rerouting before product integrity is compromised,
- **Border and Regulatory Management:** AI systems like the Border Prediction Intelligent (BPI) model analyze historical noncompliance data and international alerts to sample high-risk imported batches more accurately, enhancing border inspection efficiency (Tu et al., 2024).

3.8. Implementation Challenges and Ethical Considerations

AI adoption in food SMEs production faces significant barriers, including:

1. **Interpretability and Trust:** Many deep learning models function as "black boxes," necessitating the development of Explainable AI (XAI) to satisfy regulators and build stakeholder confidence (Beck et al., 2024; Müller, 2026)
2. **Data Scarcity and Quality:** There is a critical shortage of high-quality, labeled real-world anomaly data for training models. Reliance on synthetic data can lead to overestimating performance by up to 150% (Müller, 2026; Taguta et al., 2026),
3. **Privacy and Ethics:** Handling sensitive consumer health and consumption data requires robust protection frameworks aligned with regulations like GDPR (Dakhia et al., 2025),
4. **Scalability and Cost:** High initial investments and the need for high-frequency data processing favor centralized cloud models, though emerging Edge AI and Federated

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Learning (FL) offer pathways for decentralized, low-latency applications (Dakhia et al., 2025; Müller, 2026; Taguta et al., 2026).

Furthermore, the future of the food industry lies in the seamless integration of AI and the IoT to create a more resilient, transparent, and sustainable global food system (Amani & Sarkodie, 2022; Dakhia et al., 2025).

3.9. Local adoptions in Indonesia SMEs

In contrast to global trends, Indonesian food SMEs remain at an early stage of digital adoption, with most enterprises still relying on manual processes for quality control (Table 2). Government initiatives such as *Making Indonesia 4.0* have identified the food and beverage sector as a priority for digital transformation, while programs like the INDI 4.0 Readiness Index and e-Smart IKM have begun to introduce SMEs to digital literacy and online platforms (Kemenkop, 2022; Kemenperin, 2021). However, adoption of digital tools in production and quality monitoring remains limited, with most SMEs using digitalization primarily for marketing and e-commerce rather than for safety and traceability. Only larger SMEs or those integrated into export-oriented supply chains have experimented with IoT sensors and blockchain-based traceability systems. Barriers include limited financial resources, uneven internet access in rural areas, low digital literacy among operators, and fragmented regulatory enforcement (BPOM RI, 2023). Compared to Latin American SMEs, which increasingly adopt collective digital infrastructures through agrifood clusters (Tang et al., 2024), Indonesian SMEs remain fragmented, highlighting the need for scalable, low-cost digital solutions aligned with national standards such as SNI and international frameworks like ISO 22000.

Table 2. Global and local comparison on digitalization adoption

Aspect	Global Trends (IoT, AI, Blockchain, Smart Packaging)	Indonesia SMEs Adoption
IoT Sensors	Widely used for real-time monitoring	Limited, mostly pilot projects in dairy/processed food
AI in QC	Predictive shelf-life, anomaly detection	Rare, mostly absent in SMEs
Blockchain Traceability	Strong adoption in export-oriented industries	Minimal, only in select supply chains
Smart Packaging	Advanced biodegradable, sensor-integrated systems	Mostly QR code labels, limited sensor use
Government Support	Strong regulatory frameworks (EU, US)	Programs exist (Making Indonesia 4.0, e-Smart IKM), but uneven implementation

3.10. Potency of digitalization in Indonesian Food SMEs

Given the structural constraints faced by Indonesian food SMEs, the adoption of low-cost and scalable digital technologies represents a realistic pathway to strengthen food quality control and safety practices. Affordable IoT devices, such as simple temperature and humidity sensors, can be deployed to monitor storage and processing conditions, reducing risks of microbial contamination and postharvest losses (Liakos et al., 2018). Mobile-based applications offer accessible solutions for traceability, enabling SMEs to record production data, batch information,

and distribution channels without requiring complex infrastructure. Cloud-based quality control platforms further provide opportunities for SMEs to store and analyze data collectively, facilitating compliance with national standards such as SNI and international frameworks like ISO 22000 (BPOM RI, 2023). Smart packaging technologies, although still limited in Indonesia, can be adapted through QR code labeling and freshness indicators, enhancing consumer trust and market competitiveness (Bhatlawande et al., 2024; Imail et al., 2023). Comparative evidence from Latin America demonstrates that collective adoption of digital tools within agrifood clusters can reduce costs and improve compliance (Tang et al., 2024), suggesting that similar cooperative models could be effective for Indonesian SMEs. These technologies, if strategically introduced through phased adoption and supported by government programs, have the potential to bridge the gap between traditional practices and global digitalization trends, ensuring that SMEs remain competitive while safeguarding food safety and quality.

3.11. Case study and initiative

Several initiatives have been introduced in Indonesia to accelerate digital adoption among food SMEs, though implementation remains uneven. The *Making Indonesia 4.0* roadmap, launched by the Ministry of Industry, identifies the food and beverage sector as one of the priority industries for digital transformation, emphasizing the integration of IoT, automation, and data-driven systems (Kemenperin, 2021). Complementing this, the e-Smart IKM program has trained more than 31,000 SMEs in digital literacy and online marketing, providing a foundation for broader digital engagement (Kemenkop, 2022). Pilot projects in dairy processing and fisheries have demonstrated the potential of IoT sensors for monitoring cold chain logistics, reducing spoilage, and improving compliance with food safety standards (BPOM RI, 2023). In addition, collaborations with technology startups have introduced mobile-based traceability applications for coffee and cocoa SMEs, enabling producers to record batch data and enhance consumer trust in export markets. Despite these promising examples, adoption remains concentrated in larger SMEs or those integrated into global supply chains, while micro-scale enterprises continue to rely on manual practices. This uneven distribution underscores the importance of scaling successful pilot projects into cooperative models, where SMEs can collectively access digital infrastructure and share resources, similar to agrifood clusters observed in Latin America (Tang et al., 2024). Such initiatives, if expanded and aligned with national standards like SNI and international frameworks such as ISO 22000, could significantly strengthen food safety and quality management across Indonesia's SME sector.

Despite the growing recognition of digitalization as a strategic solution for food quality control, Indonesian SMEs face multiple barriers that hinder widespread adoption. Financial constraints remain the most significant challenge, as many SMEs operate with limited capital and perceive digital tools such as IoT sensors or blockchain platforms as costly investments beyond their reach. Digital literacy among SME operators is also limited, with many entrepreneurs lacking the technical skills required to implement and maintain digital systems effectively. Infrastructure disparities, particularly in rural areas, further exacerbate the problem, as unreliable internet connectivity restricts the use of cloud-based platforms and mobile applications (Fauziana et al., 2023). Regulatory fragmentation adds another layer of complexity, with SMEs struggling to align digital practices with national standards such as SNI and international frameworks like ISO 22000, while enforcement remains inconsistent. Comparative evidence suggests that SMEs

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in Latin America and Africa face similar challenges, but collective adoption through agrifood clusters has helped mitigate costs and improve compliance (Tang et al., 2024). In Indonesia, however, SMEs remain largely fragmented, with digital adoption concentrated in larger enterprises or those integrated into export-oriented supply chains. These challenges highlight the urgent need for targeted policies, capacity-building programs, and cooperative models to ensure that digitalization becomes accessible and sustainable for SMEs across the food sector.

The prospects for digitalization in Indonesian food SMEs are promising, provided that adoption strategies are tailored to local constraints and supported by multi-stakeholder collaboration. Phased integration of low-cost digital tools, such as IoT-based monitoring devices and mobile traceability applications, offers a realistic entry point for SMEs with limited resources. Capacity-building programs to enhance digital literacy among SME operators are essential, ensuring that entrepreneurs can effectively utilize and maintain digital systems). Cooperative models, where SMEs collectively access cloud-based platforms and share infrastructure, could reduce costs and improve compliance, drawing lessons from agrifood clusters in Latin America. Policymakers should strengthen regulatory frameworks by aligning national standards such as SNI with international benchmarks like ISO 22000, while providing incentives for SMEs to adopt digital solutions. Academic institutions and industry associations can play a pivotal role in piloting context-specific technologies and disseminating best practices. In the long term, digitalization is expected to enhance food safety, traceability, and consumer trust, while also supporting sustainability and competitiveness in regional and global markets. These recommendations highlight that digital transformation in Indonesian food SMEs is not only feasible but also necessary to bridge the gap between traditional practices and global digitalization trends.

4. Conclusions

Small and medium enterprises (SMEs) in Indonesia's food sector are central to national food security and economic resilience, yet they continue to face persistent challenges in ensuring quality and safety. Global trends demonstrate a rapid shift toward digitalization through IoT, AI, blockchain, and smart packaging, technologies that have significantly enhanced efficiency, traceability, and consumer trust in developed markets. In contrast, Indonesian SMEs remain at an early stage of adoption, with digital tools primarily used for marketing rather than production and quality control. Moving forward, phased integration of low-cost digital solutions, capacity-building programs, and stronger regulatory alignment with international standards are essential to accelerate transformation. By bridging the gap between traditional practices and global digitalization trends, Indonesian food SMEs can enhance food safety, strengthen consumer trust, and improve competitiveness in regional and international markets. This review underscores that digitalization is not merely an option but a necessity for sustaining the future of Indonesia's food industry.

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