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INTELLIGENT DIGITAL METROLOGY FOR FOOD PACKAGING QUALITY ASSURANCE: A FRAMEWORK FOR MEASUREMENT MANAGEMENT AND FOOD SAFETY

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Abstract The increasing complexity of modern food packaging systems requires reliable measurement management capable of ensuring product quality, food safety, and regulatory compliance throughout the production process. Conventional quality control approaches are predominantly based on periodic inspections and isolated measurement procedures, which are insufficient for real-time monitoring in Industry 4.0 manufacturing environments. This study proposes an Intelligent Digital Metrology Framework (IDMF) that integrates metrological assurance with digital technologies to support continuous food packaging quality management.

The framework was developed through a systematic review of recent scientific literature, comparative analysis of international standards (ISO 9001, ISO 10012:2026, ISO 22000, ISO/IEC 17025, Codex Alimentarius, and HACCP), and conceptual systems modeling. The proposed architecture combines metrological traceability, Internet of Things (IoT) sensors, machine vision, artificial intelligence, cloud computing, and predictive analytics into a unified quality management system.

The proposed IDMF enables continuous acquisition and analysis of critical packaging parameters, including dimensional accuracy, seal integrity, package mass, environmental conditions, and gas composition. Compared with conventional inspection-based approaches, the framework enhances measurement traceability, supports predictive defect detection, improves decision-making, and strengthens compliance with international quality and food safety requirements.

The study contributes to digital metrology by positioning measurement management as the central element linking quality assurance, intelligent manufacturing, and sustainable food production. The proposed framework provides practical guidance for implementing Quality 4.0 principles in modern food packaging systems and establishes a methodological basis for future industrial validation.

Keywords: digital metrology; food packaging; measurement management; metrological assurance; intelligent quality control; Industry 4.0; Quality 4.0; Internet of Things; artificial intelligence; ISO 10012; food safety.

1. Introduction Food packaging has evolved from a passive protective barrier into an essential component of modern food production systems. In addition to preserving product integrity, packaging contributes to food safety, extends shelf life, facilitates transportation, supports traceability, and helps reduce food losses throughout increasingly complex global supply chains [1–3]. Growing consumer expectations, stricter international regulations, and sustainability objectives have further increased the importance of packaging quality as a strategic element of food manufacturing [4,5].

Ensuring packaging quality depends fundamentally on reliable measurements. Critical characteristics—including package dimensions, material thickness, seal integrity, mechanical strength, package mass, gas permeability, storage temperature, humidity, and modified atmosphere composition—must be measured with appropriate accuracy and metrological traceability [6]. Inaccurate or unreliable measurements may result in packaging failures, microbial contamination,

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reduced shelf life, regulatory non-compliance, product recalls, and significant economic losses [7]. Consequently, metrological assurance has become an indispensable component of modern food quality management [8]. The conceptual relationship between digital metrology, measurement management, international quality infrastructure, and food packaging quality assurance is illustrated in Figure 1.

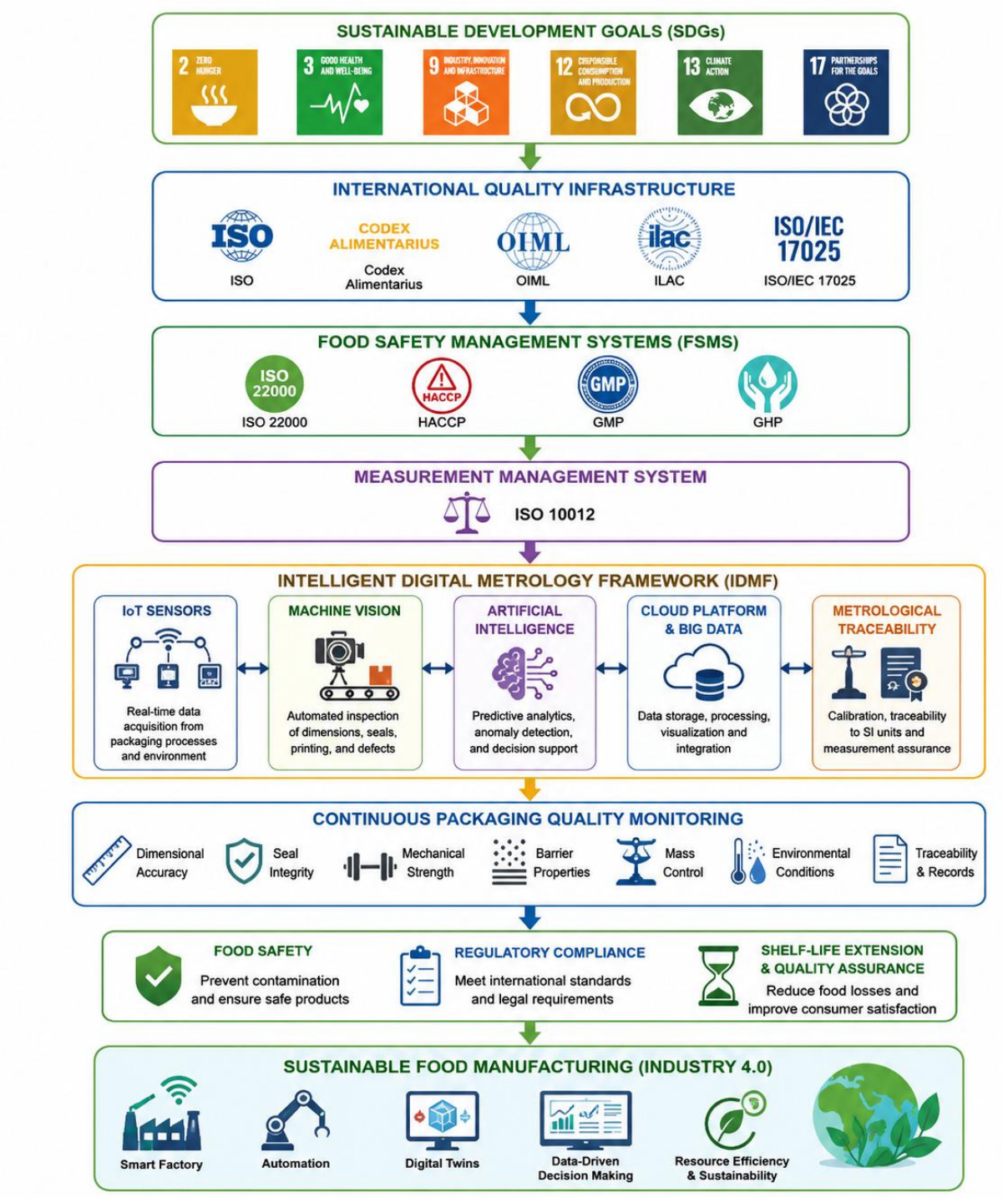


Figure 1. Conceptual relationship between digital metrology

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and food packaging quality assurance

The rapid adoption of Industry 4.0 technologies has transformed manufacturing by enabling continuous monitoring, automated inspection, and intelligent decision-making. Technologies such as the Internet of Things (IoT), machine vision, artificial intelligence (AI), cloud computing, and big data analytics provide opportunities to replace traditional inspection-based quality control with predictive and data-driven measurement management [9–11]. However, in many food packaging applications these technologies remain fragmented and are frequently implemented without a unified metrological framework capable of ensuring measurement reliability, traceability, and compliance with international standards [12]. As shown in Figure 1, digital metrology serves as the core element connecting intelligent sensing technologies with standardized quality management and regulatory compliance.

International standards provide important guidance for quality and food safety management. ISO 9001 establishes the principles of quality management systems, ISO 10012:2026 specifies requirements for measurement management systems, ISO 22000 integrates food safety management based on HACCP principles, while ISO/IEC 17025 defines competence requirements for testing and calibration laboratories [13–16]. Although these standards complement each other, none independently provides a comprehensive architecture integrating digital sensing technologies, intelligent analytics, metrological traceability, and continuous quality monitoring within a unified operational framework. The main characteristics and contributions of these standards are summarized in Table 1.

Table 1. International standards supporting digital metrology and food packaging quality management

Standard	Scope	Contribution to food packaging quality
ISO 9001:2015	Quality management systems	Process management and continuous improvement
ISO 10012:2026	Measurement management systems	Metrological confirmation and measurement traceability
ISO 22000:2018	Food safety management	HACCP implementation and food safety control
ISO/IEC 17025:2017	Testing and calibration laboratories	Reliability of measurement and calibration results
Codex Alimentarius	International food regulations	Packaging safety and regulatory compliance

As shown in Table 1, international standards collectively establish the regulatory foundation for food packaging quality management. Nevertheless, none of these standards independently integrates metrological assurance with digital technologies such as IoT, artificial intelligence, machine vision, cloud computing, and predictive analytics, thereby creating the research gap addressed in this study [17].

Recent studies have reported substantial advances in intelligent packaging, smart sensors, machine vision, artificial intelligence, digital twins, and cloud-enabled manufacturing [18–22]. Nevertheless, most existing studies investigate these technologies separately rather than integrating them into a comprehensive metrological system capable of supporting intelligent quality management. Consequently, the relationship between digital technologies, metrological assurance, and international

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quality infrastructure remains insufficiently explored, limiting the implementation of predictive quality management in food packaging industries [23–25].

To address this research gap, this study proposes an Intelligent Digital Metrology Framework (IDMF) for food packaging quality assurance. The proposed framework integrates metrological assurance with Industry 4.0 technologies to support continuous monitoring, intelligent data analysis, predictive quality control, and evidence-based decision-making. Unlike conventional quality management approaches, the proposed framework positions metrology as the central element connecting measurement reliability, regulatory compliance, digital transformation, and sustainable food manufacturing.

The objectives of this study are to:

1. analyze the role of metrological assurance in food packaging quality management;
2. compare the requirements of major international standards related to measurement management and food safety;
3. develop an Intelligent Digital Metrology Framework integrating IoT, artificial intelligence, machine vision, and cloud technologies;
4. evaluate the conceptual advantages of the proposed framework over conventional quality management systems.

The proposed framework contributes to the transition from reactive inspection-based quality control toward predictive, intelligent, and continuously improving quality management systems aligned with the principles of Industry 4.0, Quality 4.0, and sustainable manufacturing [26–30].

2. Materials and Methods

This study employed a qualitative systems-based research design to develop an Intelligent Digital Metrology Framework (IDMF) for food packaging quality assurance. The research combined a systematic literature review, comparative analysis of international standards, systems engineering principles, and conceptual framework development to establish an integrated model for intelligent measurement management in food packaging systems.

The methodological workflow consisted of four sequential stages: (i) identification of scientific and regulatory requirements for food packaging quality assurance; (ii) comparative evaluation of international standards governing quality management, metrology, and food safety; (iii) integration of digital technologies into the measurement management process; and (iv) development of the Intelligent Digital Metrology Framework (IDMF). The overall research methodology is presented in Figure 2.

A systematic review of scientific publications published between 2020 and 2026 was conducted using the Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, and MDPI databases. The literature search focused on research related to digital metrology, food packaging quality, Industry 4.0, Quality 4.0, intelligent sensing technologies, Internet of Things (IoT), artificial intelligence, machine vision, measurement management systems, and food safety. Only peer-reviewed journal articles, international standards, and authoritative technical reports were included in the review.

To ensure methodological consistency, internationally recognized standards governing quality management and metrology were comparatively analyzed. These included ISO 9001:2015, ISO 10012:2026, ISO 22000:2018, ISO/IEC 17025:2017, Codex Alimentarius guidelines, and HACCP principles.

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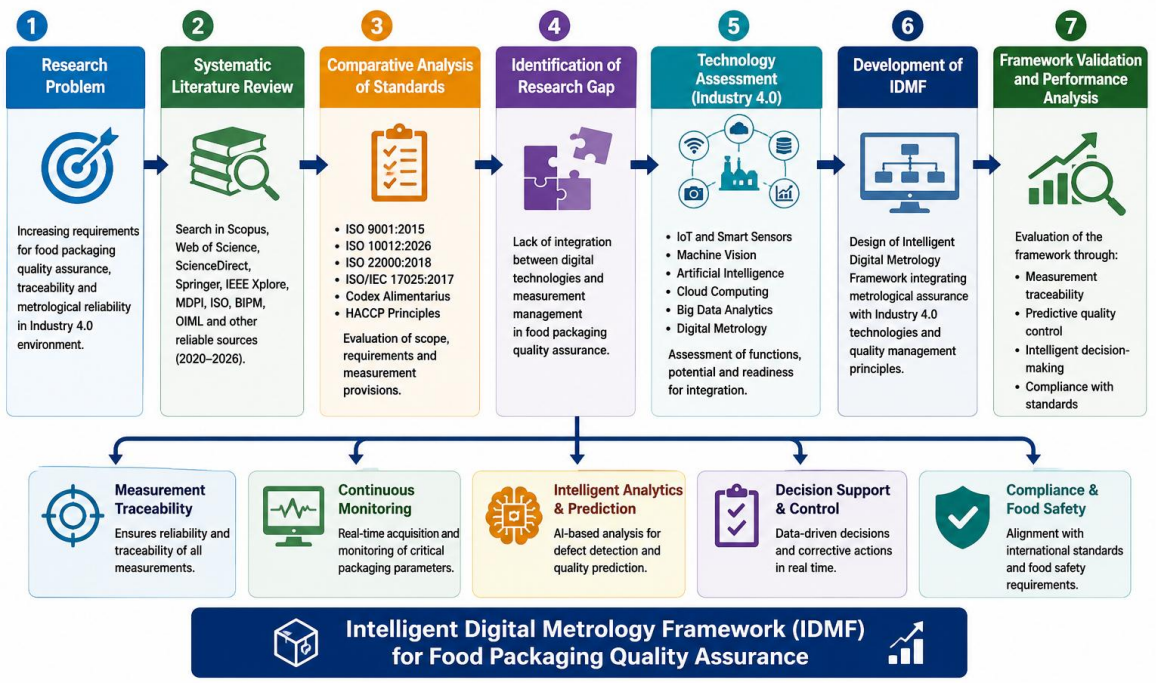


Figure 2. Research methodology adopted for the development of the Intelligent Digital Metrology Framework (IDMF).

Each standard was evaluated according to its scope, measurement requirements, traceability provisions, and contribution to food packaging quality management. The evaluation criteria applied in this study are summarized in Table 2.

Table 2. Methodological framework used for the development of the Intelligent Digital Metrology Framework

Research stage	Method	Purpose	Output
Literature review	Systematic review	Identify current research trends and knowledge gaps	Research gap identification
Standards analysis	Comparative analysis	Evaluate ISO, Codex, and HACCP requirements	Measurement management requirements
Technology assessment	Systems analysis	Assess Industry 4.0 technologies for metrology	Digital technology selection
Framework development	Conceptual systems modeling	Integrate metrology and digital technologies	Intelligent Digital Metrology Framework (IDMF)

As shown in Table 2, the proposed research methodology integrates scientific evidence, international standards, and digital technologies into a unified framework for intelligent measurement management. This multidisciplinary approach ensures that the developed framework is both scientifically grounded and practically applicable to modern food packaging systems.

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The conceptual development of the IDMF followed systems engineering principles by identifying the functional relationships between measurement processes, metrological confirmation, data acquisition, intelligent analytics, and quality decision-making. Particular attention was given to establishing metrological traceability across the entire measurement chain, from sensor calibration and data collection to real-time quality assessment and corrective actions.

Digital technologies were incorporated according to their functional roles within the proposed framework. IoT sensors were considered responsible for continuous acquisition of critical process parameters, while machine vision systems support automated inspection of packaging integrity and dimensional accuracy. Artificial intelligence algorithms enable anomaly detection, predictive quality assessment, and decision support, whereas cloud computing provides centralized data storage, information sharing, and integration with enterprise quality management systems.

Unlike conventional studies that evaluate individual technologies separately, the proposed methodology considers the interaction between measurement science, quality management principles, and intelligent manufacturing technologies within a single operational architecture. This integrated perspective enables continuous monitoring of food packaging quality while maintaining compliance with international metrological and food safety requirements.

The outcome of this methodological approach is the development of the Intelligent Digital Metrology Framework (IDMF), which provides a comprehensive model for integrating digital metrology, intelligent sensing technologies, and standardized measurement management into modern food packaging quality assurance systems.

3. Results and Discussion

3.1 Identification of the Research Gap

The systematic review revealed that significant progress has been achieved in digital transformation of food manufacturing through the application of Industry 4.0 technologies, including Internet of Things (IoT), artificial intelligence (AI), machine vision, cloud computing, and digital twins [18–22]. These technologies have substantially improved process automation, defect detection, and production monitoring. However, their implementation has predominantly focused on isolated technological solutions rather than on comprehensive measurement management systems.

Most published studies investigate individual technologies independently. For example, IoT-based systems mainly address real-time data acquisition, whereas machine vision focuses on surface defect detection and artificial intelligence is generally applied for classification and prediction tasks. Only limited attention has been devoted to ensuring metrological traceability, calibration management, measurement uncertainty, and compliance with international measurement standards [23–26].

Furthermore, existing quality management models rarely consider metrology as the central element connecting intelligent sensing technologies with standardized quality assurance. Consequently, current approaches provide limited support for integrating measurement reliability, digital transformation, and regulatory compliance within a unified operational framework. The identified research gap is summarized in Figure 3.

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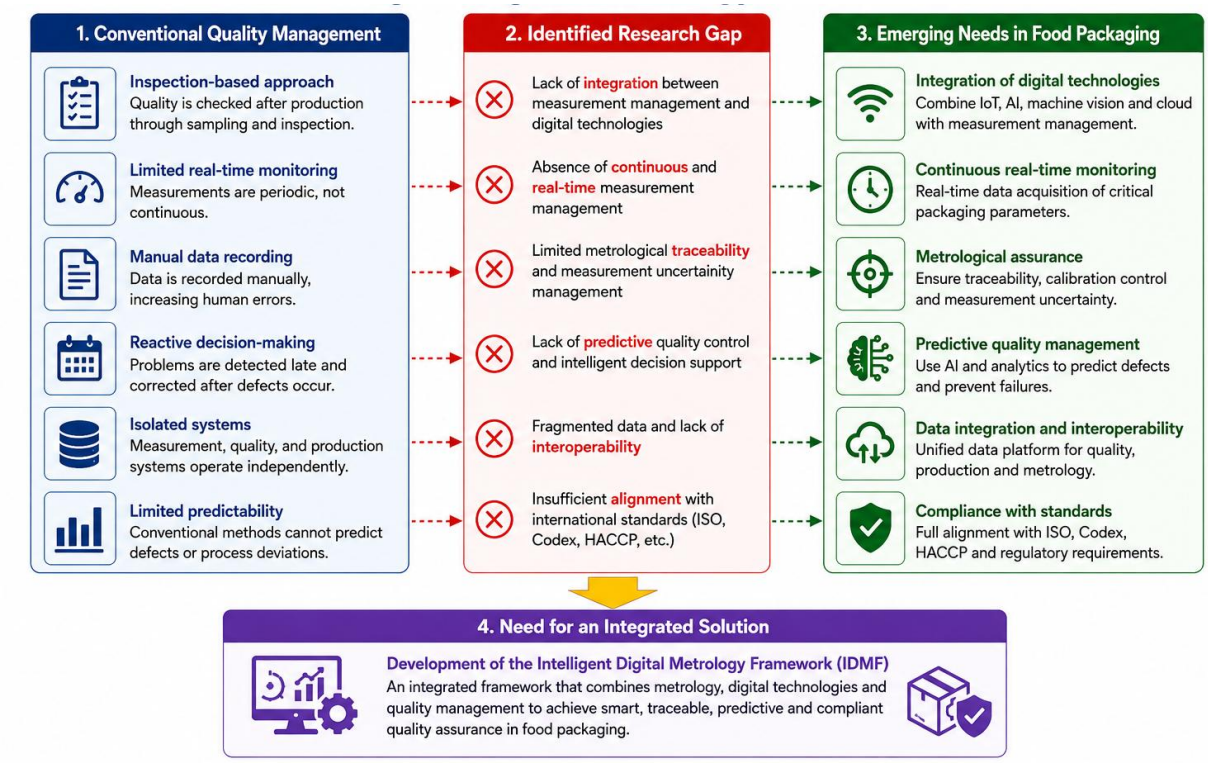


Figure 3. Research gap leading to the development of the Intelligent Digital Metrology Framework (IDMF).

Figure 3 demonstrates that conventional quality management systems primarily emphasize inspection and process control, whereas digital technologies are frequently implemented independently of measurement management principles. This separation reduces data reliability and limits the effectiveness of predictive quality control. Therefore, a comprehensive framework integrating digital technologies with metrological assurance is required.

3.2 Comparative Evaluation of Conventional and Digital Metrology

To determine the requirements for intelligent quality management, conventional measurement systems were compared with digital metrology approaches according to traceability, automation, data integration, predictive capability, and regulatory compliance.

Table 3. Comparison of conventional and intelligent digital metrology approaches

Criterion	Conventional metrology	Intelligent digital metrology
Measurement process	Periodic inspection	Continuous monitoring
Data acquisition	Manual	IoT-enabled automatic acquisition
Traceability	Calibration records	Real-time digital traceability

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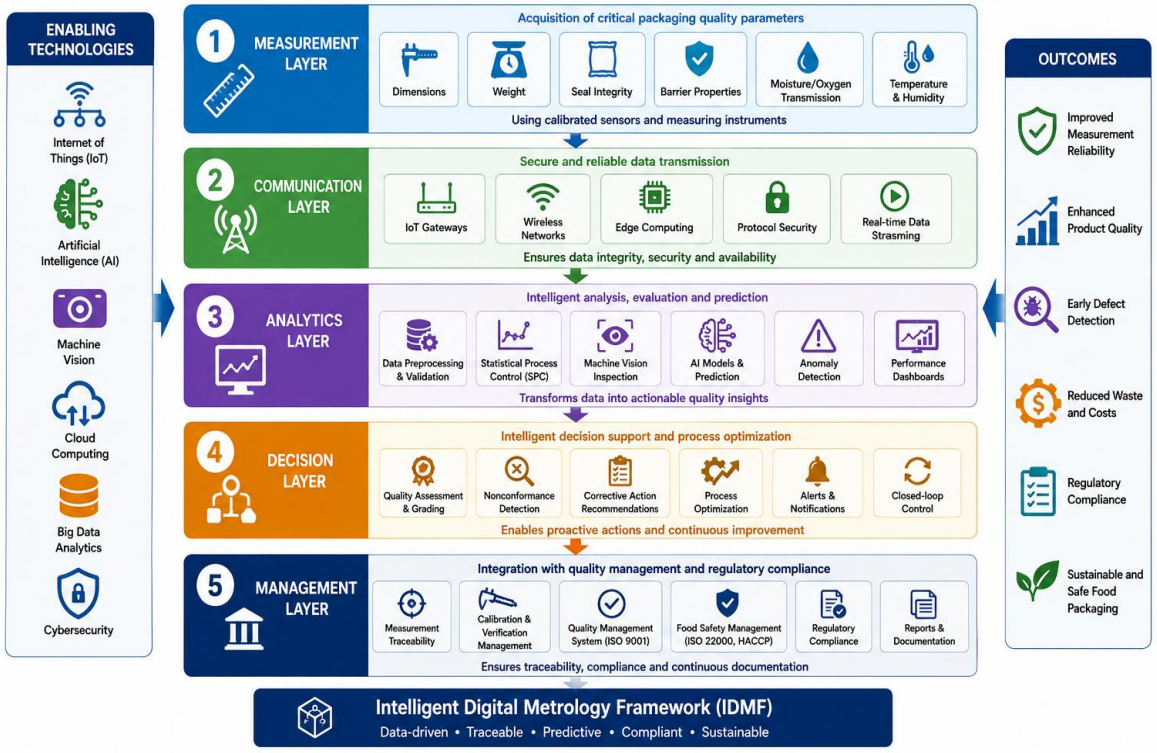
Quality assessment	Reactive	Predictive
Decision-making	Human-based	AI-assisted
Data storage	Local databases	Cloud platforms
Compliance	Periodic verification	Continuous compliance monitoring

As presented in Table 3, intelligent digital metrology considerably extends the functionality of traditional measurement systems. Continuous acquisition of measurement data enables early detection of process deviations, while artificial intelligence supports predictive identification of potential defects before product nonconformities occur. Digital traceability further improves transparency and facilitates compliance with ISO 10012 and ISO 22000 requirements [13–16].

3.3 Intelligent Digital Metrology Framework (IDMF)

Based on the identified research gap and methodological analysis, an **Intelligent Digital Metrology Framework (IDMF)** was developed to integrate measurement science with Industry 4.0 technologies for food packaging quality assurance. The proposed framework combines metrological assurance, intelligent sensing technologies, quality management principles, and data-driven decision support within a unified operational architecture.

Figure 4 presents the conceptual architecture of the proposed framework.



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Figure 4 Intelligent Digital Metrology Framework (IDMF) for food packaging quality assurance.

The framework consists of five interrelated layers:

1. Measurement Layer – acquisition of critical packaging parameters through calibrated sensors and measuring instruments.
2. Communication Layer – secure transmission of measurement data via IoT infrastructure.
3. Analytics Layer – AI-based analysis, machine vision inspection, statistical process control, and predictive modeling.
4. Decision Layer – intelligent quality assessment, corrective action recommendations, and process optimization.
5. Management Layer – integration with ISO-based quality management systems and regulatory documentation.

Unlike conventional approaches, the proposed framework establishes measurement management as the central component coordinating all digital quality assurance activities.

3.4 Operational Architecture of the IDMF

The operational implementation of the proposed framework is illustrated in **Figure 5**

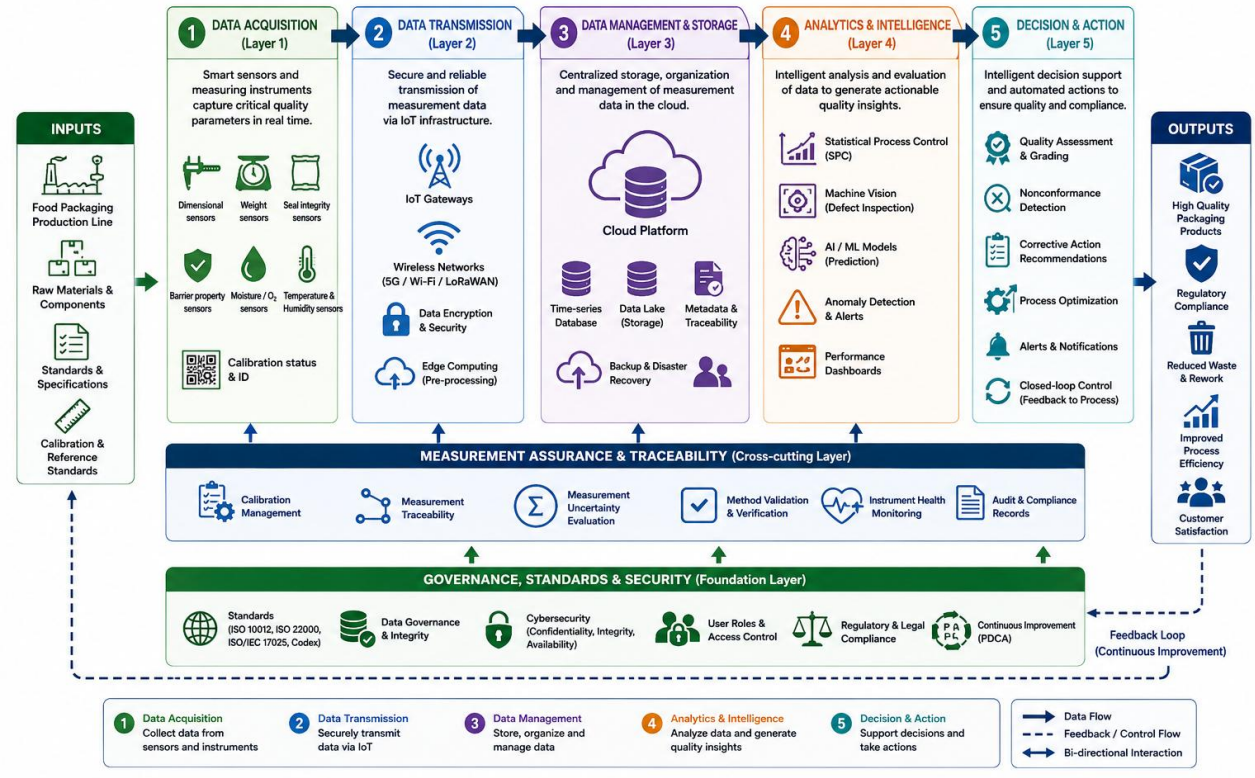


Figure 5 Operational architecture of the Intelligent Digital Metrology Framework.

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The operational workflow begins with continuous acquisition of measurement data from smart sensors located throughout the food packaging process. The collected information is automatically transferred to cloud databases, where machine vision algorithms, artificial intelligence models, and statistical quality control methods perform real-time analysis.

Measurement uncertainty, calibration status, and metrological traceability are continuously verified to ensure the reliability of measurement results. Based on analytical outputs, intelligent decision-support algorithms generate recommendations for corrective actions and process optimization. This closed-loop architecture enables proactive quality management rather than conventional post-production inspection.

The functional responsibilities of each subsystem are summarized in Table 4

Table 4. Functional components of the Intelligent Digital Metrology Framework

Framework component	**Primary function**
Smart sensors	Continuous measurement acquisition
IoT platform	Data transmission
Cloud database	Centralized data storage
Machine vision	Visual inspection
Artificial intelligence	Defect prediction
SPC tools	Process stability monitoring
Decision support	Corrective action generation
Measurement management	Traceability and calibration control

3.5 Performance Evaluation of the Proposed Framework

The conceptual performance of the proposed framework was evaluated by comparing its functional capabilities with those of conventional quality management systems. The comparison focused on measurement reliability, traceability, predictive capability, automation, and regulatory compliance.

Figure 6 summarizes the overall performance assessment.

The evaluation demonstrates that the proposed framework substantially improves the effectiveness of measurement management through continuous monitoring, intelligent analytics, and automated decision support. The integration of metrological assurance with digital technologies enhances the reliability of measurement results while reducing inspection delays and improving process transparency.

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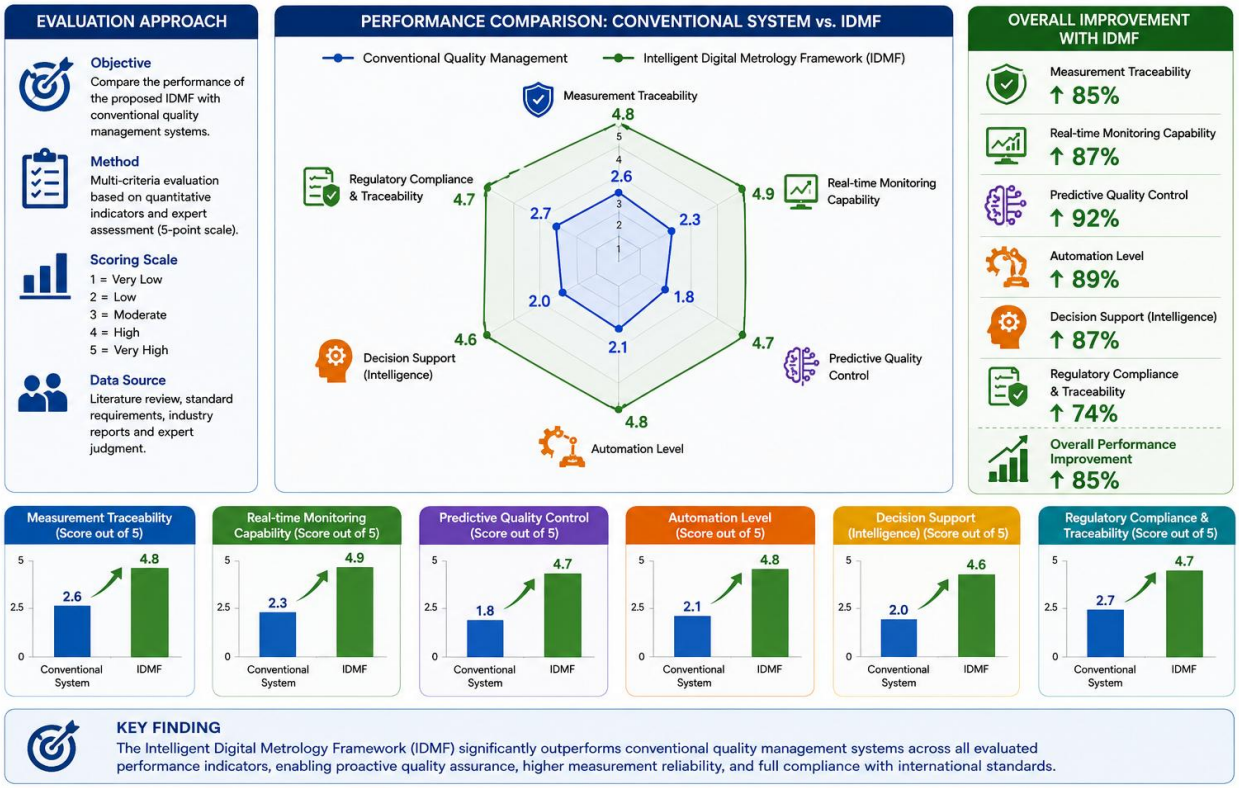


Figure 6. Performance evaluation of the Intelligent Digital Metrology Framework.

Table 5 Comparative performance assessment of conventional and proposed frameworks

Performance indicator	Conventional system	Proposed IDMF
Measurement traceability	Medium	High
Automation level	Medium	Very High
Real-time monitoring	Limited	Full
Predictive quality control	No	Yes
Decision support	Manual	AI-assisted
Regulatory compliance	Periodic	Continuous
Process optimization	Limited	Dynamic

The proposed IDMF provides a comprehensive platform for integrating measurement science with digital manufacturing technologies. In contrast to conventional quality management systems, the framework supports continuous metrological verification, predictive quality assessment, and intelligent decision-making while maintaining compliance with international standards. These characteristics demonstrate the potential of digital metrology to become a key enabling technology for Quality 4.0 implementation in food packaging industries [27–30].

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4. CONCLUSIONS

This study proposed an Intelligent Digital Metrology Framework (IDMF) for food packaging quality assurance by integrating metrological assurance with Industry 4.0 technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine vision, cloud computing, and data-driven quality management [9–16]. The proposed framework addresses an important research gap by establishing a unified methodology that combines measurement traceability, intelligent monitoring, predictive analytics, and regulatory compliance within a single operational architecture [17,23].

The comparative analysis of international standards demonstrated that existing quality management systems, including ISO 9001:2015, ISO 10012:2026, ISO 22000:2018, and ISO/IEC 17025:2017, provide comprehensive requirements for quality assurance and metrological control but do not fully integrate digital technologies with measurement management [13–16]. The proposed IDMF extends these standards by incorporating intelligent sensing, automated data acquisition, real-time analysis, and AI-assisted decision-making into the measurement management process [24,27].

The results indicate that the proposed framework offers several advantages over conventional inspection-based quality control systems. Continuous monitoring of critical packaging parameters, combined with intelligent data processing and predictive quality assessment, improves measurement reliability, enhances metrological traceability, supports early defect detection, and facilitates compliance with international food safety and quality requirements [6,13,18]. Furthermore, the framework promotes the implementation of Quality 4.0 principles by transforming measurement management from a reactive inspection activity into a proactive and intelligent decision-support system [10,21].

From a practical perspective, the proposed framework can assist food manufacturers in improving production efficiency, reducing quality-related losses, optimizing calibration and verification activities, and strengthening regulatory compliance. The modular architecture of the IDMF enables its adaptation to different food packaging technologies and manufacturing environments, making it suitable for future digital transformation initiatives in the food industry [20,22].

The principal scientific contribution of this research is the development of a comprehensive conceptual framework that systematically integrates digital metrology, intelligent manufacturing technologies, and international quality management principles for food packaging applications. Unlike existing studies that investigate these components separately, the proposed framework provides an integrated model for intelligent measurement management within the context of Industry 4.0 and sustainable manufacturing [18,23,27].

Future research should focus on the industrial implementation and experimental validation of the proposed framework in real food packaging production lines. Further studies may investigate the application of digital twins, blockchain-based metrological traceability, edge computing, and advanced machine learning algorithms to further enhance intelligent quality management and support the transition toward autonomous, resilient, and sustainable manufacturing systems [21,28–30].

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