

# Systematic Literature Review on Integrating Macro and Micro Analytical Approaches for Food Quality, Safety, and Security in Modern Food Manufacturing

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## ABSTRACT

Food quality, food safety, and food security are interrelated yet distinct. Ensuring food quality, safety, and security in modern manufacturing requires analytical systems capable of capturing both product level attributes and molecular scale variations. This review synthesizes recent advancements (2020–2026) in macro and micro analytical approaches and evaluates their combined potential to strengthen quality assurance across diverse food sector. Macrolevel methods including physical, sensory, and proximate analyses provide rapid, non-destructive assessments of texture, colour, composition, and consumer relevant attributes. In contrast, microlevel techniques such as microbial enumeration, chromatography, spectroscopy, molecular diagnostics, and metabolomics offer high resolution insights into contamination risks, biochemical transformations, and authenticity verification. Integrating these analytical scales creates a complementary framework that enhances traceability, supports regulatory compliance, and improves early detection of deviations in processing environments. The review highlights industrial applications in dairy, meat, cereal, and ready-to-eat foods, demonstrating how multiscale analytical strategies improve product consistency and safety outcomes. Emerging trends including AI-assisted analytics, biosensors, hyperspectral imaging, digital twins, and portable rapid testing platforms are accelerating the transition toward intelligent, data driven food systems. Sustainability-driven innovations such as green analytical chemistry and circular economy monitoring further expand the role of analytical science in resilient food production. While the review provides comprehensive coverage, limitations include variability in analytical protocols across studies, restricted access to nonindexed industrial data, and the early-stage maturity of several emerging technologies. Overall, the integration of macro and micro analytical approaches represents a critical pathway toward building transparent, efficient, and sustainable food manufacturing systems capable of meeting global quality and safety demands.

**Keywords:** Food quality; food safety; food security; macro analysis; micro analysis; food manufacturing

## INTRODUCTION

Food quality refers to various attributes primarily related to sensory characteristics, shelf-life, and freshness of food; however, microbiological and technological parameters also play an important role in quality food. Food quality emphasizes on fulfilling the customer expectations (Dhal & Kar, 2025). Achieving consistent quality is difficult when involving global supply chains and different standards (Dhal & Kar, 2025).

Every year, food-borne diseases outbreak has been reported across different food categories and is a concern in food processing (Hassoun, Jagtap, Trollman, et al., 2023). The contamination of food with the pathogenic microorganisms such as *Salmonella spp.* is one of the reasons the outbreak repeatedly occurring (Hassoun, Jagtap, Trollman, et al., 2023). Besides that, toxic contaminants such as pesticides, mycotoxins, and sanitizer from different sources are also reported in food recall events (Hassoun, Jagtap, Trollman, et al., 2023). Food

safety safeguards the food free from spoilage pathogens, toxins, and contaminants, thereby protecting public health (Dhal & Kar, 2025). Emerging technology, such as the mixture toxicology, where it evaluates combined exposure rather than individual risk, is getting popular for enhancing consumer protection (Dhal & Kar, 2025).

Food security ensures available, accessible, and safe food for everyone. The factors such as climate change, urbanization, and limited resources intensify the food system vulnerabilities (Dhal & Kar, 2025). The solution such as food valorisation, which turns waste into useful products and thus, promote sustainability (Dhal & Kar, 2025). The key aspect of food security, food adulteration, a dishonest activity conducted by using low nutritional and quality raw materials, and the materials are from unknown origin to gain extra profit and deceive consumers (Hassoun, Jagtap, Trollman, et al., 2023).

These three aspects, food quality, food safety, and food security are interconnected yet distinct. Hazardous food products erode quality and security, while food supply shortage undermines security regardless of the food safety or food quality (Dhal & Kar, 2025). Pressures from population rise, climate change, and shifting consumer needs are further amplify these issues (Dhal & Kar, 2025).

Ensuring food quality, safety, and security has become increasingly complex due to globalized supply chains, evolving consumer expectations, and emerging biological and chemical hazards (Ahmad et al., 2025). Modern food manufacturing must therefore adopt analytical systems capable of detecting deviations at both the product and molecular levels. Macrolevel analytical approaches such as physical, sensory, and proximate analyses offer rapid assessments of food attributes that influence consumer acceptance and regulatory compliance (Nguyen et al., 2022). However, these methods alone cannot capture the biochemical, microbial, and molecular changes that underpin spoilage, contamination, and adulteration (Ahmad et al., 2025).

Microlevel analytical techniques, including microbial enumeration, spectroscopy, chromatography, and molecular diagnostics, provide deeper insights into food composition and safety risks. Yet they often require specialized equipment, longer processing times, and expert interpretation (Gao et al., 2026).

The integration of macro and micro analytical approaches has emerged as a powerful strategy to enhance food quality assurance, improve traceability, and strengthen food security frameworks. Despite growing interest, existing literature often treats macro and micro analyses separately, with limited discussion on their synergistic potential (Ahmad et al., 2025). This review addresses this gap by synthesizing recent advancements (2020–2026) and evaluating how integrated analytical systems can support modern food manufacturing. The scope includes analytical principles, industrial applications, safety frameworks, and future technological trends (Gao et al., 2026).

## Macrolevel Analytical Approaches

### Physical Analysis

Physical analysis provides the first layer of quality assessment in food manufacturing by evaluating measurable attributes such as texture, colour, viscosity, and structural integrity. These parameters directly influence consumer perception and acceptance, making them critical indicators of product consistency.

Textural parameters including hardness, cohesiveness, springiness, gumminess, and chewiness are evaluated using instrumental methods (Hassoun, Jagtap, Garcia-Garcia, et al., 2023).

Texture Profile Analysis (TPA) quantifies hardness, cohesiveness, springiness, and chewiness, enabling manufacturers to monitor changes caused by formulation adjustments or processing conditions. Colour, a crucial parameter that has strong impact on consumer acceptance (Hassoun, Jagtap, Garcia-Garcia, et al., 2023). Colorimetry using the CIE Lab\* system allows objective measurement of colour deviations, which is particularly important for products like dairy, meat, and beverages where colour is associated with freshness and quality (Hassoun, Jagtap, Garcia-Garcia, et al., 2023).

L\* (luminosity), a\* (redness-greenness), b\* (yellow-blueness) are the three coordinates determine the exact colour of a food product in a three-dimensional colour sphere (Hassoun, Jagtap, Garcia-Garcia, et al., 2023). Rheological measurements, including viscosity and flow behaviour, help assess the stability of emulsions, gels,

and suspensions. Together, these physical analyses offer rapid, non-destructive insights that support realtime decision-making and process optimization (Sutariya et al., 2026).

### **Proximate Analysis**

Proximate analysis forms the foundation of nutritional and compositional evaluation in food quality control. It quantifies key components such as moisture, ash, protein, fat, fibre, and carbohydrates using standardized AOAC methods.

Moisture content influences microbial stability and shelf life, while ash content reflects mineral composition and potential adulteration (Omosibi et al., 2026). Protein and fat analyses are essential for nutritional labelling and regulatory compliance, especially in dairy, meat, and plant-based products.

Fiber and carbohydrate measurements contribute to understanding energy content and functional properties. Proximate analysis is widely used due to its reliability, cost-effectiveness, and relevance across diverse food categories.

In modern manufacturing, automated systems and rapid analytical tools have enhanced the speed and accuracy of proximate measurements, enabling tighter control over product specifications and batch-to-batch consistency (Wulandari et al., 2026).

### **Sensory Evaluation**

Sensory evaluation remains a cornerstone of food quality assessment because it captures human perception an aspect that instrumental methods cannot fully replicate.

Through structured sensory panels, trained assessors or consumers evaluate attributes such as aroma, taste, texture, and appearance (Ahmad et al., 2025). Descriptive analysis provides detailed sensory profiles that guide product development, reformulation, and quality improvement.

Hedonic testing measures consumer liking and acceptance, offering insights into market potential. Sensory evaluation is particularly valuable when assessing subtle changes caused by ingredient substitutions, processing variations, or storage conditions. Although subjective, sensory methods are increasingly supported by instrumental techniques such as electronic noses and tongues, which help correlate human perception with measurable chemical or physical parameters (Wulandari et al., 2026).

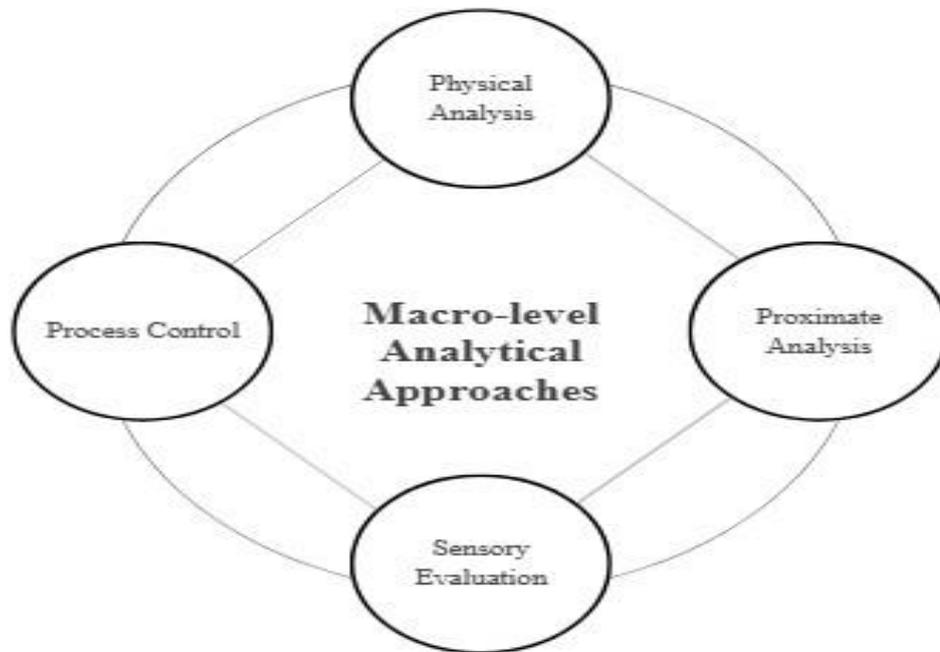
### **Process Control Systems**

During processing, quality control activities are essential to keep a check on processing conditions and food qualities, as well as their compliance with specification. Laboratory infrastructure, equipment, trained and skilled laboratory technicians, reagents and solvents, and extended duration are required for conducting these activities (Hiruy et al., 2024).

Process control systems integrate analytical tools into manufacturing lines to ensure continuous monitoring and rapid detection of deviations. In-line sensors such as Near-Infrared (NIR) spectroscopy Near-Infrared (NIR) spectroscopy, hyperspectral imaging, and laser scattering provide real-time data on moisture, composition, and surface characteristics (Yu et al., 2026). These technologies enable manufacturers to detect defects early, reduce waste, and maintain consistent product quality.

Off-line laboratory testing complements in-line systems by providing more detailed analyses when anomalies are detected. Statistical Process Control (SPC) tools, including control charts and capability indices, help track process stability and identify trends that may indicate emerging issues.

With the rise of Industry 4.0, digital monitoring platforms and automated feedback loops are increasingly used to optimize processing conditions, enhance traceability, and support predictive maintenance (Lauriau et al., 2026). Figure 1 shows the overview of macrolevel analytical approaches used in this review.



**Figure 1: Macro-level analytical approaches used in this review. Author’s own synthesis for clarity.**

## Microlevel Analytical Approaches

### Microbial Analysis

Microbial analysis is essential for ensuring food safety by detecting spoilage organisms and pathogenic microorganisms. Traditional methods such as total plate count, yeast and mold enumeration, and selective culturing remain widely used due to their reliability and regulatory acceptance. However, these methods can be time-consuming, prompting the adoption of rapid microbial detection technologies. Polymerase Chain Reaction (PCR), quantitative PCR (qPCR), and immunoassays enable faster and more sensitive detection of pathogens such as *Salmonella*, *Listeria monocytogenes*, and *E. coli* O157:H7. Rapid microbial testing kits, including ATP bioluminescence and lateral flow assays, support on-site verification and environmental monitoring. These micro-level analyses play a critical role in hazard identification, shelf-life prediction, and compliance with food safety standards.

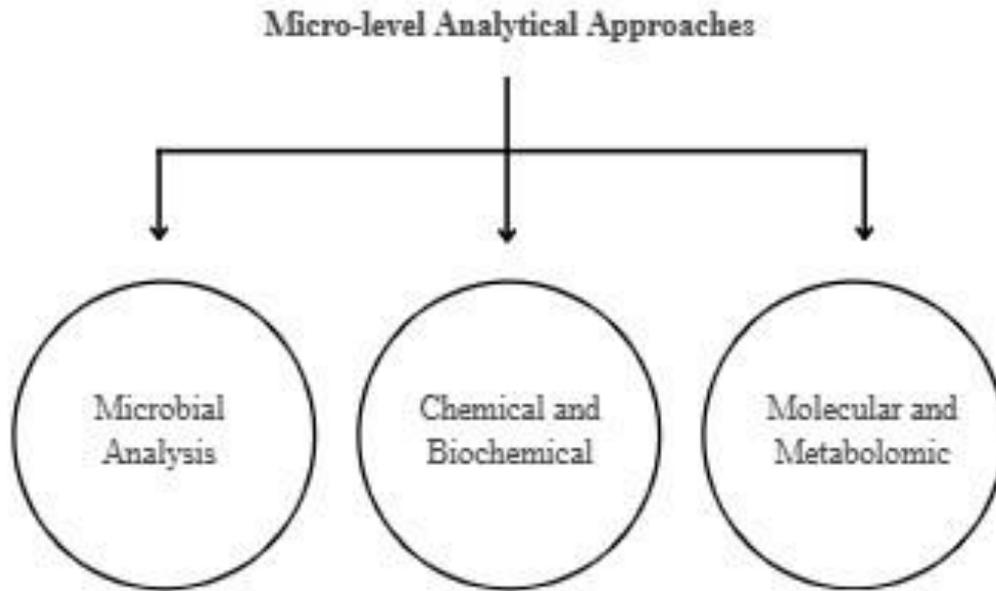
### Chemical and Biochemical Analysis

Chemical and biochemical analyses provide detailed insights into the molecular composition and chemical changes occurring in food products. Chromatographic techniques such as HPLC, GC-MS, and LC-MS/MS are widely used to quantify nutrients, contaminants, additives, and bioactive compounds. Spectroscopic methods, including FTIR, Raman, and UV-Vis spectroscopy, offer rapid, non-destructive alternatives for assessing chemical fingerprints and detecting adulteration. Enzyme activity assays help monitor biochemical reactions related to spoilage, fermentation, and quality degradation (Tan et al., 2025). These analytical tools are indispensable for verifying authenticity, detecting chemical hazards, and understanding the mechanisms underlying food deterioration. Advances in chemometrics and machine learning have further enhanced the interpretability of complex chemical datasets.

### Molecular and Metabolomic Characterization

Molecular and metabolomic techniques provide high-resolution insights into the genetic, structural, and metabolic characteristics of food systems. DNA-based assays such as DNA barcoding, qPCR, and metagenomics enable precise identification of species, detection of adulteration, and characterization of microbial communities (Wang et al, 2022). Microscopy techniques including Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Confocal Laser Scanning Microscopy (CLSM) reveal microstructural features that influence texture, stability, and processing behaviour. Metabolomics, using platforms like NMR and mass spectrometry, allows comprehensive profiling of metabolites associated with flavour, spoilage, and authenticity.

These advanced techniques support deeper understanding of food matrices and provide powerful tools for research, quality assurance, and regulatory enforcement. Figure 2 shows the overview of micro-level analytical approaches used in this review.



**Figure 2: Micro-level analytical approaches used in this review. Author’s own synthesis for clarity.**

### **Integrating Macro and Micro Analysis**

#### **Complementary Strengths**

Integrating macro and micro analytical approaches create a more robust and holistic framework for food quality assurance. Macro-level analyses offer rapid screening and provide immediate insights into physical and sensory attributes, while micro-level techniques deliver detailed information on chemical composition, microbial safety, and molecular integrity.

When combined, these methods enable manufacturers to detect deviations early, validate findings across multiple analytical layers, and ensure comprehensive quality control.

This integrated approach enhances reliability, reduces false positives or negatives, and supports more informed decision-making throughout the production process.

#### **Industrial Case Studies**

Several food sectors have demonstrated the value of integrating macro and micro analyses. In dairy industry, milk adulteration involves dilution of milk with water or whey, addition of nitrogen sources such as melamine, urea, non-diary proteins, ammonium salts to cover up the reduction of protein content in milk, addition of substances such as vegetable oils, sucrose, sodium chloride, surfactants that modify the physiochemical properties of diluted milk and prolong the shelf life of milk (Silva & Rocha, 2020).

Traditional analytical approaches, for instance, Kjeldahl and Dumas methods cannot detect the fraud as the methods are non-selective to protein and measure the total content of nitrogen (Silva & Rocha, 2020). Some other limitations include timeconsuming, require extensive use of reagents, which always lead to low sample yield and delay in decision making about the fraud milk samples (Silva & Rocha, 2020).

At present, Near-infrared (NIR) spectroscopy is the standard procedure used in the industry to evaluate the balance of the total content of proteins and fats in the milk samples (Silva & Rocha, 2020). Digital images also

being used to monitor the milk quality and safety parameters such as colour of milk, common foreign substances, and *Lactobacillus* in fermented milk (Silva & Rocha, 2020).

In cheese production, analysis of fat fraction, molecular-biological and immunological approaches have been utilised to identify the animal species in milk-based products (Rau et al., 2020). Besides that, mass spectrometry is employed to analyse the protein profiles to differentiate the animal species (Rau et al., 2020).

In meat industry, various analytical techniques have been utilised to prevent the adulteration of meat and meat products, for examples, mixing meat products with low-quality and fake food or adding of non-food grade additives to improve consumer acceptance (Du et al., 2023).

Nucleic acid-based polymerase chain reactions (PCR) have been widely used in discriminating the species of meat products (Du et al., 2023). Protein-based enzyme-linked immunosorbent assay, and metabolite-based detection techniques are employed for detection of meat and meat products authenticity (Du et al., 2023). These techniques are effective in identifying the species of raw meat (Zhang et al., 2023).

The techniques are less sensitive to processed meat products because protein denaturation can occur particularly when the meat ingredients are processed with heat treatment (Zhang et al., 2023). Morphological approach is convenient to operate and has been used in detecting the fraud in meat and meat products, but it cannot be applied to processed food due to these items are lack of specific morphological properties (Zhang et al., 2023).

Mycotoxins are naturally compounds found in agricultural products particularly the oilseeds, nuts cereal grains and dried fruits (Golge & Kabak, 2020). Deoxynivalenol (DON) and zearalenone (ZEA) are the main mycotoxins found in cereal grains, and cereal-based foods and feedstuffs (Golge & Kabak, 2020). LCMS/MS based multimethod offers quick detection by quantifying multiple mycotoxins in foods and feedstuffs (Kunz et al., 2020).

To gain more profit, the adulteration happens such as mixing of low-quality and cheap white rice with premium grade basmati rice due to the colour, shape of rice adulterant is look alike to the premium grade basmati rice and it is hard to differentiate using naked eyes or human sensory methods (Arslan et al., 2022).

DNA-based techniques, chromatography techniques, PCR, X-ray fluorescence are used to monitor the adulteration of rice but limitations such as ultrapure samples, sophisticated operation of instruments, time consuming, and destructive sample preparations may require restrict the application (Arslan et al., 2022). Colorimetric sensor array that based on chemo-responsive dyes produces colour difference map has been applied to detect and differentiate complex volatile compounds in the rice samples (Arslan et al., 2022).

Fraud adulteration is persistently observed in the spices industry by incorporating low-quality and low-grade produce, or extraneous matters into the spices products (Negi et al., 2021).

The adulteration can be categorized into intentional adulteration and accidental adulteration (Negi et al., 2021). Intentional adulteration is unapproved substance such as dyes, mineral oil, floral parts are added into spices to enhance the sensory profile of spices (Negi et al., 2021).

While for accidental adulteration, insect and their excreta, larvae, fragments, and aflatoxin secretion are found in the spices which promoting microbial activity and spoilage (Negi et al., 2021). To identify the adulterant, colour, shape, odour, and texture of spices are examined by microscopic method to observe their internal tissue features, structural, and cellular (Negi et al., 2021).

Chromatography, spectroscopy, immunology, and electrophoresis, molecular techniques are also being used for adulterant detection (Negi et al., 2021).

### **Traceability and Consistency**

Integrated analytical systems play a crucial role in enhancing traceability and ensuring product consistency across supply chains. Digital platforms that combine macro-level sensor data with micro-level laboratory results enable real-time monitoring and historical tracking of quality parameters.

Blockchain technologies further strengthen traceability by creating immutable records of analytical results, processing conditions, and supply chain movements. This integration supports transparency, facilitates rapid recall management, and builds consumer trust in food products. Figure 3 shows the integration of macro- and micro-levels analyses data with digital platform and blockchain technology support the food traceability.

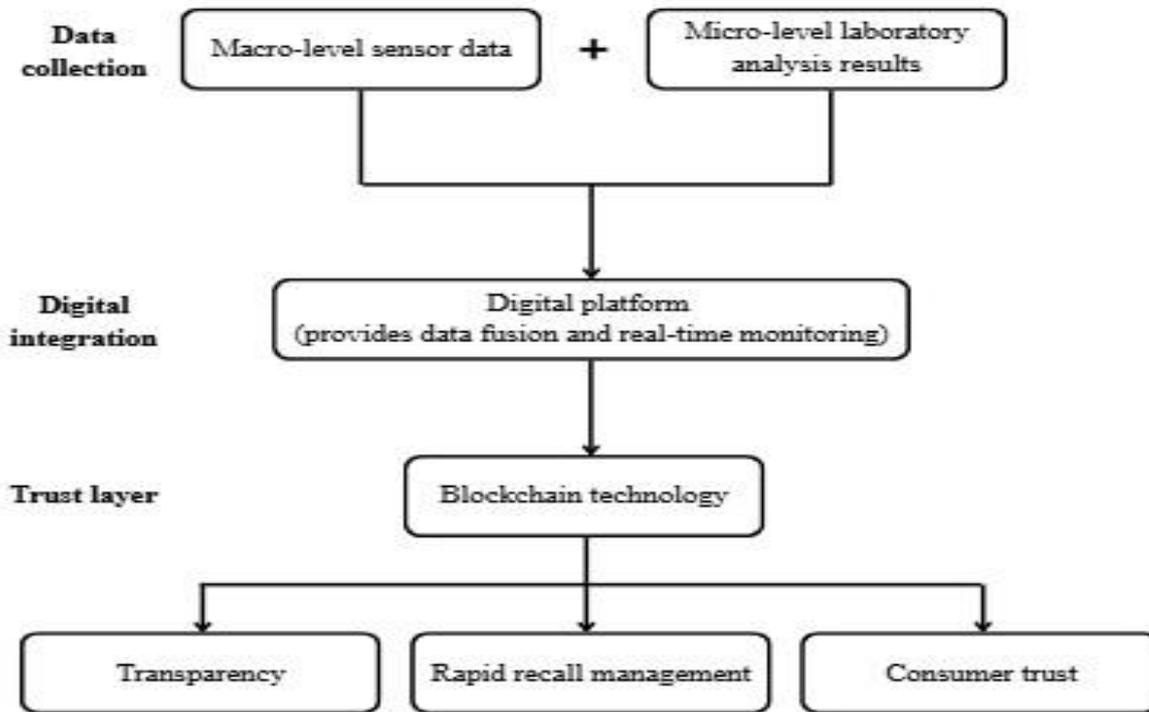


Figure 3: The synergy among analytical methods, digital, and blockchain technologies has improve the food supply chain traceability.

## METHODOLOGY

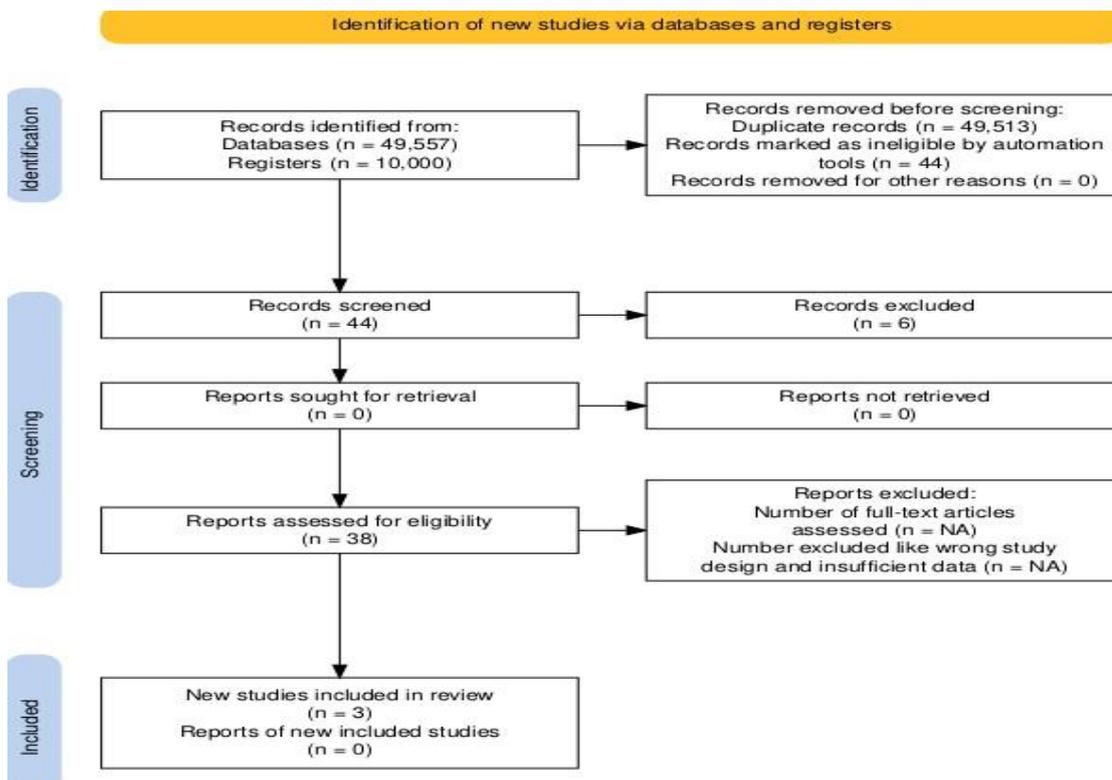


Figure 4: Flowchart of PRISMA diagram through identification of studies for the “Integrating Macro and Micro Analytical Approaches for Food Quality, Safety, and Security in Modern Food Manufacturing.”

This review adopted a structured systemic approach to identify, evaluate, and synthesize recent literature on macro and micro analytical methods used in food quality, safety, and security. A comprehensive search was conducted across major scientific databases from Scopus focusing on publications from 2020 to 2026 to ensure recency and relevance. The inclusive database and reports were screened using the software known as *Rayyan*. The search strategy incorporated combinations of keywords such as “food quality analysis,” “macro analytical methods,” “micro analytical techniques,” “food safety,” “food security,” “spectroscopy,” “chromatography,” and “microbial analysis,” using Boolean operators (AND/OR) to refine results.

Inclusion criteria were: (i) peer reviewed journal articles; (ii) studies reporting analytical methods applied in food manufacturing; (iii) research addressing quality, safety, or security outcomes; and (iv) papers published in English. Exclusion criteria removed non-indexed sources, conference abstracts, studies outside the food domain, and articles lacking methodological clarity. Titles and abstracts were screened for relevance, followed by full text evaluation of eligible papers. Selected studies were assessed for methodological rigor, analytical validity, and industrial applicability.

The final body of literature was synthesized thematically, grouping findings into macrolevel analytical approaches, microlevel analytical techniques, integration strategies, and emerging technological trends. This structured methodology ensures transparency, reproducibility, and alignment with the standards of high impact scientific journals.

### Eligibility Criteria

This review followed a systematic literature review (SLR) approach inspired by PRISMA guidelines to ensure transparency, reproducibility, and comprehensive coverage of analytical methods used in food quality, safety, and security. A structured search was performed across Scopus for articles published between 2020 - 2026. The search strategy used predefined keywords and Boolean combinations, including: “macro analysis,” “micro analysis,” “food quality assessment,” “food safety analytical methods,” “spectroscopy,” “chromatography,” “microbial detection,” and “food security technologies.”

#### Inclusion criteria:

- Peer reviewed journal articles
- Studies focusing on analytical methods in food manufacturing
- Research addressing quality, safety, or security outcomes
- Publications from 2020–2026
- English language articles

#### Exclusion criteria:

- Non-indexed journals
- Conference papers, theses, and book chapters
- Studies unrelated to food systems
- Articles lacking methodological detail

### Study Selection Process

The initial search yields a broad set of publications. Duplicates were removed, followed by title and abstract screening. Full text articles were then assessed for relevance and methodological robustness. Studies that met all criteria were included in the final synthesis.

### Data Extraction and Synthesis

Key information extracted included analytical principles, instrumentation, application context, advantages, limitations, and relevance to food quality, safety, or security. A thematic synthesis approach was used to categorize findings into macrolevel methods, microlevel techniques, integration strategies, and emerging trends.

This systematic methodology ensures that the review reflects current scientific evidence and supports high quality academic reporting.

## RESULT AND DISCUSSION

### Analytical methods to safety standards

Contamination of food products may occur at any point of the entire food supply chain. Therefore, a monitoring plan for the contaminants is prepared and crucial to the implementation of the food safety management system (Wang et al., 2022). The advancement of sensing technology and computational tools transitioned the food analysis from conventional methods to automated techniques, resulting in more objective and precise outcomes (Adade et al., 2025). With an increase in the global food supply chain and demand for transparency, and industry accountability, food analysis is important to reveal the complexities of produced foods and processes, ensuring regulatory compliance and protection of consumer health (Adade et al., 2025). Food safety management systems improve several production processes, including HACCP implementation, health and safety procedures, supplier management and traceability (Radu et al., 2023). Implementation of food safety management systems is associated with improved food quality and safety, and that effective implementation requires the integration of multiple disciplines and stakeholders (Radu et al., 2023). Successful management systems incorporate a combination of formalised processes and technology-assisted monitoring (Radu et al., 2023). There have been significant advancements in food safety technology, including the development of rapid testing methods and the use of blockchain to track the origin and movement of food products (Radu et al., 2023). These technologies have helped to reduce the risk of foodborne illness and improve the traceability of food products (Radu et al., 2023).

### Role of food analysis on traceability, supply chain transparency, sustainability

Food analysis has been transitioned from basic manual methods to more complex detection methods and techniques to manage complex food safety issues. Food traceability is the ability to track the journey of a food product from various stages. The stages include production, processing, and distribution (Rejeb et al., 2025). When investigating the root cause of quality or safety issues, traceability systems become relevant regardless of the production stage. It requires systematic documentation and record keeping for the item under consideration, with certain parameters that need to be verified through analytical techniques and tools. The authenticity of food products is verified through an analytical process, where high-throughput and rapid analytical methods are essential to meet the needs (Abdullah & Alani, 2025). Food traceability allows fast and accurate identification of food products that may pose risks to consumers, hence, avoid health hazards, minimize wastes, and prevent financial losses across the entire food supply chain. Traceability provides the transparency of the production stages by providing details of a specific product such as its origin, composition, and the history of processing. These details can form an essential part of the sustainable food supply chain and safe food products, which also contributes to an effective food quality and safety monitoring system that increases the confidence of consumers and serves as a bridge between the producers and consumers (Abdullah & Alani, 2025; Hiruy et al., 2024; Rejeb et al., 2025).

### Global and regional challenges in ensuring safe and secure food production

Almost 11% of the world population is still undernourished (Modi et al., 2021). As the world population is increasing, the sufficient supply of healthy, pure, and safe food becomes more challenging (Modi et al., 2021). Despite the innovative technologies for food processing, food packaging, and food preservation have been developed, however, the complex analytical techniques for food quality control may still limited to targeted mode and the contaminants remain undiscovered, increase the level of contamination (Modi et al., 2021).

In the food manufacturing industry, they are vulnerable to both intentional and unintentional contamination. Intentional contamination can happen by adding the contaminants into the food product due to being driven by economic benefit (Onyeaka et al., 2024). For unintentional contamination, it may come from the contaminants naturally present in the raw ingredients (Onyeaka et al., 2024). Regardless of the type of adulteration, the contaminant poses an adverse impact to human health; it is important to focus on the issues and establish control measures and monitor them closely in the food supply chain (Onyeaka et al., 2024).

In the current era, plastics have become a dominant concern. The cases like contamination of ethylene oxide in sesame seeds in Europe in late 2020, and contamination of plastic in Butterball turkey products in 2021 reflected the prevalent use of plastics in food manufacturing and distribution (Onyeaka et al., 2024). In developed countries, stringent regulations and mitigation measures of chemical contamination in food result in a decline in certain contamination issues (Onyeaka et al., 2024). However, in developing countries, they are facing challenges such as lack of infrastructure, inadequate comprehensive regulatory frameworks, and limited resources to control, monitor and address chemical contamination in food products effectively (Onyeaka et al., 2024). As the food supply chains are increasingly interconnected, this makes the contamination in one region capable of affecting consumers globally (Onyeaka et al., 2024).

Monitoring and surveillance, including routine sampling of food products for laboratory testing, and risk assessment are crucial to safeguard consumers from chemical contamination and preserve food security (Onyeaka et al., 2024). Despite the current monitoring and surveillance efforts, a few gaps and challenges are required to be addressed (Onyeaka et al., 2024). The development of precise, sensitive, and rapid analytical techniques to measure and detect chemical contaminants in food products is a challenge (Onyeaka et al., 2024). The constantly changing nature of developing chemical contaminants, for example, new pesticide residues or new food additives increase the difficulty of detection and on-going research and as well as extensive testing are required to stay up with new threats (Onyeaka et al., 2024).

Limitation of resources such as adequate finance, infrastructure, and skillful personnel may negatively impact the effectiveness and reach of monitoring operations, especially in developing countries (Onyeaka et al., 2024).

Different laws and regulatory standards in different countries can make international trade more complex and put consumers at risk (Onyeaka et al., 2024). Traditional fermented foods are famous in South-East Asia. However, the confidence level of consumers towards fermented foods is low due to the risk of microbial contamination in raw ingredients such as vegetables and meats (Onyeaka et al., 2024). There are different kinds of fermented vegetables produced on small scale through spontaneous fermentation and back-slopping fermentation due to the methods being inexpensive and reliable preservation in less-developed nations (Onyeaka et al., 2024).

In South-East Asia, temperature and humidity are favor the growth of toxin-producing microorganisms such as filamentous fungi produce mycotoxins, a toxic secondary fungal metabolites which can cause the crop yield loss due to diseases induced by toxigenic fungi, reduced the crop value, reduced animal productivity from mycotoxins-related health issues, and human health costs (Anal et al., 2020). Mycotoxin can contaminate various crops that are usually used as ingredients of traditional fermented foods (Anal et al., 2020). Mycotoxin contamination can happen in pre-harvesting or post-harvesting, resulting in finished products contaminated with the mycotoxins. It is relatively stable under high temperatures and cannot be removed safely (Anal et al., 2020)

Extensive use of antibiotics results in the growth of antibiotic-resistant bacteria. Foodborne diseases affect human health, causing hospitalization, and economic loss (Anal et al., 2020). Annually, there are an estimated 22.8 million cases of diarrheal illness with 37600 deaths caused by the Salmonellosis outbreak in South-East Asia (Anal et al., 2020). With the rapid development in South-East Asia, food products are traded internationally (Anal et al., 2020). There is a risk of spreading antibiotic resistant bacteria and genes to consumers globally (Anal et al., 2020).

### **Current Trends and Future Perspectives**

Recent advancements in analytical science are reshaping how food manufacturers monitor quality, safety, and authenticity. One of the most significant trends is the rapid adoption of AI assisted analytical systems, where machine learning algorithms interpret complex datasets generated from spectroscopy, chromatography, imaging, and sensor networks. These systems enhance prediction accuracy, automate anomaly detection, and support real time decision-making. Portable and rapid testing technologies including handheld NIR devices, smartphonebased sensors, and lab-on-a-chip platforms are also gaining prominence, enabling onsite analysis and reducing reliance on centralized laboratories. Biosensors, particularly enzyme based, immunological, and electrochemical platforms, are increasingly used for detecting pathogens, toxins, allergens, and chemical contaminants with high sensitivity and speed. Non-destructive imaging technologies such as hyperspectral

imaging further complement macrolevel assessments by providing detailed spatial and spectral information (Tan et al., 2025).

Digitalization is becoming a cornerstone of modern food manufacturing. Industry 4.0 technologies, including IoT sensors, cloud computing, and hyperphysical systems, enable continuous data collection across production lines. When combined with microlevel analytical outputs, these digital systems create integrated datasets that enhance traceability, process optimization, and predictive maintenance. Digital twins' virtual replicas of physical processes are emerging as powerful tools for simulating production scenarios, optimizing processing conditions, and predicting quality outcomes. Blockchain technology further strengthens supply chain transparency by linking macrolevel sensor data with microlevel laboratory results, creating secure and tamperproof traceability records that support regulatory compliance and consumer trust (Kumar et al., 2026).

Sustainability pressures are also influencing the development of new analytical tools and strategies. Green analytical chemistry approaches emphasize reduced solvent use, energy efficiency, and environmentally friendly materials. Techniques such as solvent free extraction, miniaturized chromatography, and biodegradable biosensors align with global sustainability goals. Analytical methods are increasingly used to support circular economy initiatives, such as monitoring food waste valorisation processes, assessing the quality of upcycled ingredients, and verifying the authenticity of sustainable products. Climate change and global food insecurity are driving the need for more robust analytical systems capable of detecting emerging contaminants, monitoring climates sensitive spoilage patterns, and ensuring the safety of alternative proteins such as plant-based meats, insect proteins, and cultured foods (Dhakal et al., 2026).

Looking ahead, the integration of macro and micro analytical approaches is expected to become increasingly seamless, supported by advancements in automation, miniaturization, and data analytics. Future analytical platforms will likely combine multimodal sensing, where physical, chemical, microbial, and molecular data are captured simultaneously and interpreted through unified AI models. Such systems will enable real-time, end-to-end quality assurance from raw materials to finished products. Autonomous quality control systems featuring robotic sampling, automated testing, and AI driven decision engines are poised to transform manufacturing environments by reducing human error and enhancing consistency. Personalized nutrition and precision food manufacturing will require highly sensitive analytical tools capable of characterizing microscale variations in composition and functionality.

Emerging technologies including AI assisted analytics, biosensors, digital twins, and portable rapid testing devices are accelerating the shift toward intelligent, data driven food systems. The future of food analysis lies in the development of unified, automated, and sustainable analytical ecosystems that seamlessly merge macro and micro data streams. These systems will enable real-time monitoring, predictive quality management, and enhanced resilience against global challenges such as climate change, supply chain disruptions, and emerging contaminants. As the food industry continues to evolve, the convergence of macro and micro analytical approaches will remain central to building safer, more transparent, and more sustainable food systems worldwide.

Despite that, emerging technologies in food quality analysis such as advanced spectroscopy, machine learning-driven predictive models, and integrated sensor networks offer exciting opportunities to bridge micro-level molecular insights with macro-level supply chain and consumer-facing applications, promising faster, more precise, and more holistic assessments of food quality. Yet, this optimism must be tempered by recognition of significant barriers to adoption. High implementation costs can deter small and medium enterprises, while specialized training requirements may limit effective use and risk misinterpretation of results. Validation and standardization challenges further complicate the integration of new methods, as reproducibility across diverse food matrices remains essential for credibility. Regulatory frameworks often lag behind technological innovation, creating uncertainty through lengthy approval processes, and the complexity of integrating microlevel laboratory insights with macro-level industrial and consumer applications demands seamless data interoperability that is not yet fully realized. Taken together, these challenges highlight that while innovation is promising, meaningful progress will depend on collaborative efforts among researchers, industry leaders, and policymakers to ensure that emerging technologies are scientifically improve, economically viable, practically implementable, and socially acceptable.

## Limitations of the Study

Although this review provides a comprehensive synthesis of macro and micro analytical approaches in food quality, safety, and security, several limitations should be acknowledged. First, the review is limited to literature published between 2020 and 2026, which may exclude earlier foundational studies or emerging research that has not yet been indexed in major databases. This time restriction ensures recency but may narrow the historical context of analytical method development. Second, the review relies primarily on peer reviewed journal articles from databases of Scopus. While this enhances scientific rigor, it may omit relevant insights from industry reports, patents, conference proceedings, and nonindexed regional publications that often contain practical innovations used in food manufacturing.

Third, the heterogeneity of analytical methods across different food sectors presents challenges in standardizing comparisons. Variations in instrumentation, sample preparation, validation protocols, and reporting formats limit the ability to directly compare performance across studies. Additionally, many emerging technologies such as AI assisted analytics, biosensors, and digital twins are still in early stages of adoption, and available literature may emphasize laboratory scale results rather than largescale industrial implementation. This may lead to an optimistic representation of their readiness for real world application.

Finally, as a systematic review, this study synthesizes findings thematically rather than conducting a quantitative meta-analysis. While this approach allows for broad conceptual integration, it does not provide statistical effect sizes or quantitative comparisons of analytical performance. Despite these limitations, the review offers valuable insights into current advancements, integration strategies, and future directions for analytical systems in modern food manufacturing (Rejeb et al., 2025; Tan et al., 2025).

## Standardization and Harmonization Challenges

Given the variability in analytical methods discussed in the limitation, method standardization, inter-laboratory validation, and regulatory harmonization are important to resolve the variability. Many official methods are designed and adopted to identify and measure specific known compounds or markers within the food samples (Jia et al., 2024). These methods act as standardised workflows, reduce the interference caused by manual errors, and ensuring rigorous and evidence-based analysis (Jia et al., 2024) In most cases, the National Reference Laboratories (NRL) develops the analytical methods, trains the regional laboratories, and conducts proficiency test after a period of method implementation (Jedziniak et al., 2023)

The performance of developed analytical methods should be validated for its accuracy, precision, specificity, recovery, and applicability (Jedziniak et al., 2023). Inter-laboratory validations can be conducted to evaluate the reproducibility and repeatability of the proposed method (Wu et al., 2024). The difference among the results of experiments should be equal or lower the limits to indicate that the robustness and effectiveness of the method (Wu et al., 2024).

The analytical techniques have become essential in identifying the adulterants and verifying food products (Marín et al., 2025). The techniques combining with data driven tools such as AI and ML can further identify the subtle fraud patterns that might not be recognized by human eyes (Marín et al., 2025). However, to exploit the advantages of these technologies, regulatory bodies should upgrade the inspection frameworks by investing and adopting these advanced technologies, incorporating rapid field tests and data analytics, for instance, routine testing and verification, and traceability practice should be conducted in vulnerable sectors by the authorities (Marín et al., 2025).

## CONCLUSION

In conclusion, the integration of macro and micro analytical approaches represents a transformative advancement in modern food manufacturing, offering a comprehensive framework for ensuring food quality, safety, and security. Macrolevel analyses provide rapid, non-destructive assessments of physical, sensory, and compositional attributes, while microlevel techniques deliver high-resolution insights into microbial dynamics, chemical composition, and molecular integrity. When combined, these analytical scales create a synergistic system capable of detecting deviations early, validating findings across multiple layers, and supporting robust quality assurance

programs. Integrated analytical systems not only enhance product consistency and regulatory compliance but also strengthen traceability and transparency across increasingly complex supply chains.

This review contributes new knowledge to the field of food quality, safety, and security by offering a comprehensive and integrated perspective on macro and micro analytical approaches an area where existing literature remains fragmented. While previous studies often examine physical, sensory, chemical, or microbial methods in isolation, this review synthesizes these analytical scales into a unified framework that highlights their complementary strengths and practical interdependence in modern food manufacturing (Lemus Ringele et al., 2026). By mapping how macrolevel assessments can be strategically paired with microlevel diagnostics, the study advances understanding of multilayered quality assurance systems capable of addressing both surface level attributes and molecular scale risks.

A second major contribution lies in the critical evaluation of emerging technologies such as AI assisted analytics, biosensors, hyperspectral imaging, digital twins, and portable rapid testing devices (Kazemi & Valizadeh, 2026). This review not only summarizes recent advancements but also contextualizes their readiness, limitations, and potential for industrial adoption. Such analysis provides valuable insights for researchers and practitioners seeking to modernize analytical workflows and transition toward intelligent, data driven food systems (Lauriau et al., 2026).

Furthermore, the study contributes to the broader discourse on food security by linking analytical innovations to traceability, transparency, sustainability, and supply chain resilience. By integrating perspectives from quality science, safety regulation, digitalization, and sustainability, the review establishes a multidisciplinary foundation for future research. Overall, this study advances theoretical understanding, identifies practical gaps, and outlines strategic directions for developing next generation analytical ecosystems in the global food industry (Ahmad et al., 2025; Kazemi & Valizadeh, 2026).

## REFERENCES

1. Abdullah, N. N., & Alani, N. H. S. (2025). Blockchain adoption in the supply chain: Enablers, barriers, and opportunities from a systematic review. In *Sustainable Futures* (Vol. 10). Elsevier Ltd. <https://doi.org/10.1016/j.sfr.2025.101429>
2. Adade, S. Y. S. S., Lin, H., Johnson, N. A. N., Nunekpeku, X., Aheto, J. H., Ekumah, J. N., Kwadzokpui, B. A., Teye, E., Ahmad, W., & Chen, Q. (2025). Advanced food contaminant detection through multi-source data fusion: Strategies, applications, and future perspectives. In *Trends in Food Science and Technology* (Vol. 156). Elsevier Ltd. <https://doi.org/10.1016/j.tifs.2024.104851>
3. Ahmad, T., Abrar, M., Bokhari, S. A. M., Iqbal, S., Alvi, A. M., Iqbal, Q., Ghani, M. A., Umar, M., & Iqbal, R. T. (2025). Amaranthus: A nutritious solution to malnutrition for underprivileged populations in Pakistan.
4. *Journal of Trace Elements and Minerals*, 12. <https://doi.org/10.1016/j.jtemin.2025.100221>
5. Anal, A. K., Perpetuini, G., Petchkongkaew, A., Tan, R., Avallone, S., Tofalo, R., Nguyen, H. Van, Chu-Ky, S.,
6. Ho, P. H., Phan, T. T., & Waché, Y. (2020). Food safety risks in traditional fermented food from SouthEast Asia. *Food Control*, 109. <https://doi.org/10.1016/j.foodcont.2019.106922>
7. Arslan, M., Zareef, M., Tahir, H. E., Zhang, J., Ahmad, W., Rakha, A., Shi, J., Xiaobo, Z., & Khan, M. R.
8. (2022). Discrimination of basmati rice adulteration using colorimetric sensor array system. *Food Control*, 132. <https://doi.org/10.1016/j.foodcont.2021.108513>
9. Dhakal, M., Banerjee, M., Pandey, K. K., & Seniya, C. (2026). Ai and IoT are no longer limited to high-tech labs but are improving nutrition-focused agricultural farming. *Discover Food*. <https://doi.org/10.1007/s44187-025-00777-w>
10. Dhal, S. B., & Kar, D. (2025). Leveraging artificial intelligence and advanced food processing techniques for enhanced food safety, quality, and security: a comprehensive review. In *Discover Applied Sciences* (Vol. 7, Number 1). Springer Nature. <https://doi.org/10.1007/s42452-025-06472-w>
12. Du, J., Gan, M., Xie, Z., Zhou, C., Li, M., Wang, M., Dai, H., Huang, Z., Chen, L., Zhao, Y., Niu, L., Zhang, S., Guo, Z., Wang, J., Li, X., Shen, L., & Zhu, L. (2023). Current progress on meat food

- authenticity detection methods. In *Food Control* (Vol. 152). Elsevier Ltd. <https://doi.org/10.1016/j.foodcont.2023.109842>
13. Gao, Z., Zhang, X., Liu, X., Zhang, M., Li, X., Zhao, J., Qiao, W., & Chen, L. (2026). Human milk flavor: an overview of odor composition, influencing factors, and flavoromics techniques. In *Journal of Future Foods* (Vol. 6, Number 4, pp. 505–518). KeAi Communications Co. <https://doi.org/10.1016/j.jfutfo.2024.10.002>
  14. Golge, O., & Kabak, B. (2020). Occurrence of deoxynivalenol and zearalenone in cereals and cereal products from Turkey. *Food Control*, 110. <https://doi.org/10.1016/j.foodcont.2019.106982>
  15. Hassoun, A., Jagtap, S., Garcia-Garcia, G., Trollman, H., Pateiro, M., Lorenzo, J. M., Trif, M., Rusu, A. V., Aadil, R. M., Šimat, V., Crobotova, J., & Câmara, J. S. (2023). Food quality 4.0: From traditional approaches to digitalized automated analysis. In *Journal of Food Engineering* (Vol. 337). Elsevier Ltd. <https://doi.org/10.1016/j.jfoodeng.2022.111216>
  16. Hassoun, A., Jagtap, S., Trollman, H., Garcia-Garcia, G., Abdullah, N. A., Goksen, G., Bader, F., Ozogul, F., Barba, F. J., Crobotova, J., Munekata, P. E. S., & Lorenzo, J. M. (2023). Food processing 4.0: Current and future developments spurred by the fourth industrial revolution. In *Food Control* (Vol. 145). Elsevier Ltd. <https://doi.org/10.1016/j.foodcont.2022.109507>
  17. Hiruy, H., Bala, S., Byrne, J. M., Roche, K. G., Jang, S. H., Kim, P., Nambiar, S., Rubin, D., Yasinskaya, Y.,
  18. Bachmann, L. H., Bernstein, K., Botgros, R., Cammarata, S., Chaves, R. L., Deal, C. D., Drusano, G. L., Duffy, E. M., Eakin, A. E., Gelone, S., ... Farley, J. J. (2024). US Food and Drug Administration, Centers for Disease Control and Prevention, and National Institutes of Health Co-Sponsored Public Workshop Summary—Development Considerations of Antimicrobial Drugs for the Treatment of Gonorrhea. *Clinical Infectious Diseases*. <https://doi.org/10.1093/cid/ciae386>
  19. Jedziniak, P., Panasiuk, Ł., Pietruszka, K., Kolano, K., & Zbytniewski, R. (2023). Inter-laboratory validation of liquid chromatography-tandem mass spectrometry multi-mycotoxin determination in animal feed - Method transfer from the reference laboratory to regional laboratories. *Journal of Veterinary Research (Poland)*, 67(3), 397–406. <https://doi.org/10.2478/jvetres-2023-0045>
  20. Jia, W., Georgouli, K., Martinez-Del Rincon, J., & Koidis, A. (2024). Challenges in the Use of AI-Driven NonDestructive Spectroscopic Tools for Rapid Food Analysis. In *Foods* (Vol. 13, Number 6).
  21. Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/foods13060846>
  22. Kazemi, M., & Valizadeh, R. (2026). Nutritional strategies for enhancing the quality of animal-derived food products. In *Discover Food* (Vol. 6, Number 1). Springer Nature. <https://doi.org/10.1007/s44187-02500759-y>
  23. Kumar, V., Kaushik, D., & Kumar, M. (2026). Synergizing microbial and artificial intelligence technologies in food Systems: Innovations, safety, and sustainable pathways. In *Renewable and Sustainable Energy Reviews* (Vol. 231). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2026.116769>
  24. Kunz, B. M., Wanko, F., Kemmlin, S., Bahlmann, A., Rohn, S., & Maul, R. (2020). Development of a rapid multi-mycotoxin LC-MS/MS stable isotope dilution analysis for grain legumes and its application on 66 market samples. *Food Control*, 109. <https://doi.org/10.1016/j.foodcont.2019.106949>
  25. Lauriau, F., Strubbia, S., Cappelier, J. M., Mahieu, B., Haddad, N., & Guillou, S. (2026). Analyzing slaughter modalities and environmental factors to improve prediction of *Campylobacter* concentration in broiler carcasses. *Journal of Applied Poultry Research*, 35(2). <https://doi.org/10.1016/j.japr.2025.100662>
  26. Lemus Ringele, G. B., Gkiouvetidis, P., Michailidis, D., Bossard, E., Gourguillon, L., Beteinakis, S., Skaltsounis, L. A., & Halabalaki, M. (2026). Annular centrifugal extraction for the recovery of non-sugar compounds from honey. *Scientific Reports*, 16(1). <https://doi.org/10.1038/s41598-025-31250-4>
  27. Marín, X., Grau-Noguer, E., Gervilla-Cantero, G., Ripolles-Avila, C., & Castillo, M. (2025). Emerging technologies for detecting food fraud: A review of the current landscape in the 2020s. In *Trends in Food Science and Technology* (Vol. 165). Elsevier Ltd. <https://doi.org/10.1016/j.tifs.2025.105313>
  28. Modi, B., Timilsina, H., Bhandari, S., Achhami, A., Pakka, S., Shrestha, P., Kandel, D., Gc, D. B., Khatri, S., Chhetri, P. M., & Parajuli, N. (2021). Current Trends of Food Analysis, Safety, and Packaging. In *International Journal of Food Science* (Vol. 2021). Hindawi Limited. <https://doi.org/10.1155/2021/9924667>
  29. Negi, A., Pare, A., & Meenatchi, R. (2021). Emerging techniques for adulterant authentication in spices and spice products. In *Food Control* (Vol. 127). Elsevier Ltd. <https://doi.org/10.1016/j.foodcont.2021.108113>
  30. Nguyen, C. J., Pham, C., Jackson, A. M., Ellison, N. L. K., & Sinclair, K. (2022). Online Food Security

31. Discussion Before and During the COVID-19 Pandemic in Native Hawaiian and Pacific Islander Community Groups and Organizations: Content Analysis of Facebook Posts. *Asian Pacific Island Nursing Journal*, 6(1). <https://doi.org/10.2196/40436>
32. Omosebi, O. M., Nicholas, C. G., Babarinsa, O. A., Oni, T. I., & Ayandiran, G. D. (2026). Characterisation of composite foodspreads produced from *Persea americana* and *Arachis hypogea*. *Discover Food*. <https://doi.org/10.1007/s44187-025-00797-6>
33. Onyeaka, H., Ghosh, S., Oibileke, K. C., Miri, T., Odeyemi, O. A., Nwaiwu, O., & Tamasiga, P. (2024). Preventing chemical contaminants in food: Challenges and prospects for safe and sustainable food production. In *Food Control* (Vol. 155). Elsevier Ltd. <https://doi.org/10.1016/j.foodcont.2023.110040>
34. Radu, E., Dima, A., Dobrota, E. M., Badea, A. M., Madsen, D. Ø., Dobrin, C., & Stanciu, S. (2023). Global trends and research hotspots on HACCP and modern quality management systems in the food industry. *Heliyon*, 9(7). <https://doi.org/10.1016/j.heliyon.2023.e18232>
35. Rau, J., Korte, N., Dyk, M., Wenninger, O., Schreiter, P., & Hiller, E. (2020). Rapid animal species identification of feta and mozzarella cheese using MALDI-TOF mass-spectrometry. *Food Control*, 117. <https://doi.org/10.1016/j.foodcont.2020.107349>
36. Rejeb, A., Rejeb, K., Molavi, H., & Keogh, J. G. (2025). A Data-Driven Topic Modeling Analysis of Blockchain in Food Supply Chain Traceability. *Information (Switzerland)*, 16(12). <https://doi.org/10.3390/info16121096>
37. Silva, A. F. S., & Rocha, F. R. P. (2020). A novel approach to detect milk adulteration based on the determination of protein content by smartphone-based digital image colorimetry. *Food Control*, 115. <https://doi.org/10.1016/j.foodcont.2020.107299>
38. Sutariya, S. G., Joshi, R., & Salunke, P. (2026). Emerging applications of hyaluronic acid in dairy and foods. *Discover Food*. <https://doi.org/10.1007/s44187-025-00776-x>
39. Tan, Y., Ni, H., Wu, T., Wang, Q., Zeng, H., & Wang, Y. (2025). Harnessing advanced biotechnology and information technology towards smart manufacture of future foods: a review. *Journal of Future Foods*. <https://doi.org/10.1016/j.jfutfo.2025.11.007>
40. Wang, X., Bouzembrak, Y., Lansink, A. G. J. M. O., & van der Fels-Klerx, H. J. (2022). Application of machine learning to the monitoring and prediction of food safety: A review. In *Comprehensive Reviews in Food Science and Food Safety* (Vol. 21, Number 1, pp. 416–434). John Wiley and Sons Inc. <https://doi.org/10.1111/1541-4337.12868>
41. Wu, Y., Zhou, Y., Jiao, X., She, Y., Zeng, W., Cui, H., & Pan, C. (2024). Development and inter-laboratory validation of analytical methods for glufosinate and its two metabolites in foods of plant origin. *Analytical and Bioanalytical Chemistry*, 416(3), 663–674. <https://doi.org/10.1007/s00216-023-04542-9>
42. Wulandari, D., Budiharjo, A., Setiarto, R. H. B., Wisastra, S. R., Purnama, J. A. S. H., & Wical, H. Z. (2026).
43. Physicochemical, sensory analysis and gastronomic significance of Sambal Tumpang as a traditional Javanese fermented condiment. *Discover Food*, 6(1). <https://doi.org/10.1007/s44187-025-00751-6>
44. Yu, S. T., Yin, X., Yin, Y. C., Zhang, Y., Dong, J. C., Gao, L. L., Sun, H. J., Yuan, G. Di, Jiang, C. J., Li, B. B., Wang, C. T., & Yu, J. (2026). Induction and characterization of a novel high-protein mutant in peanut
45. (*Arachis Hypogaea* L.). *Plant Growth Regulation*, 106(1). <https://doi.org/10.1007/s10725-026-01432-9>
46. Zhang, H., Cao, W., Zhang, Y., Chang, Y., Huang, H., Wei, T., Wu, J., Ye, L., & Shi, L. (2023). Identification for meat adulteration (pork, beef, sheep and duck) in foodstuff by microfluidic chip-based real-time fluorescent LAMP. *Journal of Food Composition and Analysis*, 119. <https://doi.org/10.1016/j.jfca.2023.105223>