Ensuring Food Integrity and Security Through Macro and Micro Analysis: Current Trends and Industrial Applications

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ABSTRACT

This review critically reassesses the analytical dichotomy between Macro and Micro-parameters to propose a validated, synergistic Data Fusion framework that bypasses the "Adulteration Gap" and the "Economic Wall" in global food systems. A systematic review was conducted utilizing a tiered search strategy across Scopus, Web of Science, and Google Scholar. The methodology progressed from macro-level contextual filtering (drivers like the "Three Lethal Cs") to micro-level technical validation of instrumental data, culminating in a nexus integration that cross-references socio-economic impacts with forensic protocols. The study identifies that traditional Macro analysis (proximate composition) is vulnerable to sophisticated fraud, as demonstrated by the melamine nitrogen loophole in milk. Conversely, Micro analysis (HPLC, IRMS) provides essential forensic specificity, identifying isotopic fingerprints in honey, but is often hindered by high operational costs. Industrial applications reveal that transitioning from "Lab" to "Line" via Process Analytical Technology (PAT) and utilizing Green Chemistry (NADES) effectively mitigates matrix interference and reduces waste. An integrated Nexus approach, employing rapid Macro-sensors as a first line of defense followed by targeted Microverification, provides a legally defensible and commercially viable standard. This framework contributes significantly to socio-economic protection, public health safety, and global environmental sustainability by bridging the divide between bulk composition and trace molecular integrity.

Keywords: Food Integrity-Security, Economically Motivated Adulteration (EMA), Process Analytical Technology (PAT), Macro-Micro Analysis Dichotomy, Analytical Data Fusion.

INTRODUCTION

In an era characterized by global instability, food systems are increasingly susceptible to the "Three Lethal Cs": COVID-19, Conflict, and Climate Change (Munialo & Mellor, 2024). These disruptions have transformed food integrity from a static quality issue into a fluid and dynamic attribute of global food security, where extended and complex supply chains create opaque entry points for Economically Motivated Adulteration (EMA) (Robson et al., 2021). The current analytical landscape is divided by a significant trade-off: an "Adulteration Gap" where cost-effective Macro analysis fails to detect sophisticated mimics like melamine, and an "Economic Wall" where precise Micro analysis remains too resource-intensive for universal application (Abedini et al., 2021; Shi et al., 2025). Understanding the relationship between these two analytical planes is essential for developing a synergistic framework that protects the global food supply chain.

METHODOLOGY

The study design for this research is a narrative review method to integrate the current literature on food security, food integrity, and advanced analytical methods for food authentication. This study design is different from a systematic review aimed at answering a specific question. This narrative design provides a wide scope to include

diverse views on food security and integrity from a multi-disciplinary perspective, from economics to the chemistry of spectroscopic food analysis.

Search Strategy

A comprehensive multi-staged search was carried out using various databases such as ScienceDirect, Web of Science, Scopus and Google Scholar to cover all relevant literature. This included peer-reviewed articles and conference papers written in English and published between 2019 and 2025. In this context, a multi-stage search strategy was used, which included a list of primary and secondary keywords. These keywords were then classified into three sets: Set A, which included Integrity-related keywords such as "food integrity", "Halal supply chain", "food fraud" and "traceability"; Set B, which included Security-related keywords such as "food security pillars", "availability", "utilization" and "stability"; and Set C, which included keywords related to technical aspects of food security such as "chemometrics", "spectroscopy", "ICP-MS", "HPLC" and "melamine detection". These sets were designed to ensure that the research process incorporates developments in postpandemic food security frameworks.

Following this, Tier 1 filtering addressed contextual frameworks by identifying high-impact studies on the global drivers of food insecurity, specifically the "Three Lethal Cs": COVID, Conflict, and Climate, and the six pillars of food security to establish the physical and economic landscape where food fraud occurs.

In the third step, Tier 2 filtering focused on technical validation by selecting studies that provided raw instrumental data and specific analytical protocols. This included research establishing calibration ranges (e.g., 0.01–5.00 ppm for trace elements), detection limits for adulterants such as melamine and the application of chemometric models like Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) to interpret complex food matrices. Tier 3 then facilitated nexus integration by cross-referencing the results from previous tiers; a source was included in the review only if it successfully bridged the gap between a micro-analytical tool and a macro-level security issue, such as using Isotope Ratio Mass Spectrometry (IRMS) to solve honey adulteration.

Finally, the papers were evaluated and synthesized to postulate the Data Fusion framework, ensuring that the final conclusions were grounded in both socio-economic realities and forensic scientific evidence.

Figure 1 illustrates the step-by-step search strategy used to build a robust and interdisciplinary literature review.

Figure 1. Step-by-Step Search Strategy Used
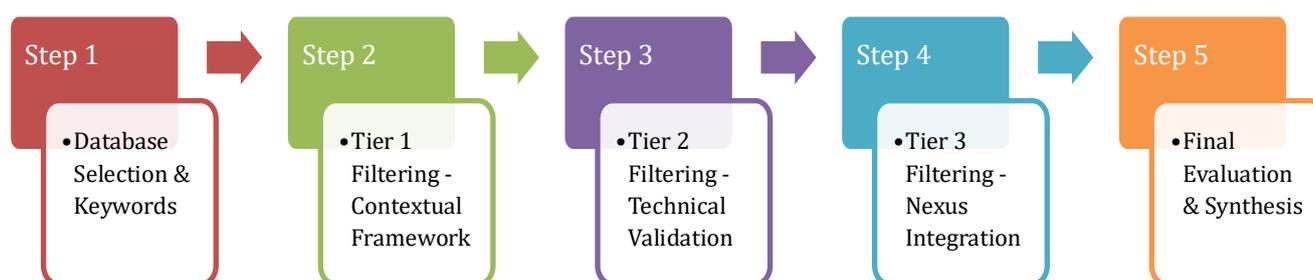
Inclusion and Exclusion Criteria

To ensure the quality of the narrative synthesis, specific inclusion and exclusion criteria were developed for the selected studies. The inclusion criteria include studies that offered empirical data on food contaminants (such as

Abedini et al., 2021), studies offering theoretical frameworks on food security (such as Pérez-Escamilla, 2024), and studies offering comprehensive reviews on green extraction or analytical techniques relevant to food safety.

However, the exclusion criteria include studies without a clear methodology presented, studies without a peerreviewed publication (such as blog posts), and studies on agricultural practices without a direct link to food safety or security.

Methodological Limitations

While this narrative method provides a holistic understanding, it is limited to the selection bias of the author. This study does not include a meta-analysis and a risk of bias assessment for each study, as done in a systematic review (PRISMA). However, rigor was ensured by giving priority to highly cited journals and geographic diversity.

LITERATURE REVIEW

Definition of Food Integrity

Food integrity is a multidimensional concept generally defined as the state of being whole, entire, or undiminished (Robson et al., 2021; Ling & Wahab, 2020). It ensures that food offered for sale is safe and of the expected quality, while honestly capturing sourcing and distribution elements (Ali et al., 2022; Ling & Wahab, 2020). Recent literature defines food integrity across four key elements: product, process, people, and data (Alrobaish et al., 2021). In the Halal industry, this extends to compliance with Islamic principles, ensuring food is free from prohibited elements like porcine DNA or alcohol (Ali et al., 2022).

To operationalize this, food integrity is divided into:

- Product Integrity: Focuses on authenticity and genuine ingredients consistent with labels (Robson et al., 2021; Alrobaish et al., 2021).

- Process Integrity: Involves verified management systems to prevent illicit imports or diversion (Fernando et al., 2021).

- People Integrity: Addresses the honesty and ethics of supply chain actors (Robson et al., 2021).

- Data Integrity: Ensures accurate documentation and health certificates to prevent fraud (Fernando et al., 2021).

The "House of Food Integrity" rests on three pillars: Food Quality, Food Safety, and Food Defence, supported by foundations of Traceability, Technology, and Assurance Systems like HACCP (Ling & Wahab, 2020).

Definition of Food Security

Food security exists when "all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food" (García-Díez et al., 2021; Pérez-Escamilla, 2024). Modern consensus expands this to six pillars:

1. Availability: Adequate amounts of quality food (Ali, 2024).

2. Access: Categorized into Physical (transport), Economic (purchasing power), and Social (acceptable means) access (Campomanes et al., 2024; Gallegos et al., 2023).

3. Utilization: Biological use of food through nutrition, sanitation, and health (Gallegos et al., 2023).

4. Stability: Steady access despite economic or climatic shocks like the "Three Lethal Cs" (Munialo & Mellor, 2024).

5. Agency: Decision-making power of communities (Sumsion et al., 2023).

6. Sustainability: Resource regeneration for future generations (Gallegos et al., 2023).

The Intersection: Where Integrity Protects Security

Contemporary supply chains face a "Dual Vulnerability". Security risks involve physical spoilage and disruption due to elaborate logistics and global crises (García-Díez et al., 2021). Integrity risks involve intentional

"Economically Motivated Adulteration" (EMA), where globalization reduces accountability across approximately 450 potential compromise points (Ling & Wahab, 2020; Robson et al., 2021).

Table 1 diagram summarizing the relationship between Food Integrity and Food Security, showing how each dimension contributes to protecting food systems.

Table 1. Relationship Between Food Integrity and Food Security

Food Integrity Pillar	Contribution to Food Security Pillar	Security Risk Mitigated
Product Integrity	Ensures **Availability** of genuine, safe food	Prevents adulteration and counterfeit products
Process Integrity	Supports **Stability** and **Utilization** through ethical and verified handling	Reduces risk of supply chain disruption and unsafe processing
People Integrity	Enhances **Agency** and **Access** by promoting ethical behavior and trust	Mitigates fraud and corruption across the supply chain
Data Integrity	Strengthens **Sustainability** and **Access** via accurate traceability and documentation	Prevents mislabeling, fraud, and loss of consumer confidence

The Analytical Dichotomy: Macro vs. Micro Analysis

The traditional separation between Macro (Bulk) and Micro (Trace) analysis is established through four distinctions.

1. Physiological Role: Macro-elements (Calcium, Magnesium) provide structural roles, while Microminerals (Iron, Zinc) act as enzyme co-factors (Singh et al., 2024; Wahid et al., 2022).

2. Concentration Abundance: Macro-units are expressed in percentages or g/kg, while Micro-units are measured in ppm or µg/g (Heghedűş-Mîndru et al., 2023). The gap can be as large as 19,000 ppm (K) vs 10 ppm (Cu) (Singh et al., 2024).

3. Methodology/Instrumentation: Macro analysis uses "Radial" viewing in ICP-OES or wet lab methods (Kjeldahl). Micro analysis requires "Axial" viewing, ICP-MS, or Atomic Absorption for sensitivity (AlOmairi et al., 2025; Sahadi & Basri, 2025).

4. Transfer and Stability: Macro elements are physiologically constant in animal products, whereas trace elements show higher variability in transfer rates (Trziszka et al., 2021).

Macro Analysis

This analysis focuses on the "Proximate" or bulk composition; the major nutrients and structural components that constitute the mass, energy, and physical form of the material.

Proximate & Bulk Composition

For the food sector, the analysis comprises the determination of moisture content, total ash, crude fat, protein, and carbohydrates (Campos et al., 2022). Carbohydrates and proteins are viewed as the dominant components in the structure of seaweed (Campos et al., 2022). For briquettes meant for energy production, "Proximate Analysis" involves the determination of the volatile content necessary for the ignition of the briquettes, together with the fixed carbon content required for the production of energy, as well as the levels of moisture and ash (Kpalo et al., 2020).

Physicochemical State & Quality:

Macro parameters establish the physicochemical state of a product. In salad cream, parameters such as viscosity, pH, and Total Titratable Acidity (TTA) are estimated to establish texture and shelf life. In animal products, macro-ingredients such as collagen, fat, and dry matter can be estimated using spectroscopy to establish Muscle Type categories through indexes such as the K-value (Chaudhary et al., 2022).

Physiological drivers

In ecological terms, macro-nutrients are considered according to their role as main drivers for a certain behavior. In ant biology, for example, carbohydrates (sucrose) and nitrogen substances (urea, amino acids) are considered "Main Parameters" as these are needed in considerable quantities for energy requirements, specifically for driving foraging behavior (Renyard et al., 2024).

Primary Metabolites

In berry authenticity testing, Macro-Analysis focuses on primary metabolites like sugars, organic acids, fatty acids, and main minerals like Na, K, Ca, Mg, and P that constitute the largest part of a compound's nutritional profile (Carrillo et al., 2023).

Micro Analysis

This analysis targets "Support Parameters"; elements, compounds, and structures present in minute quantities that are critical for safety, origin tracing, and metabolic support, but do not define the bulk mass.

Trace Elements & Fingerprinting

The main analytical method for tracing and authenticating involves Trace Element Analysis and Fingerprinting. Methods such as ICP-MS measure trace elements such as Iron, Zinc, Copper, and REE to establish trace fingerprints that identify products by their soil of origin (Carrillo et al., 2022).

In seaweed-based products, macro-elements may be present in abundance; however, specific trace elements such as Zinc and Iron reveal nutritional fingerprints identifying their specific levels for potential human health aspects in terms of N/K ratios (Campos et al., 2022).

Micro-Structural & Ultimate Analysis

Material analysis requires an analysis more refined than the composition of the material. In the analysis of fuel briquettes, while the Ultimate Analysis analysis of the briquettes assesses atomic composition (Carbon, Hydrogen, Nitrogen, Sulfur) essential in determining the emission of NOx/SOx in the environment (Kpalo et al. 2020).

It also involves Micro-Structural Analysis requires Scanning Electron Microscopy analysis of microscopic particle bonding and fractures (Kpalo et al., 2020).

Safety, Toxins & Bioactive Compounds

The main aim in this category is to identify invisible toxins and bioactive compounds that can be present in animal products such as meats, fish, and other animal foods containing microorganisms like bacteria and toxins such as microplastic contaminants (Chaudhary et al., 2022). In berries, it centers on bioactive compounds such as anthocyanins and flavonoids that can be used as markers to detect (Carrillo et al., 2023).

Metabolic Support (Non-Drivers)

Biologically speaking, micro-nutrients like Vitamins and Salts are classified under "support". Though they are required for development in a longer life cycle, they aren't responsible for influencing shortterm foraging behavior in organisms like ants to ensure that they aren't considered macro-drivers (Renyard et al., 2024).

Table 2 is summary of Macro vs. Micro analysis in Food Science. It is a structured comparison that explains how two types of analytical approaches differ in purpose, scale and technique.

Table 2. Summary of Macro vs. Micro Analysis in Food Science

Aspect	Macro Analysis	Micro Analysis
Physiological Role	Macro elements like calcium and magnesium help build body structure.	Micro elements like iron and zinc support enzyme function and biological activity.
Concentration Units	Macro elements are measured in grams per kilogram (g/kg) or percent (%).	Micro elements are measured in parts per million (ppm) or micrograms per gram (µg/g).
Analytical Methods	Techniques include radial ICP-OES and wet chemistry methods like Kjeldahl.	Techniques include axial ICP-MS and atomic absorption for high sensitivity.
Transfer Stability	Macro elements remain stable in animal products.	Micro elements vary more in how they transfer between sources.
Main Focus	Focuses on bulk composition such as moisture, fat, protein and carbohydrates.	Focuses on trace elements, toxins, bioactive compounds and origin tracing.

FINDINGS AND DISCUSSION

The Failure of Macro Analysis: The "Adulteration Gap"

Macro Analysis suffers from an "adulteration gap" due to indirect measurement (Ham et al., 2025). For example, Kjeldahl methods measure Total Nitrogen and multiply by 6.25 to estimate protein (Abedini et al., 2021).

Fraudsters exploit this by adding melamine ($C_3H_6N_6$, 66% nitrogen) to artificially inflate measured results. Melamine contamination has been detected in 94% of certain international samples (Abedini et al., 2021).

From the point of view of food integrity, this represents a clear breach of Product Integrity, where the authenticity of the raw material is misrepresented, and Data Integrity, where the analysis certificate misrepresents the actual nutritional content.

In the context of food security, this breach directly impacts the Utilization pillar, where the consumer is consuming toxic industrial chemicals rather than the vital protein necessary for biological function. Moreover, it also affects the Stability pillar, where the massive adulteration scandals cause market instability, a collapse of the supply chain, and a significant loss of consumer confidence in the availability of food.

To fill the "Adulteration Gap" in macro analysis, the strategic approach must target the blind spots of indirect analysis while ensuring both food integrity and food security.

Firstly, laboratories must employ hybrid testing models, combining rapid macro analysis (such as Kjeldahl or refractive index) with micro-verification (HPLC or IRMS) for high-risk commodities. Secondly, risk-based surveillance networks can target products most susceptible to adulteration, maximizing efficiency without the need for 100% testing of batches.

Lastly, open communication and algorithmic transparency will improve the trustworthiness of certificates of analysis, preventing potential deception. In this way, the approach above supports the integrity and security pillars of the global food system by upholding product authenticity, consumer health, and supply chain stability.

The Barrier of Micro Analysis: Cost and Complexity

While Micro analysis (GC-MS, ICP-MS) closes the gap, it faces an "Economic Wall" (Shi et al., 2025). High capital investment, "cumbersome" sample preparation, and the need for "skilled technicians" to interpret complex "black box" algorithms make 100% batch testing impractical (Kharbach et al., 2023; Shi et al., 2025).

In the food integrity arena, this hurdle affects Process Integrity because, in most cases, the high cost makes spot checking a common practice instead of continuous monitoring, thus creating entry points for Economically Motivated Adulteration (EMA). It is also a challenge to Data Integrity because the spot checking involves complex chemometric models, which require high transparency to ensure that the outcome is not prone to human or computer bias.

In the area of food security, the "Economic Wall" is a threat to Economic Access because the cost of high-precision validation is usually transferred down the chain, which may make safe food unaffordable. In addition, the long turnaround time related to complex sample preparations affects the Stability pillar because delayed for laboratory results may cause logistical delays or reduce the shelf life of perishable commodities, thus creating localized shocks in food access.

In order to fill the gap between the expensive micro-analysis and the need for accessible food testing, the industry needs to invest in portable and low-cost alternatives such as handheld spectrometers and biosensors. The industry also needs to standardize hybrid protocols that merge broad macro-screening with micro-verification.

The industry also needs to develop a network of trained technicians to democratize expertise and increase testing capacity beyond elite labs. Finally, the industry needs to ensure transparency in algorithmic interpretation to strengthen trust among producers, regulators, and consumers, ensuring that food integrity and food security are maintained.

The Nexus: Integrating Macro and Micro for Integrity

The evolution of Quality Assurance necessitates a shift to "Data Fusion" fusing Macro parameters (morphological, physical) with Micro parameters (molecular, chemical) to create a "Food Fingerprint" (Casian et al., 2022).

Case A: Milk Adulteration (The Nitrogen Loophole)

Conventional quality control depends on Macro methods such as Kjeldahl or Dumas for quantifying protein. However, these methods suffer from an inherent "blind spot" as they measure Total Nitrogen rather than specific protein molecules. Fraudsters exploit this by lacing diluted milk with Melamine ($C_3H_6N_6$), an industrial chemical containing 66% nitrogen.

Because macro-level tests fail to differentiate between protein-based nitrogen and nonprotein nitrogen, the adulterated milk appears to have "normal" or even "premium" protein levels despite being nutritionally deficient and toxic. Integrity is restored only through forensic Micro analysis using HighPerformance Liquid Chromatography (HPLC), which identifies the specific molecular signature of Melamine, exposing the fraud that bulk tests legitimize (Abedini et al., 2021).

Case B: Honey Adulteration (The Isotopic Fingerprint)

Honey is frequently adulterated with high-fructose corn syrup (HFCS) or cane sugar because these syrups share a similar bulk physical profile (Macro chemistry) with natural honey. Standard tests like the refractive index or simple sugar profiling fail to detect this fraud because the macro-parameters of the syrup mimic those of bee nectar. The solution involves atomic physics: plants like corn (C4 photosynthetic pathway) fix carbon differently than the C3 plants visited by bees.

By employing Isotope Ratio Mass Spectrometry (IRMS), a sophisticated Micro analysis, researchers can detect the distinct Carbon-13 isotopic fingerprint of the adulterant. This allows analysts to verify botanical authenticity where traditional sugar tests only provide a superficial mask of quality (Dua et al., 2025; Shi et al., 2025).

Figure 2 showing how both Macro Analysis (Adulteration Gap) and Micro Analysis (Economic Wall) create vulnerabilities in food integrity and security, along with strategic solutions.

Figure 2. Macro vs. Micro Analysis: Failure → Impact → Solution
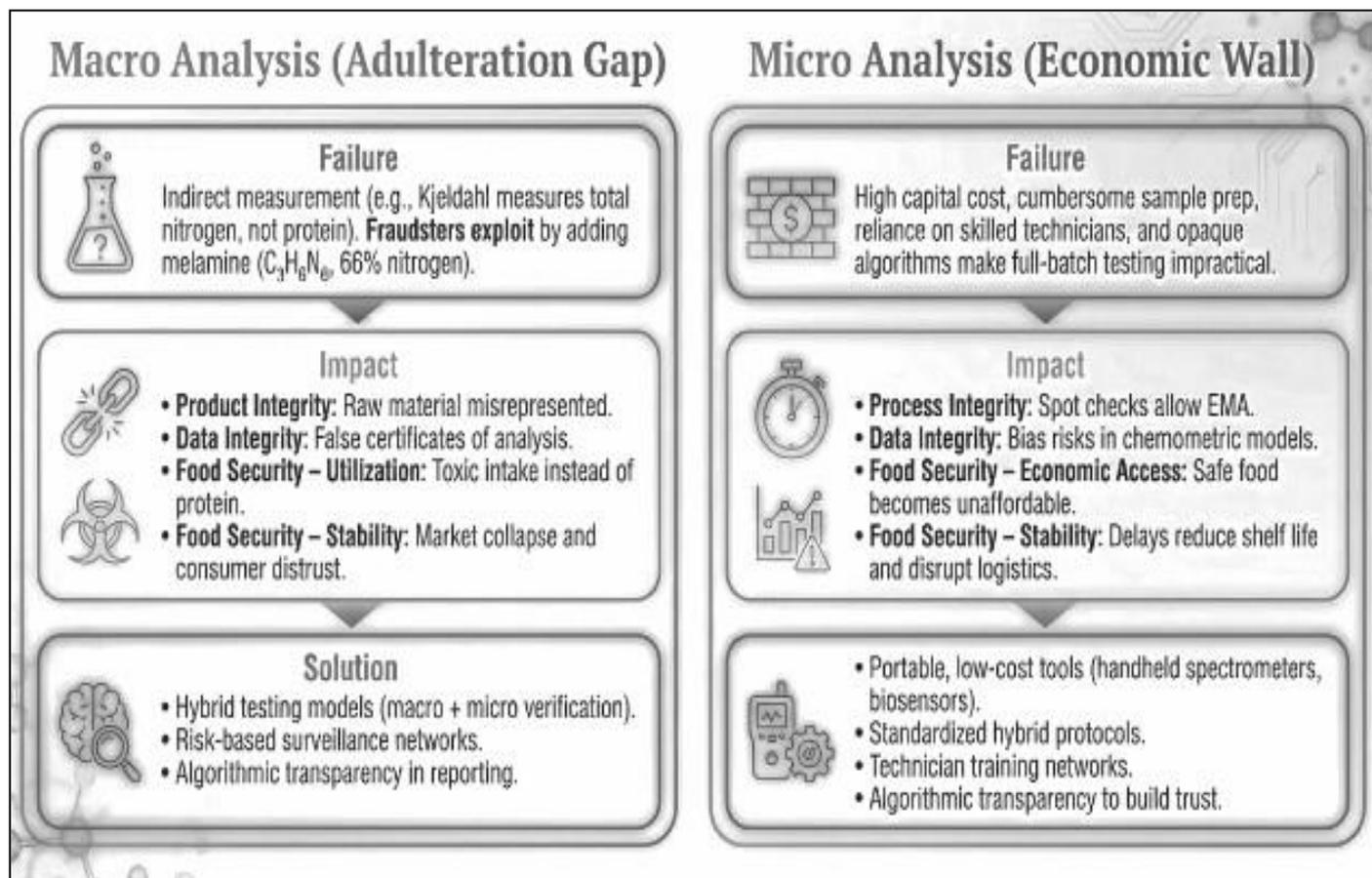
Industrial Applications: Moving from "Lab" to "Line"

Modern industry is transitioning from offline laboratory testing to real-time analysis directly on the production line to ensure immediate quality control.

- Real-Time Monitoring: This transformation requires the use of Process Analytical Technology (PAT) to develop a "batch fingerprint" which encompasses the characteristics of the material and process conditions, instead of doing laboratory analysis (Casian et al., 2022).

- Real-Time Monitoring of processes for instance now emphasizes the use of "Data Fusion" which involves the combination of machine vision (Macro) with spectral information (Micro) (Casian et al., 2022).

- Example (NIR Sensors): An example tool used for this "line" analysis that has been highlighted as important is Near-Infrared (NIR) spectroscopy, which can simultaneously measure "Macro" parameters such as "fat, protein, etc." present in milk without a lag in production time (Chaudhary et al., 2022)

- Speed: Detection of dangerous chemicals and toxins in food materials by the use of Terahertz (THz) spectroscopy is now accomplished in under 5 seconds and is therefore very suited to fast industrial production lines (Chaudhary et al., 2022).

Comparative Framework for Micro-Analytical Techniques

Table 3 serves as a selection guide for researchers and policy-makers to align laboratory capabilities with food security pillars (Safety, Authenticity, and Nutrition).

Table 3. Micro-Analytical Techniques Selection Guide

Technique	Target Analytes	Sensitivity	Cost / Sample	Sample Prep	Turnaround	Reference(s)
HPLC / LC-MS	Non-volatile organics (Melamine, Mycotoxins)	High	Medium	Moderate (Extraction)	Fast (15–30 min)	Abedini et al. (2021); Papadopoulou et al. (2025)
Technique	Target Analytes	Sensitivity	Cost / Sample	Sample Prep	Turnaround	Reference(s)
GC-MS	Volatiles, Pesticides, Fatty acids	High	Medium/High	High (Derivatization)	Medium (30–60 min)	Rodríguez-Blázquez et al. (2025)
ICP-MS	Heavy metals & Trace elements (Pb, Cd, As, Fe)	Ultra-High	High	High (Acid digestion)	Fast (2–5 min)	Sahadi & Basri (2025); Couto & Keating (2025)
IRMS	Stable Isotopes (C^{13}, O^{18}) for Origin	High	Very High	Moderate	Slow	Dua et al. (2025)
NIR / Raman / UV-Vis	Bulk composition, Adulterants, Fingerprinting	Low/Moderate	Very Low	Minimal/None	Instant	Basri (2025); Kharbach et al. (2023)
Aptasensors (Magnetic)	Foodborne Pathogens (Bacteria)	High	Low/Medium	Moderate	Fast	Kiani-Salmi et al. (2025)

Challenges: Matrix Interference and Green Chemistry

High-fat and protein-based food matrices (Macro-parameters) create inherently complex environments that can impede the detection of trace contaminants (Micro-parameters), directly threatening food integrity (Papadopoulou et al., 2025). These matrices can "poison" electrodes in biosensors or cause turbidity that interferes with optical signals, leading to false negatives in safety screenings (Kiani-Salmi et al., 2025). This "Micro" analysis becomes a victim of "Macro" interference, necessitating advanced extraction methods to isolate components without degradation (Nascimento et al., 2025). From a food security perspective, the requirement for multi-step, time-consuming sample preparation to overcome matrix interference can delay product release, affecting the "Stability" and "Access" pillars of the supply chain (Papadopoulou et al., 2025).

However, to overcome these challenges in a sustainable manner, the sector is moving towards Green Chemistry. The use of Natural Deep Eutectic Solvents (NADES) or Supercritical CO_2 instead of toxic petroleum-based solvents ensures that the analytical procedure maintains "Process Integrity" without causing secondary contamination (Chemat et al., 2019; Rodríguez-Blázquez et al., 2025). Additionally, the use of Ultrasonic Assisted Extraction (UAE) technology not only cuts down energy and processing time compared to conventional techniques but also supports the "Sustainability" aspect of food security by ensuring that food monitoring systems are efficient, environmentally friendly, and able to conserve resources for posterity.

Limitations of the Review

This review has certain limitations, and it is imperative to understand and address them. Firstly, this review is based on literature available to date, and it may have a certain bias. Studies with successful results in implementing analytical techniques have a greater chance of getting published compared to those with

unsuccessful results. Secondly, with the changing nature of analytical techniques, particularly with the incorporation of AI and chemometrics, certain technical parameters may change with the advent of new techniques.

CONCLUSION

Summary of Findings

Food integrity cannot be guaranteed through a single plane of analytical complexity. This review has demonstrated that exclusive reliance on Macro Analysis creates a dangerous "Adulteration Gap" where sophisticated fraud such as melamine spiking can flourish under the guise of legitimate bulk composition (Abedini et al., 2021). Conversely, the "Economic Wall" surrounding Micro Analysis makes high-precision forensic tools impractical for continuous industrial throughput (Shi et al., 2025). To resolve this, the industry is moving toward a Synergistic Strategy of Data Fusion, utilizing rapid Macro-sensors as a "first line of defense" and reserving Micro-validation for forensic confirmation (Casian et al., 2022).

Impact of the Study

The impact of this study review is that it offers a workable roadmap to close the gap between academic instrumental sensitivity and industrial operational scalability. By codifying the Macro-Micro Divide, this review:

- Identifies Vulnerabilities: It reveals the particular "blind spots" in the global supply chain that are being leveraged by nefarious actors in the "Three Lethal Cs" crisis.

- Advocates for Process Analytical Technology (PAT) Integration: It argues for a shift from "offline" testing to real-time Process Analytical Technology (PAT), which is imperative for the high-speed production process.

- Promotes Scientific Literacy in Fraud Prevention: It breaks down complex chemometric and isotopic principles (such as C3/C4 patterns in honey) into industrial processes.

Future Directions and Emerging Technologies

As the global food system becomes increasingly more complex, the move towards Food Industry 4.0 becomes more and more necessary. From the synthesis of the literature, three main technological frontiers have been identified that will shape the future of food security and integrity in the next decade.

Blockchain-Based Traceability Systems

The current systems have limitations in the form of "information silos" whereas blockchain provides a transparent and immutable ledger. This change can prove to be revolutionary for the Halal supply chain, in which integrity at religious and quality levels is of prime importance. Using blockchain, each and every stakeholder in the supply chain, starting from the producer to the consumer, can trace the integrity of the product in real-time and ascertain whether the product is "Halal to Tayyib" in nature, thereby eliminating the risk of "food fraud" and "substitution".

AI and Data Fusion

The future of food authentication is in the combination of high-tech equipment and Artificial Intelligence (AI). Chemometrics is being replaced by Machine Learning (ML) techniques that can be used to execute "Data Fusion" techniques. This is because AI is capable of combining information from different sources, such as using a combination of spectroscopy and chromatography, to identify complex patterns of adulteration that cannot be identified using a single technique.

Rapid Analysis in the Field

There is a significant move from laboratory-centralized testing to *on-site* field analysis. The invention of portable devices like handheld NIR spectrometers and smartphone-integrated aptasensors enables rapid screening at the point of need. Such tools enable regulatory authorities and quality assurance managers to perform instant checks

at the port, warehouse, or retail stores, greatly reducing the response time for safety interventions while ensuring the stability of food products.

Global Contributions

This review makes the following transformative contributions to the world:

- Socio-Economic Protection: By providing frameworks to combat Economically Motivated Adulteration (EMA), it safeguards consumer confidence and prevents multi-billion-dollar financial losses in markets worldwide.

- Public Health and Safety: By emphasizing molecular specificity, it directly prevents toxic contamination events, such as the powdered milk crisis, to ensure that "security" necessarily means "safety".

- Environmental Sustainability: By promoting Green Chemistry and Natural Deep Eutectic Solvents (NADES) extraction, it helps to decrease the use of harmful petroleum-based solvents and energy consumption in laboratories worldwide.

- Regulatory and Legal Standards: This research helps to provide a "legally defensible" standard of integrity to ensure that regulatory agencies have the scientific basis to require holistic, multi-level testing protocols.

In the end, the future of food security is contingent upon this integration of intelligence to bridge the gap between "Bulk Composition" for economic success and "Trace Composition" for health and safety.

ACKNOWLEDGMENT

REFERENCES

1. Abedini, R., Jahed Khaniki, G., Molaee Aghaee, E., Sadighara, P., Nazmara, S., Akbari-Adergani, B., & Naderi, M. (2021). Determination of melamine contamination in chocolates containing powdered milk by high-performance liquid chromatography (HPLC). Journal of Environmental Health Science and Engineering, 19(1), 165–171. https://doi.org/10.1007/s40201-020-00590-w
2. Ali, D. H. A. (2024). Food security in Malaysia: An empirical analysis of macroeconomic determinants. International Journal of Academic Research in Economics and Management Sciences, 13(3). https://doi.org/10.6007/IJAREMS/v13-i3/22076
3. Ali, M. H., Iranmanesh, M., Tan, K. H., Zailani, S., & Omar, N. A. (2022). Impact of supply chain integration on halal food supply chain integrity and food quality performance. Journal of Islamic Marketing, 13(7), 1515–1534. https://doi.org/10.1108/JIMA-08-2020-0250
4. Al-Omairi, M., Alamir, S. G., Salman, B. I., El Deeb, S., Alrashdi, Y. B. A., Al-Harrasi, A., & Ibrahim, A. E. (2025). Investigating trace and macro-element composition of herbal and nutraceutical dietary supplements marketed in Oman: Insights into safety and labeling. Biological Trace Element Research, 203(5), 2911–2923. https://doi.org/10.1007/s12011-024-04343-w
5. Alrobaish, W. S., Jacxsens, L., Luning, P. A., & Vlerick, P. (2021). Food integrity climate in food businesses: Conceptualization, development, and validation of a self-assessment tool. Foods, 10(6), Article 1302. https://doi.org/10.3390/foods10061302
6. Ascencio-López, W. J., Zayas-Pérez, M. T., Munguía-Pérez, R., Nevárez-Moorillón, G. V., Huerta-Lara, M., Avelino-Flores, M. D. C. G., . . . Avila-Sosa, R. (2025). Food security in a college community: Assessing availability, access, and consumption patterns in a Mexican context. International Journal of Environmental Research and Public Health, 22(9), Article 1314. https://doi.org/10.3390/ijerph22091314
7. Basri, K. N. (2025). Integration of spectroscopy and chemometric analysis for food authentication: A review. Halalsphere, 5(2), 69–79. https://doi.org/10.31436/hs.v5i2.127
8. Bento, J. A. C., Silva, M. A., Rosário Neto, A., Souza Neto, M. A. D., Narciso, M. G., Colombari Filho, J. M., & Bassinello, P. Z. (2024). Integration of physicochemical and instrumental quality data to estimate

the texture of polished rice. Ciência Rural, 54, Article e20230327. https://doi.org/10.1590/01038478cr20230327

9. Calloway, E. E., Carpenter, L. R., Gargano, T., Sharp, J. L., & Yaroch, A. L. (2023). New measures to assess the "other" three pillars of food security—availability, utilization, and stability. International Journal of Behavioral Nutrition and Physical Activity, 20(1), Article 51. https://doi.org/10.1186/s12966023-01451-z

10. Campomanes, F., Marshall, M., & Nelson, A. (2024). A method for estimating physical and economic food access at high spatial resolution. Food Security, 16(1), 47–64. https://doi.org/10.1007/s12571-023-014041

11. Campos, B. M., Ramalho, E., Marmelo, I., Noronha, J. P., Malfeito-Ferreira, M., Mata, P., & Diniz, M. S. (2022). Proximate composition, physicochemical and microbiological characterization of edible seaweeds available in the Portuguese market. Frontiers in Bioscience-Elite, 14(4), Article 26. https://doi.org/10.31083/j.fbe1404026

12. Carrillo, C., Tomasevic, I. B., Barba, F. J., & Kamiloglu, S. (2023). Modern analytical techniques for berry authentication. Chemosensors, 11(9), Article 500. https://doi.org/10.3390/chemosensors11090500

13. Casian, T., Nagy, B., Kovács, B., Galata, D. L., Hirsch, E., & Farkas, A. (2022). Challenges and opportunities of implementing data fusion in process analytical technology—A review. Molecules, 27(15), Article 4846. https://doi.org/10.3390/molecules27154846

14. Chaudhary, V., Kajla, P., Dewan, A., Pandiselvam, R., Socol, C. T., & Maerescu, C. M. (2022). Spectroscopic techniques for authentication of animal origin foods. Frontiers in Nutrition, 9, Article 979205. https://doi.org/10.3389/fnut.2022.979205

15. Chemat, F., Abert-Vian, M., Fabiano-Tixier, A. S., Strube, J., Uhlenbrock, L., Gunjevic, V., & Cravotto, G. (2019). Green extraction of natural products: Origins, current status, and future challenges. TrAC Trends in Analytical Chemistry, 118, Article 248. https://doi.org/10.1016/j.trac.2019.05.037

16. Couto, C., & Keating, E. (2025). Trace elements in food: Nutritional and safety issues. Foods, 14(16), Article 2802. https://doi.org/10.3390/foods14162802

17. Dragoev, S. G. (2024). Lipid peroxidation in muscle foods: Impact on quality, safety and human health. Foods, 13(5), Article 797. https://doi.org/10.3390/foods13050797

18. Dua, A., Bahman, S., Kelly, S., Dogra, S., & Sharma, K. (2025). Authentication of Indian honey based on carbon stable isotope ratio analysis—Verification of Indian regulatory criteria. Foods, 14(8), Article 1289. https://doi.org/10.3390/foods14081289

19. Fernando, Y., Saedan, R., Shaharudin, M. S., & Mohamed, A. (2021). Integrity in halal food supply chain towards the society 5.0. Journal of Governance and Integrity, 4(2), 103–114. https://doi.org/10.15282/jgi.4.2.2021.5948

20. Frigerio, J., Campone, L., Giustra, M. D., Buzzelli, M., Piccoli, F., Galimberti, A., . . . Labra, M. (2024). Convergent technologies to tackle challenges of modern food authentication. Heliyon, 10(11), Article e32297. https://doi.org/10.1016/j.heliyon.2024.e32297

21. Gallegos, D., Booth, S., Pollard, C. M., Chilton, M., & Kleve, S. (2023). Food security definition, measures and advocacy priorities in high-income countries: A Delphi consensus study. Public Health Nutrition, 26(10), 1986–1996. https://doi.org/10.1017/S1368980023000915

22. García-Díez, J., Gonçalves, C., Grispoldi, L., Cenci-Goga, B., & Saraiva, C. (2021). Determining food stability to achieve food security. Sustainability, 13(13), Article 7222. https://doi.org/10.3390/su13137222

23. Ham, J. H., Lee, Y. J., Lee, S. S., & Kim, H. Y. (2025). Food fraud in plant-based proteins: Analytical strategies and regulatory perspectives. Foods, 14(9), Article 1548. https://doi.org/10.3390/foods14091548

24. 24. Heghedűş-Mîndru, G., Negrea, P., Trașcă, T. I., Ștef, D. S., Cocan, I., & Heghedűş-Mîndru, R. C. (2023). Food intake of macro and trace elements from different fresh vegetables taken from Timisoara Market, Romania—Chemometric analysis of the results. Foods, 12(4), Article 749. https://doi.org/10.3390/foods12040749

25. Henry, B., Garai, R., & Kiong, W. S. (2025). Food security: Perspectives from the Bidayuh community, Sarawak, Malaysia. International Journal of Research and Innovation in Social Science. https://doi.org/10.47772/IJRISS.2025.908000442

26. Kharbach, M. (2025). AI-powered advances in data handling for enhanced food analysis: From chemometrics to machine learning. Foods, 14(19), Article 3415. https://doi.org/10.3390/foods14193415

27. Kharbach, M., Alaoui Mansouri, M., Taabouz, M., & Yu, H. (2023). Current application of advancing spectroscopy techniques in food analysis: Data handling with chemometric approaches. Foods, 12(14), Article 2753. https://doi.org/10.3390/foods12142753

28. Kiani-Salmi, N., Bahramian, B., Abedi-Firoozjah, R., Ebrahimi, A., Khezerlou, A., Tavassoli, M., & Ehsani, A. (2025). Recent advances and trends in magnetic nanoparticle-assisted aptasensors for foodborne bacteria monitoring: Applications, challenges, and updates. Food Chemistry: X, 25, Article 103156. https://doi.org/10.1016/j.fochx.2025.103156

29. Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2020). Production and characterization of hybrid briquettes from corncobs and oil palm trunk bark under a low pressure densification technique. Sustainability, 12(6), Article 2468. https://doi.org/10.3390/su12062468

30. Ling, E. K., & Wahab, S. N. (2020). Integrity of food supply chain: Going beyond food safety and food quality. International Journal of Productivity and Quality Management, 29(2), 216–232. https://doi.org/10.1504/IJPQM.2020.105963

31. Liu, X., Zhu, X., Han, Z., & Liu, H. (2025). Recent advances in the mechanisms of quality degradation and control technologies for peanut butter: A literature review. Foods, 14(1), Article 105. https://doi.org/10.3390/foods14010105

32. Munialo, C. D., & Mellor, D. D. (2024). A review of the impact of social disruptions on food security and food choice. Food Science & Nutrition, 12(1), 13–23. https://doi.org/10.1002/fsn3.3752

33. Nascimento, A. P. S., Duarte, M. E. M., Rocha, A. P. T., & Barros, A. N. (2025). Bioactive compounds, technological advances, and sustainable applications of avocado (Persea americana Mill.): A critical review. Foods, 14(15), Article 2746. https://doi.org/10.3390/foods14152746

34. Papadopoulou, A., Boti, V., & Nannou, C. (2025). Towards greener sample preparation: A review on microQuEChERS advances and applications in food, environmental, and biological matrices. Separations, 12(12), Article 339. https://doi.org/10.3390/separations12120339

35. Pérez-Escamilla, R. (2024). Food and nutrition security definitions, constructs, frameworks, measurements, and applications: Global lessons. Frontiers in Public Health, 12, Article 1340149. https://doi.org/10.3389/fpubh.2024.1340149

36. Renyard, A., Gooding, C., Chalissery, J. M., Petrov, J., & Gries, G. (2024). Effects of macro- and micronutrients on momentary and season-long feeding responses by select species of ants. Scientific Reports, 14(1), Article 5727. https://doi.org/10.1038/s41598-024-56133-y

37. Robson, K., Dean, M., Haughey, S., & Elliott, C. (2021). A comprehensive review of food fraud terminologies and food fraud mitigation guides. Food Control, 120, Article 107516. https://doi.org/10.1016/j.foodcont.2020.107516

38. Rodríguez-Blázquez, S., Gómez-Mejía, E., Rosales-Conrado, N., & León-González, M. E. (2025). Recent insights into eco-friendly extraction techniques for obtaining bioactive compounds from fruit seed oils. Foods, 14(13), Article 2271. https://doi.org/10.3390/foods14132271

39. Sahadi, N. A., & Basri, H. (2025). Determination of trace elements concentration in Saba banana samples at different maturation stages via ICP-MS. Enhanced Knowledge in Sciences and Technology, 5(2), 353–361. https://doi.org/10.30880/ekst.2025.05.02.042

40. Saleh, M., & Lee, Y. (2023). Instrumental analysis or human evaluation to measure the appearance, smell, flavor, and physical properties of food. Foods, 12(18), Article 3453. https://doi.org/10.3390/foods12183453

41. Shi, S., Zhang, K., Tian, N., Jin, Z., Liu, K., Huang, L., . . . Jiang, Y. (2025). Spectroscopic techniques combined with chemometrics for rapid detection of food adulteration: Applications, perspectives, and challenges. Food Research International, 192, Article 116459. https://doi.org/10.1016/j.foodres.2025.116459

42. Singh, A., Nagpoore, N. K., Singh, B. N., & Thakur, M. (2024). Comprehensive analysis of micro and macro-minerals, phytochemicals and proximate composition of Cordia dichotoma G. Forst fruits. Journal of Food Science and Technology, 61(9), 1790–1799. https://doi.org/10.1007/s13197-024-05957-7

43. Sumsion, R. M., June, H. M., & Cope, M. R. (2023). Measuring food insecurity: The problem with semantics. Foods, 12(9), Article 1816. https://doi.org/10.3390/foods12091816

44. Trziszka, T., Dobrzański, Z., Chojnacka, K., Bubel, A., Beń, H., Korczyński, M., . . . Tronina, W. (2021). Assessment of macro-, micro-, trace, and ultratrace element concentration in green-legged partridge hens' eggs from a free-range system. Agriculture, 11(6), Article 473. https://doi.org/10.3390/agriculture11060473

45. Wahid, D. N. A., Jawan, R., Nazarie, W. F. W. M., Gansau, J. A., Syahir, A., & Sabullah, M. K. (2022, August). Comparison of macro, trace and ultra-trace minerals contents of kelulut honey (Heterotrigona itama sp) from the West Coast of Sabah. Journal of Physics: Conference Series, 2314(1), Article 012002. https://doi.org/10.1088/1742-6596/2314/1/012002