

Analytical Chemical Approaches for Detecting and Quantifying Adulterants in Common Food Items

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Abstract: Food adulteration, intentional or accidental substitution, addition, or misrepresentation of food components poses serious threats to public health, consumer trust, and economic integrity. With the globalization of food supply chains, the sophistication of adulteration practices has increased, necessitating robust, sensitive, and rapid analytical methods for detection and quantification. This review presents a comprehensive overview of contemporary analytical chemical approaches employed to identify and quantify common adulterants in widely consumed food items such as milk, honey, spices, edible oils, and meat products. Emphasis is placed on techniques developed or significantly advanced over the past five to ten years, including chromatographic, spectroscopic, mass spectrometric, and biosensor-based methods. The review highlights the principles, advantages, limitations, and real-world applicability of these techniques, while also addressing emerging trends such as portable sensors, data-driven analytics, and multi-omics integration. The goal is to provide research scholars and scientists with a concise yet critical assessment of the current state-of-the-art in food authenticity testing and to outline future directions for ensuring food safety and integrity.

Keywords: Food adulteration; Analytical chemistry; Food authenticity; Spectroscopy; Chromatography; Mass spectrometry; Biosensors; Food fraud detection

Introduction

Food adulteration is a persistent global challenge, driven by economic incentives, supply shortages, and complex distribution networks. From the historical use of chalk in milk to modern-day melamine scandals and synthetic dyes in spices, adulterants range from harmless fillers to toxic compounds capable of causing acute poisoning or chronic disease. Regulatory bodies such as the FDA, EFSA, and FSSAI have established stringent guidelines, but enforcement relies heavily on accurate, reliable, and often high-throughput analytical

methods [1-4]. Traditional wet chemistry techniques are increasingly inadequate for detecting low-level or structurally sophisticated adulterants. Consequently, modern analytical chemistry has become indispensable in food safety laboratories worldwide. This review focuses on recent advances (2015–2025) in chemical methodologies tailored to detect and quantify adulterants in five high-risk food categories: dairy, honey, spices, edible oils, and meat. By evaluating the performance, accessibility, and innovation of these techniques, this article aims to guide researchers in selecting appropriate tools and inspire further development of next-generation food authentication platforms [5,6].

Chromatographic and Hyphenated Techniques

Chromatographic methods, particularly when coupled with selective detectors, remain the gold standard for separating and identifying complex mixtures in food matrices. High-performance liquid chromatography (HPLC) and gas chromatography (GC), especially when integrated with mass spectrometry (MS), offer high sensitivity, specificity, and quantitative accuracy.

In dairy analysis, HPLC-MS/MS is routinely used to detect melamine, urea, and whey protein adulteration in milk and infant formula. A 2021 study demonstrated a UHPLC-QTOF-MS method capable of simultaneously quantifying 12 nitrogen-rich adulterants at parts-per-billion (ppb) levels, with minimal sample preparation. Similarly, GC-MS is employed to profile fatty acid methyl esters (FAMES) in edible oils, enabling the detection of cheaper oil blends (e.g., palm oil in olive oil). Recent work has combined GC×GC-TOFMS (comprehensive two-dimensional GC) with chemometrics to distinguish extra virgin olive oil from adulterated samples with >98% accuracy.

For honey, HPLC with refractive index or evaporative light scattering detection is used to quantify sugar syrups (e.g., corn or rice syrup). However, stable carbon isotope ratio mass spectrometry (IRMS) remains the official AOAC method for detecting C4 plant sugars. Newer approaches integrate LC-IRMS to improve resolution and reduce false positives.

Despite their power, chromatographic methods are often time-consuming, require skilled operators, and involve expensive instrumentation and solvents—limiting their use in field settings or resource-constrained regions [7].

Spectroscopic and Imaging-Based Methods

Spectroscopic techniques offer rapid, non-destructive alternatives that are gaining traction for routine screening. Fourier-transform infrared (FTIR), Raman, near-infrared (NIR), and nuclear magnetic resonance (NMR) spectroscopies provide molecular "fingerprints" that can be analyzed using multivariate statistics to identify anomalies.

FTIR spectroscopy coupled with partial least squares discriminant analysis (PLS-DA) has been successfully applied to detect starch, urea, and detergents in milk within minutes. Portable FTIR devices now enable on-site testing at collection centers. Similarly, handheld Raman spectrometers can identify synthetic dyes like Sudan I–IV in chili powder and turmeric at concentrations as low as 10 ppm, even through packaging.

NMR spectroscopy, though less accessible due to cost, provides unparalleled structural information. A 2020 study used ¹H-NMR metabolomics to differentiate authentic saffron from adulterated samples containing gardenia or beetroot extracts, based on subtle differences in flavonoid and carotenoid profiles.

Hyperspectral imaging (HSI)—which combines spectroscopy with spatial mapping—has emerged as a powerful tool for surface adulteration detection. For example, NIR-HSI systems can visualize and quantify the distribution of metanil yellow in turmeric powder across an entire sample batch, offering both qualitative and quantitative insights [8].

Biosensors and Point-of-Need Platforms

To address the need for rapid, low-cost, and user-friendly detection, significant progress has been made in biosensor development. These devices combine biological recognition elements (e.g., antibodies, aptamers, enzymes) with transducers to generate measurable signals upon target binding.

Electrochemical aptasensors have shown promise for detecting melamine in milk, with limits of detection (LOD) down to 0.1 ppb and results in under 15 minutes. Lateral flow assays (LFAs), similar to home pregnancy tests, have been commercialized for allergen and antibiotic residue screening in meat and dairy. A recent innovation uses smartphone-based colorimetric readouts to enhance LFA quantification, improving reliability [9].

Fluorescent nanosensors based on quantum dots or carbon dots can detect Sudan dyes in oils via fluorescence quenching, with visual or instrumental readouts. One 2023 study reported a

paper-based microfluidic chip embedded with carbon dots for on-site detection of argemone oil in mustard oil—a common adulterant in South Asia linked to epidemic dropsy .

While biosensors excel in speed and portability, challenges remain in stability, shelf life, matrix interference, and regulatory validation for official control purposes.

Data Integration and Emerging Frontiers

The future of food adulterant detection lies in the convergence of analytical hardware with artificial intelligence (AI) and multi-omics approaches. Machine learning algorithms (e.g., support vector machines, random forests, deep neural networks) are now routinely trained on spectral or chromatographic datasets to classify authentic vs. adulterated samples with high accuracy, even in complex mixtures .[10]

Furthermore, integrated "foodomics" strategies—combining genomics, proteomics, and metabolomics—are being explored to establish comprehensive authenticity markers. For instance, DNA barcoding coupled with LC-MS metabolite profiling can simultaneously verify species origin (e.g., beef vs. horse meat) and detect added preservatives or fillers [11-13].

Blockchain-enabled traceability, when paired with analytical verification at key supply chain nodes, offers a holistic anti-fraud framework. However, the success of such systems depends on the availability of reliable, standardized analytical data.

Conclusion

The fight against food adulteration demands a multi-tiered analytical strategy. While chromatographic and mass spectrometric methods provide definitive, court-admissible evidence, spectroscopic and biosensor platforms enable rapid screening and field deployment. Over the past decade, innovations in miniaturization, data analytics, and multi-modal detection have significantly enhanced our capacity to safeguard food integrity. Nevertheless, gaps persist in standardization, accessibility, and real-time monitoring. Future efforts should focus on developing universally validated reference methods, affordable point-of-need devices, and open-access spectral libraries. For research scholars and scientists, the path forward involves not only refining existing techniques but also fostering interdisciplinary

collaboration between chemists, data scientists, engineers, and regulators to build a more transparent and trustworthy global food system.

References

1. Ellis, D. I., et al. (2012). *Analyst*, 137(18), 4215–4223.
2. Zhang, Y., et al. (2021). *Food Chemistry*, 345, 128765.
3. Li, X., et al. (2020). *Talanta*, 219, 121234.
4. Cabañero, A. I., et al. (2019). *Journal of Agricultural and Food Chemistry*, 67(15), 4253–4260.
5. Bansal, S., et al. (2017). *Food Control*, 73, 1119–1125.
6. Dhakal, S., et al. (2022). *Sensors and Actuators B: Chemical*, 351, 130987.
7. Consonni, R., & Cagliani, L. R. (2020). *Food Chemistry*, 309, 125712.
8. Liu, C., et al. (2021). *LWT - Food Science and Technology*, 147, 111589.
9. Wang, J., et al. (2020). *Biosensors and Bioelectronics*, 165, 112345.
10. Xu, Y., et al. (2022). *ACS Sensors*, 7(3), 789–797.
11. Gupta, A., et al. (2023). *Microchimica Acta*, 190, 112.
12. Wu, D., et al. (2021). *Trends in Food Science & Technology*, 112, 1–12.
13. Galobart, J., et al. (2019). *Analytical and Bioanalytical Chemistry*, 411, 6035–6045.