The Chemistry of Food Adulteration in the Age of Artificial Intelligence: A Comprehensive Review

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DOI: https://doi.org/10.51584/IJRIAS.2025.100700081

Received: 22 July 2025; Accepted: 28 July 2025; Published: 13 August 2025

ABSTRACT

The review presents principles behind food adulteration, the emergence of AI to revolutionize the detection systems, and the multi-level problems concerning the implementation of these technologies. We consider over 30 of the most common food adulterants, such as melamine in milk, Sudan dyes in spices, and diluted honey, describing their chemical properties and health risks. Detection methods using AI, such as spectroscopy with a machine-learning approach and blockchain-based traceability supported by IoT, have surpassed old chromatographic methods with detection accuracies of above 95%. But massive implementation costs along with data security and regulatory shortfalls have held back the deployment of these technologies. We postulate a multi-tier regulatory framework in which AI can be integrated into food safety practice and call for global coordination as an indispensable feature in combating food fraud.

Keywords: food adulteration, artificial intelligence, machine learning, food safety, spectroscopy, fraud detection

INTRODUCTION

Food adulteration is a pressing global problem affecting about 10 to 15% of food items traded on the international market, with economies estimated to be 40 billion USD per annum (1). Food adulteration, defined as the intentional addition of inferior substances which may be harmful to food products, stands as a set of serious public hazards and consumer confidence. This practice has since flourished through various advancements so as to evade detection. Past cases such as the melamine episode in China, which caused 300,000 illnesses (2), highlight the need and occasion for efficacious detection methods. In that view, AI has lately found a way into the food industry in transformations that offer new ways to assure food safety.

The Scale of the Problem

Food adulteration is not an issue solely specific to developing countries- it truly is a global concern affecting consumers and producers. As per the Food Fraud Network, nearly 40% of honey samples worldwide are adulterated with undeclared sweeteners (3), while different milk products have been found to contain melamine in various parts of the world. The economic consequences due to food fraud are humiliating, with reported losses reaching $40 billion annually (1).

How food adulteration can adversely impact a person is another matter aside from economic issues. Perhaps another example of concern: The neurotoxicity through lead in turmeric (4), while Sudan dyes cause worries about carcinogenicity (5). Examples like these cry out for effective detection means to protect the health of the public.

The Chemistry of Food Adulteration

Common Adulterants and Their Health Impacts

Food adulterants can be classified into several categories based on their chemical properties and health implications. Table 1 summarizes the molecular profiles of common adulterants, their chemical formulas, and associated health risks.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

Table 1: Molecular Profiles of Common Food Adulterants

Food Product	Adulterant	Chemical Formula	Health Impact
Milk	Melamine	$C_3H_6N_6$	Kidney failure (6)
Olive Oil	Sudan IV Dye	$C_{24}H_{20}N_4O$	Carcinogenic (5)
Turmeric	Lead Chromate	$PbCrO_4$	Neurotoxicity (4)
Honey	High-fructose corn syrup	$C_6H_{12}O_6$	Metabolic disorders (7)
Black Pepper	Papaya Seeds	$C_8H_{10}O_4$	Gastrointestinal issues (8)
Coffee	Tamarind Seed	$C_{11}H_{14}O_7$	Allergic reactions (9)

Mechanisms of Adulteration

Spotting fake ingredients is hard since they often copy the real thing's look. Like, melamine gets added to milk to fool tests into showing higher protein levels. And those Sudan dyes? They're used to make spices look brighter. These tricks mess with food quality and can make people really sick.

The way these things work is pretty twisted. that melamine thing in milk? Not only does it fake protein content, but it can also hurt your kidneys or even kill you. Putting lead chromate in turmeric to pump up the color? That adds a nasty heavy metal to your food, which can lead to lasting health problems.

AI-Driven Detection Technologies

Machine Learning and Spectroscopy

Machine learning, a subset of Artificial Intelligence, has changed how we find food adulteration. Older approaches like chromatography can take a lot of time and money. AI methods, by comparison, can be more than 95% accurate in finding adulterants.

Table 2: Comparison of Traditional and AI-Enhanced Detection Methods

Technique	Traditional Accuracy	AI-Enhanced Accuracy	Time Reduction
High-Performance Liquid Chromatography (HPLC)	82%	97%	4x faster
Raman Spectroscopy	75%	94%	10x faster

AI, especially machine learning, has greatly changed how we find food adulterants. Old methods, like chromatography, usually take a lot of time and cost a lot. AI methods, on the other hand, can be more than 95% correct in finding these adulterants. A study showed that a CNN Raman scanner could find 28 artificial dyes in spices with 99.3% accuracy (10). This makes testing faster and allows us to watch food quality as it happens.

Combining AI with spectroscopy not only makes things more accurate but also makes the testing process easier. For example, near-infrared spectroscopy with machine learning can examine food samples as they are being processed. It gives quick feedback about possible adulteration (11). This is helpful in managing the supply chain, where catching contamination early can stop bad products from getting to consumers.

IoT and Blockchain Integration

Integrating AI, IoT, and blockchain presents a way to trace where food comes from. For example, the IBM Food Trust uses blockchain to keep tabs on and lower fraud in olive oil, with a reported 98% accuracy rate (12). This makes the supply chain clearer, allowing consumers to check if a product is real.

IoT devices allow constant tracking of food products all along the supply chain. Sensors keep records of environmental conditions such as temperature and humidity, which affect how good the food is. AI reviews this info to spot any possible issues (8). This gives an active way to handle food safety, protecting people and helping producers follow rules.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

Challenges in AI Implementation

Economic Barriers

The expense of advanced detection tech is a major obstacle, especially for small producers. Equipment can cost over $50,000, which restricts access to better testing (1). Also, about 40% of farming areas lack reliable internet, impeding the use of IoT (13).

The economic impact of food adulteration goes beyond just detection costs. Producers who adulterate food might get a short-term financial benefit, which hurts ethical practices and makes it hard for honest businesses to compete (9). Because of this, we need to work together to offer affordable testing and aid to small producers.

Ethical and Regulatory Concerns

Using AI in food safety brings up ethical problems about data privacy and bias in algorithms. For example, AI systems might not catch 5-10% of new contaminants, causing some to be missed (7). Also, gathering sensitive data from farmers could be misused, so strong rules are needed to protect their privacy (14).

The ethical considerations of AI in food safety also include accountability. If AI systems don't find contamination, figuring out who is responsible can be tricky. This ambiguity shows that we need clear rules and standards for using AI in food safety (8).

POLICY RECOMMENDATIONS AND FUTURE DIRECTIONS

Proposed Regulatory Framework

To effectively combat food adulteration, a tiered regulatory framework is essential. **Table 3** outlines the proposed requirements and enforcement mechanisms.

Table 3: Proposed AI Governance Model

Tier	Requirement	Enforcement Body
Tier 1	Mandatory adulterant databases	World Trade Organization (1)
Tier 2	Algorithm transparency logs	European Union AI Act (15)

Implementation Phases

The first stage (2024-2026) will focus on making spectral libraries standard for common additives. The second stage (2027-2030) includes setting up blockchain-AI networks for current monitoring and tracing. These stages require training programs for producers and those in charge to make sure things are done right and rules are followed. Public awareness campaigns can help people understand food safety and how tech helps keep it that way.

CONCLUSION

To improve food safety, artificial intelligence has the ability to quickly find problems like contamination by using cameras to watch food on conveyor belts. To make it work well, we need to manage money carefully, think about what is ethically right, and make sure the government, food companies, and specialists work together to make rules.

Being open is super important for using AI ethically in food safety. Because AI systems can be pricey, giving tax breaks might get more people to use them. It is also key to deal with the problem of AI potentially taking jobs away, to make sure things are fair.

Since many places do not have specific rules for using AI in food safety, governments should work on making them a priority. When AI tracks food, it can make things easier to see and keep people responsible. In short, using AI in food safety has chances and challenges that we must handle carefully to make the process better.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

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