Forensic Traceability Technologies as a Mechanism for Reducing Global Food Waste

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Introduction

Global food waste presents one of the most pressing ethical, environmental, and economic challenges of our time, with approximately one third of all annual food production lost or wasted each year (ReFED 2021). Technologies such as DNA barcoding, stable isotope ratio analysis, and blockchain systems offer promising solutions by enhancing transparency, verifying food authenticity, and improving supply chain efficiency. However, these forensic and traceability tools are only as effective as the systems in which they operate. Without consumer education, policy enforcement, and behavioral change, even the most advanced technologies may fail to produce a lasting impact. This review explores how integrating these technologies with social, regulatory, and economic frameworks can drive meaningful reductions in global food waste.

Background Research

Food traceability technologies such as DNA barcoding, stable isotope ratio analysis, and blockchain systems each offer unique contributions to verifying the authenticity and origin of food products. DNA barcoding uses a standardized 648-base pair region of the cytochrome c oxidase I (COI) gene to generate genetic "barcodes" that reliably identify species based on conserved yet variable regions of their DNA (Ratnasingham et al. 2007). Complementing this, stable isotope ratio analysis leverages environmental signatures in elements like carbon, nitrogen, and oxygen, which vary predictably by geography, climate, and farming practices, enabling scientists to authenticate a product's origin even when documentation is lacking (Lees & Reimann 2021). Blockchain technology adds a digital layer of security by functioning as a decentralized, tamper-resistant ledger that transparently records the entire lifecycle of a food product, from source to consumer (Galvez et al. 2018). When integrated with forensic techniques like DNA barcoding and stable isotope ratio analysis, blockchain systems allow for real-time, verifiable, and cross-referenced traceability, strengthening consumer trust and reducing opportunities for fraud or mislabeling (Bumblauskas et al. 2020).

In today's globalized food systems, the origin and authenticity of food products are often obscured by complex, multi-layered supply chains. This lack of transparency contributes to food fraud, regulatory failures, and consumer mistrust, all of which may lead to increased food waste. Scientific tools from forensic science, such as DNA barcoding, stable isotope ratio analysis, and blockchain systems, are novel technologies that can address these challenges by providing objective data about a food product's species and geographic origin.

However, even when forensic data is available, it is rarely made accessible to consumers or integrated into everyday supply chains. This is where blockchain technology offers a complementary solution. Blockchain provides a secure, decentralized platform for recording and sharing data across stakeholders, ensuring that forensic findings are not tampered with or selectively reported. When paired with forensic science, blockchain systems could create a trusted, verifiable chain of custody for food products from origin to point of sale. Despite this potential, these tools remain underutilized in mainstream food traceability efforts.

Data Collection

Having established the scientific basis and practical potential of forensic traceability technologies, it is important to examine how these tools are currently being used in real-world contexts. The following section summarizes the documented applications of DNA barcoding, stable isotope ratio analysis, and blockchain systems in food systems, alongside their roles in reducing food waste, limitations, and areas for improvement. This snapshot provides a foundation for evaluating both the promise and the challenges of scaling these technologies effectively.

Summary of Forensic Traceability Technologies and Their Roles in Reducing Food Waste

	DNA Barcoding	Stable Isotope Ratio Analysis	Blockchain Systems
Current Use	• Seafood identification (Galimberti et al. 2013) • Meat authentication (Galimberti et al. 2013)	• Geographic origin verification (Kelly et al. 2005) • Spoilage detection potential (Rossmann 2001)	• Traceability for seafood, beef, produce (Galvez et al. 2018)

Food Waste Reduction	• Reduces mislabeling → fewer unnecessary recalls • Maintains consumer trust → prevents premature disposal (Galimberti et al. 2013)	• Detects fraud → reduces waste from rejected products • Potential to predict spoilage better than current "best by" labels	• Improves recall speed and targeting • Increases transparency → prevents unnecessary discards
Identifying the Gap	• Limited accessibility in informal or low-resource markets (Fanelli et al. 2021) • Lack of public awareness about seafood fraud and its	• Expensive and requires specialized equipment • Limited integration into real-time supply chain monitoring (Mai et al. 2019)	• Human error in data entry • Digital divide in rural/agricultural settings (Galvez et al. 2018)

	environmental impacts (Stern et al. 2017)		
Potential Solution/ Bridge the Gap	• Citizen science/public initiatives to raise awareness (Staffen et al. 2017)	• Integrate isotope data into smart labeling and blockchain systems (Kelly et al. 2005)	• Standardized data input protocols (Galvez et al., 2018) • Mobile-accessible blockchain solutions (Kamilaris et al. 2019)

Findings

While DNA barcoding, stable isotope ratio analysis, and blockchain systems offer scientifically robust solutions for improving food traceability and reducing waste, their practical impact remains limited without broader behavioral and institutional support—despite evidence of their potential in current applications, adoption and accessibility barriers continue to hinder widespread implementation. As summarized earlier, each technology addresses a different point in the supply chain, but all face adoption barriers rooted in accessibility and awareness. DNA and isotope-based techniques have shown promise in identifying mislabeling, fraud, and geographic inconsistencies in food products, (Wong et al. 2008) while blockchain systems have demonstrated potential to secure and transparently share these data across supply chains (Galvez et al. 2018). However, these tools are not self-executing: they require human input, consistent use, and societal trust to function effectively. For instance, accurate isotope databases rely on industry cooperation and transparency, while blockchain systems require reliable data entry and buy-in from producers, regulators, and consumers.

Moreover, the success of these technologies is constrained by limited public awareness, gaps in education, and uneven access to digital infrastructure. Many stakeholders, particularly in low-resource contexts, may lack the resources or training to implement these systems at scale (Fanelli et al. 2021). Without consumer demand for traceable, authenticated food or industry incentives to adopt these tools, even the most advanced technologies remain underutilized. Thus, while the scientific foundation for reducing food fraud and waste is strong, its real-world application hinges on social behavior, institutional trust, and cultural values around food transparency.

Implications

These findings highlight a crucial truth: technological tools like DNA barcoding, stable isotope ratio analysis, and blockchain systems will not substantially reduce food waste unless they are embedded within supportive social and behavioral frameworks. The effectiveness of these technologies depends not only on their scientific precision but also on how people use, interpret, and respond to them across the food system.

For instance, DNA barcoding can verify species authenticity and detect mislabeling, but its success requires behavioral change among producers, who must be willing to submit to transparent verification, and among consumers, who must demand verified labeling. Educational campaigns can empower consumers to choose traceable products, thereby incentivizing retailers to adopt barcoding protocols (Wong et al. 2008). Stable isotope ratio analysis, which tracks food origins through environmental chemical signatures, faces barriers if suppliers are not trained in sample collection protocols or if legal bodies lack the expertise to interpret isotope data in fraud investigations. Scaling up these systems requires training initiatives and cross-sector collaboration between scientists, regulators, and food businesses (Camin et al. 2017).

Blockchain systems are especially dependent on behavioral consistency and trust: unless every actor in a supply chain inputs accurate data, the transparency benefit collapses. Social trust, inter-organizational cooperation, and digital literacy are foundational for the success of blockchain traceability (Galvez et al. 2018). Consumers must also be educated about what blockchain-based transparency means, so they can recognize and support ethically sourced food. Real-world implementations show the potential of integrating these technologies with behavioral initiatives: Walmart's blockchain pilot significantly improved recall speed and reduced waste by fostering supply chain accountability (Kamath 2018), Norwegian retailers using Keep-it indicators empowered staff and consumers to better manage food shelf life, reducing over-disposal (“Keep-It” 2022), and FoodWise’s behavioral platform paired traceability tech with awareness campaigns to reduce campus food waste (Yu et al. 2023). Together, these examples underscore that scientific traceability methods must be matched with behavioral interventions, education, and social trust-building to create food systems that are not just technologically capable but socially equipped to prevent waste.

Conclusion

Overall, the integration of forensic traceability technologies, such as DNA barcoding and stable isotope ratio analysis, paired with technological innovations, such as blockchain systems, provide a novel mechanism to identify food fraud and limit wasted food. These tools offer a method of scientific precision and data transparency that has the potential to create smarter, more accountable food systems. However, the success of such systems relies not solely on technological advancement, but also on the social, behavioral, and institutional frameworks in which they are applied. Thus, without widespread consumer engagement, education, and supportive policy enforcement, these technologies risk becoming underutilized solutions to deeply entrenched problems. For these traceability systems to be truly effective, stakeholders across the food supply chain (producers, regulators, retailers, and consumers) must align around shared values of transparency, sustainability, and trust. By embracing both innovation and collaboration, society can begin to address the root causes of wasted food and move toward a more equitable and efficient global food system. As global food systems face rising pressure, solutions that unite science, policy, and public engagement offer a promising path forward.

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