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Precision food safety: Advances in omics-based surveillance for proactive detection and management of foodborne pathogens

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ABSTRACT

The field of food safety is undergoing a paradigm shift from reactive detection to precision-based prediction and prevention, driven by advances in omics technologies and high-resolution surveillance methods. Among the most novel developments are microbiome-based monitoring strategies, which have the potential to serve as early indicators of increased contamination risk or pathogen persistence by identifying shifts in microbial community composition in food and food processing environments. Additionally, wastewater-based surveillance is emerging as a powerful, population-level early warning system with the potential to enhance traditional case-based surveillance by detecting elevated levels of foodborne pathogens in the community before clinical cases are reported. These innovations, alongside advances in whole-genome sequencing, metagenomics, and quasimetagenomics, form the foundation of precision food safety by enabling granular insights into pathogens across the supply chain. While artificial intelligence is not yet widely implemented in food safety, it is increasingly being explored as a tool to integrate and interpret complex omics and other data. In the future, AI has the potential to optimize resource allocation, improve the accuracy of risk assessments, and support earlier, more targeted interventions. This review summarizes recent innovations in sequencing-based detection and characterization of microbial hazards and discusses how omics data can be leveraged to enhance food safety surveillance and decision-making.

1. Introduction

The globalization of food supply chains and the increasing complexity of food production and processing have increased the need for a framework that integrates modern technologies and innovative tools to enhance food safety and traceability (FDA, 2024). The United States Food and Drug Administration (FDA) developed a vision for smart food safety, which consists of four core elements focused on (i) tech-enabled traceability, (ii) smarter tools and approaches for prevention and outbreak response, (iii) new business model and retail modernization, and (iv) food safety culture (FDA, 2024). The second core element includes precision food safety, previously characterized as high-resolution pathogen detection, characterization, and risk assessment using omics data (Kovac et al., 2017). The growing adoption of machine learning in food safety (Njage et al., 2020; Pascoe et al., 2024) has created new opportunities to enhance precision food safety methods (particularly those based on next-generation sequencing) with AI analytics, offering an opportunity to develop proactive early warning systems for microbial hazard contamination, outbreak detection, as well as prevention. AI refers to the simulation of human cognitive functions by computer systems and encompasses several key subfields. Among these are machine learning (ML), which focuses on algorithms that enable systems to learn from data and improve their performance over time without explicit programming; deep learning (DL), which uses multi-layered neural networks to model complex, high-dimensional data patterns; as well as natural language processing (NLP) that enables computers to interpret, and generate human language, playing a central role in text and speech-based applications. Further, explainable AI (XAI)

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