

Integrated approaches to food and beverage safety: assessing contaminants, nutritional quality, and emerging detection technologies for public health enhancement

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ABSTRACT

This review synthesises integrated strategies for safeguarding food and beverage safety, with emphasis on emerging contaminants, nutritional quality, and public health implications. Key contaminants, particularly microplastics (MPs) and synthetic dyes, are increasingly detected in packaged foods, bottled water, salt, and beverages, raising significant safety concerns. Recent studies reported a wide variability in MPs contamination across regions and food types, reflecting the absence of standardised detection protocols. Advances in analytical technologies, including nanomaterial-based electrochemical sensors, green microextraction techniques, and artificial intelligence (AI)-assisted detection platforms, have improved sensitivity and selectivity, although further validation and industrial scalability remain necessary. Similarly, research on synthetic dyes highlights progress in sustainable extraction and detection methods, such as deep eutectic solvent (DES) microextraction and sensor innovation, aligning with the growing shift toward eco-efficient analytical practices. This review also evaluates the nutritional and metabolic impacts of ultra-processed foods (UPFs), which represent a major component of modern diets and are consistently associated with obesity, metabolic syndrome, and other non-communicable diseases. Cross-country analyses revealed excessive sugar, salt, and fat content in UPFs, alongside gaps in front-of-package labelling systems and limited consumer literacy. These findings underscore the need for harmonised nutritional profiling frameworks and product reformulation policies. In addition, the role of probiotics in enhancing microbial safety and functional beverage quality is examined. Emerging microencapsulation techniques show promise in improving probiotic survival and bioactivity during storage and digestion, though mechanistic insights remain limited. Policy assessments indicate that fiscal measures, advertising regulations, and labelling requirements are inconsistently applied across nations, revealing persistent misalignment between technological innovations, regulatory implementation, and consumer behaviour. Three major research gaps are identified: (i) the lack of standardised, validated analytical methods for emerging contaminants; (ii) limited mechanistic understanding of probiotic stability and functionality in beverage systems; and (iii) insufficient integration of culturally adaptive, consumer-centred policy strategies. Future research should prioritise harmonised analytical frameworks, scalable and sustainable detection technologies, a clearer understanding of probiotic mechanisms, and comprehensive nutritional databases. Strong multisectoral collaboration among scientists, industry, and policymakers is crucial to translate these advances into effective public health actions. Collectively, this review highlights the need for an integrated, multidisciplinary approach that unites technological innovation, nutritional science, and evidence-based regulation to ensure the safety of food and beverages worldwide.

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1. INTRODUCTION

The modern food supply is confronted with multifaceted safety challenges due to increased industrialisation, complex food processing, and contaminant exposure. As a result, chemical and physical contaminants

are becoming increasingly pervasive, making food and beverage safety paramount to public health. Among emerging concerns, microplastic (MPs) contamination has gained significant attention due to the widespread presence in a variety of food matrices, including packaged foods and beverages, and the potential for bioaccumulation in human

tissues (Mir et al., 2025; Ahmad et al., 2025). The detection of MPs in consumables such as bottled water, salt, and human tissues underscores the pressing need for effective monitoring methodologies (Codrington et al., 2025; Bocker & Silva, 2025). Concurrently, synthetic dyes and additives widely used in food production have raised safety questions, culminating in the development of advanced analytical techniques for sensitive and selective detection (Mistry et al., 2024; Narouei & Rahmani, 2024).

Another critical factor influencing health outcomes globally is nutritional quality. The rapid expansion of ultra-processed foods (UPFs) in diets has been linked to increasing rates of obesity, metabolic syndrome, and non-communicable diseases (Hafner et al., 2025; Ghosh-Jerath et al., 2024). Comprehensive mapping and nutritional profiling studies have revealed poor-quality nutrient composition in UPFs, such as elevated sugar levels, saturated fat, and salt, contributing to adverse health impacts (Young et al., 2024; Olarewaju et al., 2025). These trends are compounded by dietary patterns characterised by high consumption of sugar-sweetened beverages and discretionary foods with poor nutritional value, necessitating public health interventions and regulatory frameworks to enhance consumer awareness and product reformulation.

Advances in detection technologies serve as pivotal tools to address food safety concerns. Innovations such as superhydrophobic surface modifications in flexible capacitive sensors have demonstrated enhanced accuracy and resistance to liquid interference, enabling reliable performance in complex food matrices and harsh industrial conditions (Xiao et al., 2025). Additionally, nanostructure-based electrochemical sensors employing materials such as copper ferrite / zero-valent copper ($\text{CuFe}_2\text{O}_4/\text{Cu}^0$) hierarchical nanostructures have been developed for ultra-sensitive detection of food colourants such as sunset yellow, Malachite Green, and tartrazine in various beverages (Fan et al., 2024). The integration of green chemistry principles through deep eutectic solvent (DES)-based microextraction methods further exemplifies the trend toward sustainable, rapid, and efficient contaminant analysis (Kizil, 2024; Olgun et al., 2024). Such multidisciplinary technological progress enhances the capacity for continuous quality control and risk assessment within the food industry.

The scrutiny of labelling and marketing practices addresses consumer transparency and public health. Studies investigating the nutritional composition and voluntary front-of-package labelling schemes reveal disparities in information completeness, particularly concerning nutrients such as sodium, potassium, and phosphorus critical for vulnerable populations (Asan et al., 2025; Hafner et al., 2025). The pervasive influence of high-fat, salt, and sugar (HFSS) food

marketing, particularly through digital platforms, raises concerns regarding dietary behaviours, urging regulatory policy advancements and consumer education (Vaughan et al., 2025; Fretes et al., 2025). These dimensions collectively highlight the need for integrated approaches that encompass contamination detection, nutritional evaluation, and regulatory oversight to safeguard food and beverage safety comprehensively.

Figure 1 maps key challenges discussed in this review, conceptually framed along the axes of analytical complexity and public health impact, highlighting the urgent need for advanced solutions in high-priority areas such as MPs and synthetic dyes.



Figure 1: Conceptual framework for prioritising emerging food safety challenges

This review aims to synthesise evidence on integrated strategies for detecting chemical and physical contaminants, assessing nutritional quality, and applying emerging advanced technologies to food and beverage safety. Prevalence and health risks associated with contaminants such as MPs and synthetic dyes are examined, alongside profiling the nutritional impact of UPFs and dietary patterns. In addition, the review evaluates state-of-the-art detection methodologies, including novel sensors and green microextraction techniques, emphasising the role in improving safety monitoring and quality assurance. Furthermore, public health implications are discussed in the context of regulatory frameworks, policy measures, and consumer awareness, with a view toward holistic food safety enhancement and informed future research directions.

2. MICROPLASTIC CONTAMINATION

The MPs, defined as plastic particles smaller than 5 mm, have been increasingly reported in a wide range of food and beverage products. The widespread occurrence of this material is attributed to environmental contamination and the extensive use of plastic packaging and processing equipment

throughout the food supply chain. The presence of MPs has been documented in various food matrices such as packaged foods, bottled water, tea bags, salt, fish, milk, sugar, honey, and beverages, raising significant public health concerns (Mir et al., 2025; Ahmad et al., 2025; Codrington et al., 2025; Irfan et al., 2025; Zhao et al., 2025).

Recent investigations have quantified MP contamination across diverse food products. For instance, Ahmad et al. (2025) analysed 112 commercial food and beverage samples in Riyadh, Saudi Arabia, and reported considerable variations in MP size and polymer composition. The highest concentrations were observed in tea bags, followed by sugar, honey, and salt, which were consistent with the findings of Zhao et al. (2025). The detection of MPs in human biological tissues further emphasises the potential for bioaccumulation and related toxicological effects. Codrington et al. (2025) detected seven polymer types in penile tissue samples, suggesting deep tissue penetration and systemic exposure, while Wieland et al. (2024) highlighted similar bioaccumulation patterns in other human tissues. A meta-analysis of South Asian food items reported elevated MP concentrations in salt, fish, milk, and drinking water, frequently exceeding global levels, with polyvinyl chloride and polyester identified as dominant polymer types (Mondal et al., 2025; Wieland et al., 2024).

The detection and quantification of MPs in food systems remain technically challenging due to methodological inconsistencies among studies. Variations in sampling procedures, filter pore sizes, and analytical techniques have contributed to discrepancies in reported data (Canga et al., 2024; Jeong et al., 2017). Standardised analytical protocols incorporating harmonised sampling, validated particle-size classifications, and consistent reporting units are required to enhance data comparability and reliability. In recent years, the application of advanced detection methods such as artificial intelligence (AI)-assisted image recognition and multispectral imaging has improved precision and throughput; however, the widespread adoption of these technologies in industrial and regulatory contexts remains limited (Fretes et al., 2025; Zou et al., 2023).

The health implications of MP ingestion have been examined through *in vivo* and *in vitro* studies. Exposure to MPs has been associated with inflammatory responses, oxidative stress, and cellular dysfunction, potentially leading to gastrointestinal, reproductive, neurotoxic, and cardiovascular disorders (Bocker & Silva, 2025; Jin et al., 2022). Nanoplastics can cross biological membranes more readily due to the smaller particle size, and may induce hypersensitivity and developmental toxicity (Hernandez et al., 2019; Hore et al., 2024). These findings indicate a potential cumulative risk of exposure and underscore the need for

standardised detection protocols and stronger regulatory frameworks to mitigate public health concerns (Mir et al., 2025; Zou et al., 2022).

The remediation of MPs from food matrices and the environment involves multiple approaches encompassing physical, chemical, biological, and hybrid methods (Chowdhury et al., 2025; Deng et al., 2017). Each approach presents distinct mechanisms, advantages, and limitations depending on operational conditions and matrix complexity. Biological interventions have shown promising outcomes. Liu and Shimizu (2025) demonstrated that dietary supplementation with chitosan promoted faecal excretion of polyethylene MPs in rat models, indicating a potential biocompatible strategy to reduce bioaccumulation. Similarly, Huo et al. (2025) reported that specific dietary additives can facilitate MP elimination, suggesting a feasible avenue for human dietary interventions.

Overall, the increasing evidence of MP contamination in food and beverage systems calls for an integrated research approach combining detection science, toxicological evaluation, and policy intervention. Future studies should emphasise the development of standardised analytical frameworks, the advancement of scalable detection technologies, and the establishment of evidence-based regulations to reduce exposure. Collaborative efforts among scientists, policymakers, and the food industry are crucial to ensuring effective monitoring and management of microplastic contamination, thereby safeguarding public health and promoting sustainable food system practices.

3. CHEMICAL CONTAMINANTS: DYES AND ADDITIVES

Synthetic food dyes such as Sunset Yellow and Sudan dyes are widely employed to enhance the visual appeal of beverages and processed foods, yet excessive intake of these substances poses health concerns, prompting stringent regulatory scrutiny. Advanced and sensitive analytical methods have been developed to monitor these dyes effectively within complex food matrices.

Mistry et al. (2024) engineered a highly sensitive electrochemical sensor utilising copper oxide-zirconium dioxide (CuO-ZrO₂) nanocomposites for detecting Sunset Yellow in foods and beverages, reporting a broad detection range (0.01–50 ppm) and rapid response with high sensitivity. Similarly, Zhang et al. (2025) developed red-emissive carbon dots as fluorescent probes for Sunset Yellow quantification, achieving detection limits as low as 0.026 µg/mL with excellent recovery rates, thus offering a promising approach for routine food safety monitoring.

Complementary techniques such as electrochemical sensing using biochar-modified electrodes have been explored. Tong et al. (2024) fabricated a (cobalt oxide)

Co₃O₄@biochar modified pencil graphite electrode to detect Sunset Yellow with a low detection limit (1.3×10^{-6} M), demonstrating cost-effectiveness, selectivity, and stability suitable for beverage analysis.

Sustainable solvent systems have enhanced the extraction and preconcentration of these dyes. Kizil (2024) introduced a green DES for liquid-liquid microextraction of Lissamine Green B, achieving low detection and quantification limits with minimal environmental impact. Olgun et al. (2024) similarly developed a hydrophobic DES-based microextraction method for Brilliant Blue FCF in beverages, illustrating high recoveries (95–101%) and ecological green certifications (AGREE and GAPI). Narouei and Rahmani (2024) extended these approaches for Ponceau-4R detection using vortex-assisted eutectic solvent microextraction, attaining a 50-fold enrichment and excellent recovery in fruit juice matrices.

Additionally, Jafari and Roushani (2025) synthesised covalent organic frameworks grafted on copper foam as sorbents for thin film microextraction of phthalate esters, coupling extraction with gas chromatography-flame ionisation detection to ensure sensitive and reliable quantification. Such multifaceted extraction and detection modalities demonstrate the progression towards efficient, sustainable, and precise monitoring of chemical additives in food and beverage safety assessments.

4. UPFs AND NUTRITIONAL COMPOSITION

The growing consumption of UPFs has garnered substantial attention due to the negative implications for nutritional quality and public health. Ghosh-Jerath et al. (2024) conducted an extensive mapping of UPFs in the Indian food market, identifying a diverse range of commonly consumed products. Their investigation revealed a lack of uniformity in defining UPFs in India but confirmed 81 food items as UPFs, which were categorised into 23 groups, such as breads, chips, and sugar-sweetened beverages. The results underscore the complexity of UPF classification and call for the development of quick screening tools for consumption data to inform policy and regulatory frameworks.

Hafner, Hribar, and Pravst (2025) analysed the Slovenian food supply and found that UPFs account for 54.5% of prepackaged food products, predominantly in confectionery, bread, and convenience foods. Their nutritional assessment revealed significantly poorer UPF profiles compared to less processed foods, with elevated sugar, salt, and saturated fat contents and lower protein. They also highlighted the selective use of voluntary front-of-package nutrition labelling (FOPNL) schemes predominantly on UPFs, suggesting potential marketing motives rather than consumer guidance.

Quantitative evaluations using the Health Star Rating (HSR) system have further characterised packaged food nutritional trends. Olarewaju, Say, and Chia (2025) reviewed interventions aiming to reduce salt intake in out-of-home food sectors but also referenced the low average HSR of ready-to-eat Indian snacks (Alhalabi et al., 2024), highlighting the prevalence of energy-dense, nutrient-poor products high in sugar, sodium, and saturated fat. Similarly, Young et al. (2024) analysed 17,795 packaged foods from top New Zealand manufacturers between 2015 and 2019, documenting a modest but statistically significant decrease in total sugar content and a slight increase in mean HSR, with no notable reduction in sodium or saturated fat. Their findings illustrate limited but positive nutritional transitions, implying the need for stronger regulatory actions.

Consumption patterns of discretionary and UPFs have demonstrated associations with several health outcomes. Cavalcante et al. (2025) employed a rat model fed diets high in salt and sucrose and reported metabolic syndrome features, including elevated adiposity and organ dysfunction despite normal body weight, simulating the human "skinny fat" phenotype. Tekeba et al. (2025) evaluated unhealthy feeding practices in young children across sub-Saharan African countries, finding that 62.4% of children aged 6 – 23 months engaged in unhealthy feeding patterns linked with socioeconomic factors. Moreover, Large et al. (2024) systematically reviewed the impact of unhealthy food and beverage consumption on dental caries risk in children, finding consistent positive associations, particularly with sugar-sweetened beverages and free sugar-rich foods, despite many studies having a serious risk of bias.

5. SALT AND SUGAR INTAKE STRATEGIES

Addressing salt and sugar consumption has become a focal point in public health interventions worldwide. Olarewaju et al. (2025) systematically reviewed salt reduction initiatives in the out-of-home (OOH) food sector, encompassing a variety of strategies including nutrition education, food reformulation, labelling, and environmental modifications. The meta-analysis demonstrated that these interventions effectively reduced salt intake and improved blood pressure outcomes without compromising consumer acceptance, highlighting the potential for scaling such approaches.

Focusing on Malaysia, Harun et al. (2024) outlined a supplementary salt reduction policy targeting OOH sectors, emphasising the integration of monitoring, awareness, and product reformulation. The policy aims to achieve a population mean salt intake reduction to 6.0 grams per day by 2025. The document detailed multi-sectoral collaboration, legislative enforcement, and research promotion to curb excessive salt consumption, particularly from foods prepared outside home.

Fiscal policy measures have been examined for the role in mitigating the consumption of HFSS foods. Dogbe et al. (2024) conducted a scoping review of global dietary fiscal interventions, concluding that such policies generally enhance consumer health by raising prices on unhealthy foods, shifting purchases toward healthier options, and generating government revenue. Tax responsiveness was higher among low-income groups, suggesting potential equity benefits. Likewise, Pineda et al. (2024) reviewed scientific studies on health taxes targeting HFSS foods worldwide, reporting decreased sales and intakes following tax implementation, particularly when combined with subsidies for healthy foods. The highest tax rates correlated with the most significant reductions, though concerns about regressive financial impacts were mitigated when subsidies were included.

Understanding socio-behavioural determinants influencing unhealthy food intake contributes to designing effective interventions. Werner and Mallan (2024) synthesised evidence on parental feeding practices, revealing that restrictive feeding is often unrelated or even beneficial to children's intake of healthy foods and reduction of discretionary foods, challenging common perceptions. Jindaratnaporn et al. (2024) investigated Thai populations' attitudes towards sodium taxation and food marketing restrictions, discovering substantial disagreement with such policies despite nearly universal consumption of HFSS foods. Socio-demographic factors, including gender, age, education, and BMI, influenced policy agreement but not actual HFSS intake, indicating a gap between policy support and behavioural change.

A study by Drywień et al. (2025) explored discretionary food consumption in Polish schoolchildren, identifying four distinct dietary patterns linked to BMI, body fat content, physical activity, and nutritional knowledge. This finding highlighted the complex interplay of lifestyle and socioeconomic factors in dietary behaviours, indicating the need for the development of targeted education and policy interventions aimed at reducing unhealthy food consumption among vulnerable populations.

The collective evidence foregrounds the persistent challenges posed by UPFs and excessive salt and sugar intake, emphasising the need for comprehensive nutrition profiling, effective policy implementation, behaviour change strategies, and ongoing monitoring to improve population health outcomes. Therefore, emerging food safety detection technologies are critical for ensuring the integrity of the global food supply. Recent advances, particularly in sensor development and analytical extraction techniques, have significantly enhanced the capability for rapid, sensitive, and eco-friendly monitoring of contaminants and additive compounds in foods and beverages.

6. EMERGING FOOD SAFETY DETECTION TECHNOLOGIES

6.1 Sensor Development and Applications

Innovative sensor platforms inspired by biological systems have been developed to increase detection accuracy and robustness. For instance, Wang et al. (2025) designed a tongue-inspired dual-mode sensing system that integrates a non-contact piezoresistive force sensor with a triboelectric nanogenerator (TENG). This system combines triboelectric responses with force measurement, enabling comprehensive liquid profiling by mimicking human gustatory processes. Employing superhydrophobic layers and a motor-actuated impact mechanism, the sensor overcomes conventional limitations such as performance degradation and signal attenuation due to ionic concentrations. Enhanced further through machine learning algorithms, this dual-mode sensor achieved over 99.4% accuracy in differentiating common beverages and salt solutions, demonstrating exceptional durability and potential for broad applications in food safety and industrial quality control.

Electrochemical sensors have advanced with the integration of nanomaterials to detect food colourants and contaminants with high sensitivity. Fan et al. (2024) fabricated a 3D hierarchical $\text{CuFe}_2\text{O}_4/\text{Cu}^0$ nanosheet electrode on carbon fibre paper, a binder-free sensor that exhibited remarkable detection limits for Malachite Green, Sunset Yellow, and Tartrazine in various food matrices, including beverages and fruit powders. The sensor enhanced surface area and active sites, allowing detection to the micromolar and sub-micromolar levels, matching results from conventional HPLC techniques.

Tong et al. (2024) developed an eco-friendly electrochemical sensor by modifying a pencil graphite electrode with Co_3O_4 @biochar nanocomposites derived from pyrolysed absorbent cotton. This sensor enabled the quantitative determination of Sunset Yellow in beverages with a low detection limit of 1.3×10^{-6} M, along with excellent selectivity and repeatability, costing only 0.5 Yuan per electrode, thus promising scalability and cost-effectiveness.

In parallel, Sun et al. (2025) engineered a layered Mn-metal organic framework (Mn-MOF) modified with carbon quantum dots (CQDs) for highly sensitive hydrogen peroxide (H_2O_2) detection. The CQD incorporation increased sensor conductivity and catalytic active sites, achieving a detection limit of $14.7 \mu\text{M}$ and outperforming pure Mn-MOF sensors by nearly fivefold in sensitivity. Besides the impressive selectivity against common interfering substances, the sensor successfully quantified H_2O_2 in fruit juices and beer samples.

6.2 Advanced Extraction and Analytical Techniques

Green and sustainable microextraction methods have gained traction as alternatives to traditional solvent-heavy approaches. Kizil (2024) introduced a novel DES synthesised from eco-friendly components for dispersive liquid-liquid microextraction (GDES-DLLME) of Lissamine Green B dye. This method attained a low detection limit of 0.76 ng/mL and a high preconcentration factor of 22.5 while avoiding toxic emulsifiers and dispersants, validating the efficacy in complex food matrices.

In a similar study, Narouei and Rahmani (2024) developed a vortex-assisted DES-based microextraction for quantifying Ponceau-4R in beverages, optimising parameters such as extraction solvent volume, salt concentration, pH, and extraction time through multivariate analysis. This method demonstrated a linear range up to 1200 µg/L with recovery efficiencies close to 98%, providing a rapid, sensitive, and environmentally conscious analytical alternative.

The use of covalent organic frameworks (COFs) as sorbents is another emerging frontier. Jafari and Roushani (2025) prepared COF-coated copper foam (CuF@COF) for thin film microextraction of phthalate esters from complex matrices, including beverages. The method achieved low limits of determination (0.026 -- 0.27 µg/L) and high recoveries (90 – 98%) under optimised conditions, along with wide linear response ranges. This advancement highlights COFs as efficient sorbents for simultaneous multi-contaminant monitoring in food safety applications.

Complementing these extraction advances, Neto et al. (2025) developed a dilution-assisted dispersive liquid-liquid microextraction combined with comprehensive two-dimensional gas chromatography and flame ionisation detection (GC×GC/FID) for ethyl carbamate determination in distilled beverages. This method offers rapid, efficient extraction with high enrichment factors, achieving detection limits capable of monitoring thresholds below the stipulated regulations. Analytes were also recovered quantitatively with high reproducibility, supporting the suitability for routine quality control.

These diverse sensing and extraction technologies collectively represent a significant leap forward in the detection capabilities for food and beverage safety, providing sensitive, selective, cost-effective, and green analytical solutions adaptable to complex matrices and regulatory requirements.

7. PROBIOTICS AND MICROBIAL SAFETY IN BEVERAGES

7.1 Isolation and Characterisation of Probiotic Strains

Lactic acid bacteria (LAB) and yeasts derived from

traditional fermented beverages are increasingly recognised in enhancing food safety and contributing to human health through their probiotic properties. Several studies have focused on isolating and characterising these microorganisms from diverse regional fermented foods. Sengun et al. (2025) isolated 48 LAB strains from fermented black carrot juice (Shalgam) and identified *Pediococcus acidilactici* as the most prevalent strain (56.25%), followed by *Lactocaseibacillus* sp., *Lentilactobacillus buchneri*, and *Lactobacillus paracasei*. These strains demonstrated crucial survivability characteristics, including viability at low pH, resistance to bile salts, enzymes (pepsin and pancreatin), and phenol tolerance. The strains also exhibited variable auto-aggregation, co-aggregation, and hydrophobicity, reflecting their adhesion potential, which is essential for their colonisation of the gastrointestinal tract. Notably, selected strains produced significant amounts of short-chain fatty acids such as acetate, butyrate, and propionate, implicating their beneficial metabolic impact upon consumption.

Albene et al. (2024) investigated LAB from Cheka, a fermented Ethiopian beverage. Among 27 pure isolates, 11 were confirmed as LAB encompassing *Lactobacillus*, *Lactococcus*, *Pediococcus*, and *Leuconostoc* genera, with *Weissella paramesenteroides* and *Leuconostoc pseudomesenteroides* identified via 16S rRNA sequencing. The isolated ChK-11 exhibited exceptional survival rates under acidic and bile salt stress, indicating strong probiotic potential. Yehuala et al. (2025) further identified promising starter culture candidates for Ethiopian traditional beverage Tella, including *Lactiplantibacillus plantarum* TDM41 and *Pediococcus pentosaceus* TAA01, which demonstrated superior acidification rates and stress tolerance while producing significant amounts of lactic acid and other organic acids.

The probiotic potential of yeasts isolated from Ethiopian fermented beverages has also been explored. Bitew et al. (2024) isolated *Saccharomyces cerevisiae* strains exhibiting growth under low pH, bile salts, and simulated gastrointestinal conditions, with high surface hydrophobicity, auto-aggregation capacity, hydroxyl radical scavenging activity, and mild antibacterial effects against pathogens including *Escherichia coli* and *Staphylococcus aureus*. Similarly, Resende et al. (2025) developed microencapsulated formulations of probiotic yeasts *Pichia kluyveri* CCMA 0615 and *S. cerevisiae* CCMA 0732 using spray drying with whey powder and sodium alginate. Microencapsulation substantially improved yeast viability during storage and maintained fermentation capability in functional beverages, demonstrating better survival through simulated gastrointestinal digestion.

Manzoor et al. (2025) characterised *P. acidilactici* DS3 isolated from Kanji, a fermented black carrot beverage,

highlighting its acid and salt tolerance, strong adhesion properties to intestinal cell lines, bile salt hydrolase activity, cholesterol removal capacity, and enzyme activities such as amylase and protease, all of which underpin the probiotic functionality.

7.2 Application and Stability of Microencapsulated Probiotics

Innovative microencapsulation strategies have been developed to enhance probiotic viability and functionality in beverage applications. Jike et al. (2024) compared two microcapsule formulations encapsulating *L. plantarum* 90 using different wall materials: a conventional sodium alginate-chitosan double layer (Lp-AC) and a novel soy protein isolate (SPI)-reducing sugar conjugate single-layer microcapsule (Lp-MRP). Both microcapsules demonstrated high encapsulation efficiency (>80%) and significantly improved bacterial survival under diverse stressors, including gastric pH, bile salts, thermal processing, mechanical forces, and simulated digestion. The SPI-based microcapsules (Lp-MRP) displayed superior protective effects, maintained higher viability in milk and orange juice during a 28-day refrigerated storage, and induced smaller rheological changes, indicating the potential for incorporation into functional beverages.

Hinojosa-Avila and García-Cayuela (2024) contributed insights on probiotic optimisation in beverage fermentation, emphasising the challenge of maintaining LAB viability amidst brewing stresses such as ethanol and hop compounds. The study identified strains capable of surviving specific beer fermentation conditions, suggesting strain-specific adaptability which could inform probiotic-enriched beverage development.

Spray drying microencapsulation has been explored to protect probiotic yeasts, enhancing their survival over extended storage at refrigeration and ambient temperatures (Resende et al., 2025). The microcapsules preserved yeast fermentative activity during functional beverage production, maintained viability exceeding 84% independently and above 94% within the food matrix under simulated gastrointestinal conditions, underscoring the relevance for probiotic delivery in beverages.

The viability of probiotic strains during processing and storage is reportedly influenced by wall material, encapsulation method, and beverage type. For instance, encapsulated *L. plantarum* exhibited antioxidant activity and prebiotic properties post simulated digestion (Jike et al., 2024). In plant-based matrices, microencapsulated probiotics maintained functional and sensory attributes without detrimental changes over storage periods.

Collectively, these studies advance the understanding of probiotic strain selection, characterisation,

and innovative encapsulation technologies tailored for beverages, highlighting the importance of microbial safety and functional benefits in food products.

8. IMPACT OF DIETARY CONTAMINANTS

The MP contamination in foods and beverages represents an emerging public health concern, with evidence increasingly implicating MPs in various cellular and systemic toxicities. Bocker and Silva (2025) review extensive *in vivo* studies, demonstrating that MPs can trigger inflammatory responses, oxidative stress, and cellular dysfunction, which together contribute to gastrointestinal disorders, neurotoxicity, reproductive toxicity, and cardiovascular risks. Polyethylene, polypropylene, and polystyrene are the major MPs detected in several human biological tissues, underlining the ubiquity of exposure and bioaccumulation potential.

Complementing this finding, Mir et al. (2025) emphasise the toxic hazards posed by MPs, particularly nanoplastics capable of crossing biological barriers, heightening carcinogenic and immunotoxic risks. The review also identified immune disturbance and oxidative stress as key mechanisms whereby MPs exert adverse health effects, suggesting pathways leading to hypersensitivity and developmental cytotoxicity. Hore et al. (2024) highlight additional concerns regarding MP transfer across trophic levels, including maternal-foetal transfer via the placenta and breast milk, underscoring risks across all life stages. Such comprehensive assessments reflect the pressing need to understand and monitor human MP exposure longitudinally.

Physical-chemical characteristics of MPs, coupled with the persistence and interaction with environmental pollutants, complicate toxicity profiles (Mir et al., 2025). The heterogeneity in particle size and composition, along with incomplete standardisation in detection methods, pose challenges in exposure assessment and risk quantification. Despite these gaps, cumulative evidence links MPs to multiple adverse biological outcomes through mechanisms involving oxidative damage, immunomodulation, and interference with cell signalling pathways. Advances in analytical detection and *in vivo* toxicological models are serving to clarify these relationships, yet substantial work remains to elucidate long-term health implications.

8.1 Nutritional and Metabolic Consequences

Unhealthy dietary patterns characterised by excessive intake of UPFs, HFSS, and low nutrient density are strongly associated with metabolic syndrome components, accelerated biological ageing, and chronic diseases. Polak-Szczybyło and Tabarkiewicz (2025) examined the influence of body composition, lifestyle, and diet on pro-inflammatory adipokines, adiponectin, and resistin in obese individuals.

These findings revealed that resistin levels correlated positively with BMI and subcutaneous fat, while adiponectin decreased with increasing lean tissue and carbohydrate intake, highlighting complex interactions between diet, body composition, and metabolic regulation. The adiponectin-resistin (AR) index, posited as a marker of inflammatory status, was associated positively with saturated and monounsaturated fatty acid intake but inversely with carbohydrate consumption, indicating dietary modulation of inflammatory and metabolic pathways.

Zhang et al. (2024) conducted a prospective cohort study in less-developed ethnic minority regions, linking adherence to healthy dietary patterns, notably the Dietary Approaches to Stop Hypertension (DASH) diet, with deceleration of biological age acceleration. Beneficial foods included tea and soy products, while salt and processed vegetables were identified as harmful. The causal mediation analysis implicated gut microbiota genera *Synergistetes* and *Pyramidobacter* as partial mediators, suggesting a microbiota-driven pathway influencing diet-mediated ageing effects.

Genetic epidemiology further elucidates dietary impacts on chronic disease risk. Zhang et al. (2024) applied two-sample Mendelian randomisation analyses encompassing 29 dietary exposures and identified protective effects against idiopathic pulmonary fibrosis from oily fish, yoghurt, and dried fruit consumption. In contrast, alcoholic beverages and beef intake were linked to increased risk. Such studies revealed the potential impact of specific nutritional components in modulating disease pathways, supporting targeted dietary recommendations.

Cavalcante et al. (2025) utilised a rodent model to simulate high salt and sucrose intake, which resulted in increased body adiposity, liver lipid infiltration, and induced end-organ injury without overt obesity. This outcome mimicked the human metabolic syndrome phenotypes with visceral adiposity despite normal BMI. Therefore, metabolic detriments are linked to unhealthy dietary exposures beyond overt weight gain. Dietary patterns also contribute to comorbid conditions such as perimenopausal syndrome and hypertension. Li et al. (2024) found a prevalence of hypertension (16.58%) and perimenopausal syndrome (9.9%) in South Chinese women, with sugar-sweetened beverages among several dietary risk factors elevating syndrome risk. This finding further connects an unhealthy diet to metabolic dysregulation across life stages.

Collectively, these reports emphasise the considerable role of diet-induced metabolic imbalances, inflammatory mediators, and microbiome interactions in shaping health outcomes and ageing. The integration of epidemiological, molecular, and genetic studies illuminates pathways for potential intervention through nutrition and

lifestyle modulation.

9. REGULATORY FRAMEWORKS, POLICIES, AND PUBLIC AWARENESS

9.1 Food Marketing and Advertising Regulations

Effective regulation of food marketing, particularly HFSS foods, remains a cornerstone for improving public health outcomes. Nevertheless, enforcement and policy scopes vary considerably across countries, often limiting the protective effects, particularly for children. For instance, Bassi et al. (2024) identified significant gaps in the existing regulatory framework for HFSS food advertising in India. The study revealed that only one of 13 identified policies, which is the Guidelines for Prevention of Misleading Advertisements and Endorsements for Misleading Advertisements (2022), explicitly restricts HFSS food advertisements directed at children across all media. Key weaknesses included narrow definitions of 'child-targeted' advertisements and the absence of clear, evidence-based criteria for defining HFSS foods. This limitation constrained the effectiveness of the policies in shielding children from exposure to unhealthy food marketing. The authors advocate for a robust regulatory framework incorporating clear classification criteria and broader media coverage to adequately protect vulnerable populations.

Complementing these findings, Vaughan et al. (2025) conducted a scoping review of children's and parents' awareness and attitudes towards digital food marketing (DFM). This work highlighted the limited awareness among children and parents about digital marketing tactics that promote unhealthy foods and beverages. Children demonstrated varied abilities to recognise digital advertisements, with a preference for influencer marketing formats and native advertising styles that seamlessly integrate product promotion. Parental awareness was consistently low, and opinions on the need for regulation were unclear, underscoring a critical gap in stakeholder engagement and knowledge transfer. The rapidly evolving digital environment further complicates regulation enforcement, necessitating transdisciplinary approaches to increase digital literacy, advocacy, and policy development.

Fretes et al. (2025) reviewed the scope of DFM of HFSS foods to children and adolescents worldwide, emphasising extensive exposure that increases with age and employs tailored marketing strategies. Despite the evidence linking exposure to increased consumption of unhealthy products, most studies were limited by a lack of rigorous exposure assessment and confounding control. The analysis supports the critical need for governmental regulatory mechanisms and monitoring technologies, drawing on the experiences from Latin American and Caribbean countries for evidence-informed policymaking.

9.2 Food Labelling and Nutritional Information

Transparent and comprehensive nutrition labelling is essential for informing consumer choices and enabling public health interventions. Nonetheless, significant gaps exist in the availability and accuracy of labelling nutrient contents critical for managing health conditions. Asan et al. (2025) surveyed labelling in Malaysian supermarkets and revealed that while 79.4% of packaged foods displayed sodium content, only 11.7% and 2.0% disclosed potassium and phosphorus levels, respectively. Furthermore, additives containing these minerals were frequently present but often ambiguously labelled under various names ('salt' for sodium; E numbers for phosphorus), complicating public comprehension. The study accentuated the challenge faced by patients with chronic kidney disease and other vulnerable groups reliant on precise dietary mineral information and calls for enhanced regulatory standards and labelling practices.

Aligning with labelling transparency, Hafner et al. (2025) analysed the prevalence and nutritional composition of UPFs within the Slovenian food supply, and the uptake of voluntary FOPNL schemes. The study found that UPFs constituted over half of branded products and exhibited poorer nutritional profiles, with higher sugars, salt, and saturated fats compared to less processed foods. Although 33.8% of products carried at least one FOPNL or subjectively nutrition-related element, FOPNL was predominantly applied to UPFs, often used selectively as a marketing tool rather than a transparent nutritional guide. The study raises concerns about voluntary labelling schemes facilitating consumer misperception, advocating for harmonised and mandatory policies that ensure labelling accuracy and utility.

9.3 Fiscal and Structural Interventions

Economic and structural interventions, including taxation and reformulation policies, have demonstrated effectiveness in reducing the consumption of HFSS foods and mitigating associated health risks. Dogbe et al. (2024) synthesised global evidence on fiscal policies targeting unhealthy food and beverages, establishing the role in improving public health by increasing prices of HFSS products, raising government revenue, and nudging consumption toward healthier alternatives. Higher tax rates yielded more pronounced reductions in consumption, particularly among lower-income groups who are often disproportionately affected by the burden of diet-related diseases. Pineda et al. (2024) reinforced these findings, demonstrating combined fiscal measures including taxes on HFSS foods and subsidies on healthy options to mitigate regressive financial impacts and maximise health benefits. Nevertheless, the study noted the current lack of clarity surrounding unintended consequences such as substitution

effects and economic impacts on employment, suggesting the need for comprehensive policy evaluation.

Salt reduction strategies are emphasised due to the global burden of hypertension and cardiovascular diseases. Harun et al. (2024) presented the comprehensive Salt Reduction Strategy in Malaysia, stressing the need for monitoring, consumer awareness, product reformulation, and legislative enforcement that focused on retail and OOH food sectors. The strategy defines explicit reformulation targets across 14 food categories and promotes intersectoral collaboration by recognising the considerable salt intake from foods consumed outside the home to achieve reductions in population-level salt intake. Complementarily, Olarewaju et al. (2025) reviewed interventions in OOH food sectors across diverse settings, revealing effective salt reduction outcomes without compromising consumer acceptance or food quality. The multifaceted approaches include nutrition education, menu reformulation, labelling, and environmental modifications. Nevertheless, the study identified gaps such as limited geographical scope and a lack of interventions in informal food sectors (street vendors), calling for expanded research and policy action.

In summary, these varied regulatory and fiscal policy perspectives collectively underscore the multifactorial challenges of controlling unhealthy food marketing and composition. The evidence supports integrated strategies combining stricter advertising regulations, transparent labelling standards, fiscal measures, and ongoing public education as essential to mitigating the health impacts of HFSS foods and beverages globally.

10. MULTI-DISCIPLINARY STRATEGIES FOR FOOD SAFETY

The modern landscape of food safety demands a multi-faceted approach that integrates cutting-edge detection technologies with robust nutritional surveillance and progressive regulatory policies to holistically safeguard public health. Advances in sensor development, such as the tongue-inspired dual-mode sensing system integrating triboelectric responses and force measurements, have shown remarkable capabilities in accurate liquid identification under challenging environmental conditions (Wang et al., 2025). Likewise, superhydrophobic modifications of dielectric layers in capacitive sensors have demonstrated resilience in liquid-rich environments, enhancing sensor reliability for food safety applications (Xiao et al., 2025). These sensor innovations, alongside eco-friendly electrochemical sensors for detecting food colourants such as Sunset Yellow and Malachite Green using nanocomposites (Fan et al., 2024; Tong et al., 2024), illustrate transformative potentials for real-time monitoring of chemical contaminants and additives in complex food matrices.

Nutritional quality surveillance benefits from systems such as Health Star Ratings and branded food composition databases (TABULA™ project in Spain) that track and characterise UPFs, enabling policy makers to identify areas that require intervention (Redruello-Requejo et al., 2025; Hafner, Hribar, & Pravst, 2025). Such databases inform reformulation programmes and public health strategies targeting reductions in salt, sugar, and saturated fats (Olaewaju, Say, & Chia, 2025). Integration of these data-driven nutritional assessments with technological detection creates opportunities for comprehensive food safety systems that simultaneously address chemical contaminants and nutritional risk factors

Policy frameworks are essential in aligning technological and nutritional strategies towards public health goals. Systematic reviews highlight the effectiveness of fiscal policies in reducing consumption of HFSS foods at a population level, particularly in combination with subsidies, to promote healthier alternatives (Dogbe et al., 2024; Pineda et al., 2024). Regulations targeting food marketing that emphasise vulnerable populations such as children remain critical, but challenges, including imprecise definitions and limited scope, hinder the effectiveness of these policies (Bassi et al., 2024; Vaughan et al., 2025). Furthermore, salt reduction in the OOH sector requires sustained, enforceable monitoring and education combined with industry reformulation efforts to achieve measurable impacts (Harun et al., 2024; Olaewaju et al., 2025). The synergy of these multi-level interventions exemplifies how multi-disciplinary strategies can produce systemic impact in food safety.

11. SUMMARY OF REVIEWED STUDIES

Table 1 summarises key studies related to food and beverage safety to provide a clear and structured overview of the literature reviewed in this work, covering major thematic areas such as microplastic contamination, synthetic dyes and additives, UPFs, salt and sugar reduction strategies, detection technologies, probiotics, and regulatory policies.

The table consolidates the authors, research objectives, methodologies, and major findings, offering a comparative perspective across diverse studies. This summary enhances interpretability and highlights the interconnectedness between emerging contaminants, detection advancements, and public health implications.

The summarised findings in Table 1 underscore the multifaceted nature of food safety research, spanning chemical contaminants, technological innovations, and policy frameworks. Collectively, these studies reveal the pressing need for standardised analytical methods, sustainable mitigation strategies, and integrated governance mechanisms

to safeguard public health and ensure responsible food production practices.

12. RESEARCH GAPS AND EMERGING PRIORITIES

Despite the progress in food safety measures, significant research gaps remain that warrant urgent attention to enable more effective approaches. The key solution lies in the standardisation of detection methods for emerging contaminants such as MPs. The notable inconsistency in MP measurements across foods and beverages is attributed to heterogeneous sampling, detection limits, and analytical protocols, complicating risk assessment and regulatory decision-making (Canga et al., 2024; Zhang et al., 2024). Improving and harmonising analytical procedures, including appropriate filter size selection, validation of MP identity, and representative sampling, are imperative in establishing reliable exposure metrics.

A deeper understanding of probiotic functionality and survival in complex beverage systems is essential in ensuring food safety. Studies demonstrate promising probiotic strains isolated from traditional fermented beverages, which exhibit strain-specific resilience to stressors such as low pH, bile salts, and digestive enzymes (Sengun et al., 2025; Manzoor et al., 2025). Microencapsulation using novel materials such as SPI-reducing sugar conjugates has enhanced probiotic viability and stability in plant-based and dairy beverages (Jike et al., 2024; Resende et al., 2025). Future investigations should focus on elucidating mechanisms of probiotic-host interactions, survivability through gastrointestinal transit, and optimisation of delivery matrices to maximise functional benefits.

Developing consumer-centred policies that reconcile health imperatives with cultural acceptability and industry innovation remains a vital priority. Empirical evidence reveals varied public attitudes towards sodium taxation and marketing restrictions, underscoring the need for tailored communication strategies and inclusive policy design sensitive to socio-demographic diversity (Jindaratnaporn et al., 2024; Bassi et al., 2024). Coordinated efforts integrating legal frameworks, public education, and industry collaboration are crucial to foster healthier food environments without unintended socio-economic burdens.

In a nutshell, the next generation of integrated food safety strategies must embrace technological innovation, rigorous scientific standardisation, and nuanced policy formulation to address the evolving challenges of the food system, ultimately contributing to enhanced public health outcomes.

Table 1: Summary of Reviewed Studies Related to Food and Beverage Safety

Theme / Area	Author(s) & Year	Objective / Focus	Methods / Approach	Key Findings / Outcomes
Microplastic contamination	Ahmad et al. (2025)	Quantified MPs in commercial foods and beverages in Riyadh	Analysed 112 samples for MP size and type	Tea bags showed the highest contamination; variations across foods confirmed widespread MP presence
	Mondal et al. (2025)	Meta-analysis of South Asian foods for MPs	Comparative analysis of food categories	Salt, fish, and milk showed higher MP levels than global averages; polyvinyl chloride (PVC) and polyester were the dominant polymers
	Canga et al. (2024); Jeong et al. (2017)	Reviewed MP detection inconsistencies	Literature review	Methodological variations in sample prep and pore size cause data discrepancies
	Frete et al. (2025); Zou et al. (2023)	Emerging MP detection techniques	AI-assisted and multispectral imaging	Improved precision but limited industrial scalability
	Liu & Shimizu (2025); Huo et al. (2025)	MP remediation through biological interventions	Animal model and dietary studies	Chitosan and dietary additives promote MP excretion; potential biocompatible mitigation strategies
Synthetic dyes and additives	Mistry et al. (2024)	Detection of Sunset Yellow using CuO-ZrO ₂ sensor	Electrochemical sensing	High sensitivity (0.01–50 ppm) and rapid response in food matrices
	Zhang et al. (2025)	Quantification of Sunset Yellow	Fluorescent carbon dot probes	Detection limit 0.026 µg/mL; high recovery; effective for beverages
	Tong et al. (2024)	Detection of Sunset Yellow using a biochar electrode	Electrochemical sensor	Low-cost detection with LOD 1.3×10^{-6} M; eco-friendly and stable
	Kizil (2024); Olgun et al. (2024); Narouei & Rahmani (2024)	Green microextraction for dyes	Deep eutectic solvents (DES)-based liquid-liquid microextraction	High recovery (95–101%); eco-friendly; low detection limits
Ultra-processed foods (UPFs)	Ghosh-Jerath et al. (2024)	Mapping UPFs in India	Market mapping and nutritional profiling	Identified 81 UPF types across 23 groups; need for standard classification
	Hafner et al. (2025)	Nutritional assessment of Slovenian UPFs	Food composition database analysis	UPFs = 54.5% of packaged foods; poorer nutritional profile; selective use of FOP labels
	Young et al. (2024)	Trends in packaged food nutrition in New Zealand	Health Star Rating system	Slight sugar reduction; minimal improvement in sodium and fat
	Cavalcante et al. (2025)	High-salt/sugar diet model in rats	Controlled feeding experiment	Induced metabolic syndrome-like features without obesity
Salt and sugar reduction strategies	Olarewaju et al. (2025)	Global review of salt reduction in the out-of-home sector	Systematic review/meta-analysis	Effective salt reduction and BP improvement without affecting acceptance
	Harun et al. (2024)	National salt reduction policy in Malaysia	Policy document analysis	Multisectoral strategy targeting 6.0 g/day salt intake; focus on OOH foods
	Dogbe et al. (2024); Pineda et al. (2024)	Fiscal interventions on HFSS foods	Global scoping and systematic review	Taxes and subsidies improve diet quality and reduce unhealthy food purchases
Detection technologies	Wang et al. (2025)	Tongue-inspired dual-mode sensor	Piezoresistive + TENG dual-mode system	99.4% accuracy in liquid identification; durable and machine-learning optimised
	Fan et al. (2024); Tong et al. (2024)	Electrochemical detection of dyes	CuFe ₂ O ₄ /Cu ⁰ and Co ₃ O ₄ @biochar sensors	High sensitivity; low-cost; scalable detection for colourants
	Sun et al. (2025)	Hydrogen peroxide detection	Mn-MOF + CQD composite sensor	5× improved sensitivity; applied to fruit juice and beer
	Kizil (2024); Jafari & Roushani (2025)	Green and sustainable extraction	DES-DLLME and COF-based microextraction	Eco-efficient, high-recovery techniques for contaminants
Probiotics and microbial safety	Sengun et al. (2025); Albene et al. (2024)	Isolation of probiotic LAB from fermented beverages	Microbial isolation and characterisation	Identified LAB species with acid, bile, and phenol tolerance; Short-chain fatty acids (SCFA) production
	Jike et al. (2024)	Microencapsulation of <i>L. plantarum</i>	SPI- and chitosan-based encapsulation	Enhanced probiotic survival in juice/milk; > 80% encapsulation efficiency
	Resende et al. (2025)	Probiotic yeast microencapsulation	Spray drying with whey-alginate matrix	>94% viability under GI simulation; suitable for functional beverages
Policy and regulation	Bassi et al. (2024)	HFSS food marketing to children	Policy review (India)	Only one national policy restricts HFSS advertisements; limited scope
	Vaughan et al. (2025); Frete et al. (2025)	Digital food marketing awareness	Surveys and scoping reviews	Low parental/child awareness; increasing exposure to HFSS advertising
	Asan et al. (2025)	Nutritional labelling in Malaysia	Market survey	Sodium is labelled in 79.4% products; phosphorus is rarely labelled; need for stricter standards
	Dogbe et al. (2024); Harun et al. (2024)	Fiscal and structural food policy	Policy and review synthesis	Effective tax/reformulation interventions; success depends on enforcement and education

Notes: MP, microplastics; AI, artificial intelligence; LOD, limit of detection; LAB, lactic acid bacteria; HFSS, high-fat, sugar, and salt; FOP, front-of-package .

13. FUTURE DIRECTIONS

The future of food and beverage safety research should adopt a robust and integrated approach that bridges detection technologies, nutritional science, and policy development. Addressing significant gaps identified in current practices can lead to enhanced safety measures and public health outcomes. Several key research directions are proposed to navigate these challenges effectively.

13.1 Development of Standardised Detection Frameworks

Developing internationally harmonised analytical protocols is key to effectively addressing the risks posed by emerging contaminants such as MPs and synthetic dyes. The existing variability in methods across different studies leads to discrepancies in data comparability and hinders regulatory efforts (Katsara et al., 2022; Cella et al., 2022). Future research should focus on creating standardised frameworks that encompass sampling strategies, detection limits, polymer identification, and data reporting standards (Ma et al., 2024). Collaborative initiatives involving researchers, industry stakeholders, and government regulators will ensure that these protocols are scientifically robust and practical for global implementation, thereby facilitating reliable monitoring (Katsara et al., 2024).

13.2 Advancement of Sustainable and Scalable Technologies

Transitioning from laboratory-controlled environments to scalable, field-deployable detection technologies is imperative. Future research should prioritise the integration of advanced methodologies, such as nanomaterial-based sensors and AI-driven analytics, into portable monitoring platforms (Savaş & Gharibzahedi, 2025; Mukherjee et al., 2025). Emerging technologies such as smartphone-integrated electrochemical sensors promise greater sensitivity and affordability, enabling on-site contaminant detection in real-time (Savaş & Gharibzahedi, 2025; Mukherjee et al., 2025). Enhancing the accessibility of these technologies can facilitate stakeholders in the food industry to implement quality control measures that effectively monitor contaminant levels and ensure consumer safety across supply chains (Mukherjee et al., 2025; Govedarica et al., 2025).

13.3 Mechanistic Elucidation of Probiotic Functionality

A comprehensive understanding of probiotic functionality in beverage systems remains crucial for developing effective functional foods. Future studies should

investigate the complex interactions between probiotics and the beverage matrices, focusing on encapsulation materials, processing conditions, and the influence on probiotic viability and bioavailability (Mazlan et al., 2017; Ortega-Sanz & Rajković, 2025). Employing multi-omics techniques can yield insights into the metabolic pathways of probiotics, guiding the design of beverages that deliver health benefits and maintain quality during storage and distribution (Mazlan et al., 2017; Ortega-Sanz & Rajković, 2025).

13.4 Establishment of Integrated Nutritional Databases

Developing harmonised databases that link food composition, processing levels, and health outcomes is essential in bolstering nutritional surveillance. Integrating machine learning within these databases can facilitate predictive modelling, supporting policymakers in targeting interventions effectively, particularly UPF consumption (Katsara et al., 2022; Liu et al., 2015). Such comprehensive databases will allow researchers to assess associations between dietary intake and public health more accurately, ultimately supporting informed regulatory and reformulation efforts (Saylan et al., 2024; Ma et al., 2024).

13.5 Integration of Behavioural and Policy Research

Food safety cannot be relegated solely to technological solutions, requiring social responsiveness in policy design. Future research should integrate insights from behavioural sciences to better understand consumer perceptions, policy acceptance, and risk communication (Chaturvedi & Chakraborty, 2020). Creating culturally adaptive and equity-focused interventions, such as reformulation incentives and transparent labelling, will enhance the effectiveness of regulations and lead to sustained improvements in public health (Chaturvedi & Chakraborty, 2020; Ma et al., 2024).

13.6 Strengthening Multisectoral Collaboration

A strong emphasis on multisectoral collaboration is essential to translate scientific advancements into actionable policies. Establishing networks that promote data sharing, access to innovative technologies, and collaborative research projects will facilitate rapid advancements toward safer food systems (Ma et al., 2024). Engaging academia, industry, and government will ensure a holistic approach to food safety, fostering impactful solutions that address the multifaceted nature of food-related challenges (Ma et al., 2024).

Overall, the future of food and beverage safety research hinges on the development of standardised protocols, sustainable technologies, thorough mechanistic

studies, integrated databases, behavioural insights in policy, and enhanced collaboration across sectors. These collective initiatives will strengthen the framework for assessing and ensuring food safety as public health outcomes remain at the forefront.

14. CONCLUSION

The review underscores the significance of adopting integrated, multidisciplinary strategies to enhance food and beverage safety and public health. Progress in detection technologies, understanding of contaminants, and nutritional assessment has contributed to a better understanding of food safety challenges. Despite that, gaps exist in the standardisation, scalable detection methods, and consumer-centred policies. Addressing these challenges requires harmonised standards, advanced technologies, and effective regulatory frameworks to ensure safer, healthier food supplies. Therefore, future research should focus on developing sustainable detection solutions, improving probiotic stability, and fostering policy synergies to mitigate risks and promote public health.

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