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Food circular economy and safety considerations in waste management of urban manufacturing side streams

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In food circular economy, the utilization of food manufacturing side streams (FMSS) offers significant potential instead of being discarded. However, reincorporating FMSS into the food value chain raises food safety concerns due to potential food hazards. This perspective explores food safety risks associated with circular management of FMSS by using a 'Quad-Modal hazard dynamic' approach with case studies. Future research and advancements in food safety control strategies are also discussed.

Food loss and waste (FLW), alongside unsustainable resource use associated with the traditional model of food production and consumption[1,2], as well as its important global environmental and socioeconomic impacts[3], have outlined the critical need for a paradigm shift in our global resource management strategies[4]. Within this context, the circular economy (CE) has been conceived as a transformative approach focused on the restorative use of resources, emphasizing on efficiency, waste reduction, and sustainability[5]. The global food systems face significant challenges, with an alarming 25–30% of FLW of the total food produced worldwide, contributing to ~8–10% of total anthropogenic GHG emissions and costing about 1 trillion USD per year between 2010 and 2016[3]. The CE model inspires a vision of a food circular economy (FCE)[6], promising to alleviate the strain on limited resources by endorsing a model of production and consumption, where waste and loss are minimized through the continuous prevention of waste, and the reuse, recycling, and regeneration of resources in a closed-loop system[7,8].

Yet, as we evolve into this transformative landscape towards more sustainable systems, the imperative of food safety cannot be overstated. Significantly, food manufacturing side streams (FMSS) present a growing area of interest for reutilization as viable materials and products that are reinserted into the food supply chain, including valuable food ingredients[9]. However, the reintegration of these substances into the food supply chain potentially carries the inherent risk of introducing chemical, biological, physical hazards and allergens[10,11].

This potential public health concern, while limitedly addressed in literature that primarily focuses on the valorization of side streams[12–16], remains a crucial discussion on the potential food hazards emerging from their reuse within a FCE framework. However, the comprehensive reviews by Rao et al.[12], Focker et al.[11], and Socas-Rodríguez et al.[13], alongside other related studies, notably bridge this gap by highlighting the valorization of FMSS, addressing the balance between food safety and sustainability, with an orientation to the European Union (EU) context. They establish a foundation in understanding the valorization process's complexities, particularly emphasizing the importance of food safety, by identifying food hazards related to products derived from food side streams, which will be reissued in different stages of the food supply chain.

As has been explored by the available body of evidence, as the food system moves towards more sustainable and circular models, understanding the full spectrum of food safety risk factors associated with FMSS becomes paramount, including the food hazards dynamics along closed-loop chains. However, as has also been briefly noted, the food safety implications of reintroducing FMSS into the food supply chain expand beyond a hazard-based perspective. This critical overview highlights a pressing need for adopting holistic perspectives on control strategies.

To do so, here we provide our perspective seeking to broaden the discussion on the multiple considerations in the complex interplay of food safety and circular economy principles. Illustrated at a very general level, we discuss the intersections that we envision for the scope of food side streams, via an integrative and food-chain approach. By advocating for a quad-modal approach grounded in the evidence available, we propose to delve into and elucidate some pathways through which food safety hazards in circular systems may emerge, particularly focusing on the reintroduction of FMSS into the food value chain. Enriched with targeted case studies, we seek to not only present some potential food safety risks but also to discuss strategies and interventions that may fortify our food control systems.

Interlink between food safety and food circular economy: a quad-modal approach to describe dynamics of food safety hazards

Within the circular economy (CE) paradigm, waste is avoided and resources are continuously reused, recycled and regenerated in a closed-loop system[5].

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Table 1 | Definition and scope of food waste and food loss concepts under UN framework

Concept	Definition	Food supply chain stage scope	Related SDG target and indicator	Reported by (Source)
Food Loss	Decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the food chain, excluding retail, food service providers and consumers.	- On farm post-harvest/ Slaughter operations - Transport, storage and distribution - Processing and packing	SDG Target 12.3 Indicator: SDG 12.3.1 (a) Food Loss Index (FLI)	Food and Agriculture of the United Nations - FAO[16]
Food waste	Food and the associated inedible parts removed from the human food supply chain in the retail, Food service, Households stages.	- Retail - Public and household consumption	SDG Target 12.3 Indicator: SDG 12.3.1 (b) Food Waste Index (FWI)	United Nations Environment Program - UNEP[17]

Table 2 | Summary of major sources of food manufacturing side streams and their associated intrinsic hazards and valuable ingredients

Source	Intrinsic hazards	Manufacturing side streams	Valuable ingredients
Fruits and Vegetables	Toxin (amygdalin[82], glycoalkaloids[83]), mycotoxin (patulin[84]), pesticides[85,86], potential biological hazards	Pomace, seeds, pulp, peel and stems[87]	Pectin[88], dietary fiber, bioactive compounds[89]
Grains and legumes	Pesticides, potential biological hazards[90]	Okara, rice bran, wheat bran	Dietary fiber, protein, polyunsaturated fatty acids and isoflavones[90,91]
Meat	Various microorganisms and associated toxins[44], veterinary drugs[44]	Skin and bone[44]	Collagen[28] and gelatine[26]
Seafood	Toxic contaminants (POPs, PCBs, PCDD/F), heavy metals (As, Cd, Pb, Hg)[35,36], drug residues[92]	Viscera (organs), heads, cut-offs (trimmings), skin[25]	Protein[93], omega-3 (ω-3)-rich fish oils (EPA and DHA)[35], gelatine[27], collagen[94]
Dairy	Heavy metals (Cd, Pd, and Hg)[95,96], veterinary drugs[45–47]	Whey[42]	Protein[42], lactose[97], minerals, lactic and citric acids, urea and uric acid, B-group vitamins[97]
Breweries and distilleries	Potential biological hazards[53], mycotoxins (enniatin, zearalenone, T-2, HT-2)[98–100]	Brewer's spent grain (BSG)[50], spent brewer's yeast[101]	Hemicellulose, cellulose, lignin and proteins[51], yeast extract[101]

In the context of the food circular economy (FCE), these principles will be applied to address sustainability issues associated with FLW throughout the multiple stages of the food supply chain.

As previously reported[14], there is a high heterogeneity on the definition of FLW, resulting in not only conceptual differences, but also substantial differences in root-causes and driving factors, mitigation strategies and challenges applicable to different types of FLW. This may be led by their inherent nature and characteristics of the waste, the stage of the food chain where they are generated, as well as the specific national context[3,14,15]. The United Nations built a harmonized conceptual and monitoring framework for FLW, which recognizes differences in the terms of food loss and food waste, establishing scopes based on the stages of the food chain that each covers[16–18] (Table 1).

In this article, food manufacturing side streams (FMSS) refer to substances or residual materials generated from primary food production that are not the primary intended food product. These may include waste, by-products, and initially inedible "fragments" as defined in the conceptual framework for FLW proposed by FAO[16]. However, cultural, economic, and technological factors should also be considered when assessing the categorization of these food fragments as edible or inedible. For instance, soybean residue (okara), often viewed as inedible residue of soy beverage or tofu production, is a valued food ingredient in some countries, such as *unohana* in Japan, *kongbiji jjigae* in Korea and *xiao doufu* in China. Considering this, defining side streams based on their production processes may provide a more inclusive approach. In addition, it is also important to note the distinction between side streams and by-products. While side streams encompass a broader category of materials with varying degrees of commercial viability, the term "by-products" is frequently used, often interchangeably with "side streams", though it is a subset of side streams characterized by their immediate commercial value and are desired products. In this article, we use FMSS to include both materials with current commercial applications and those in the research stage that may hold potential for future utilization.

To narrow our discussion within the established scope of this perspective article, our examination will be focused on the food safety implications related to food loss scope FMSS. Globally, around 14% of food produced, valued at $400 billion per year, is lost during post-harvest up to the point just before retail[19], reaching over 20% in regions like Central and Southern Asia[16]. In that sense, it is imperative to sustainably manage these food losses and FMSS. Specifically for food loss, some interlinks are distinguished between food safety and the management measures applied. During routine food safety monitoring, several issues can arise from various points of the food supply chain, such as the detection of pathogens or breaks in the cold chain, compromising on food safety and quality and hence generating production discards, which are considered as food loss. This relationship highlights that adhering to general principles of food hygiene[16] is a way to minimize food loss. On the contrary, certain measures applied by food business operators to minimize food loss, such as the excessive use of pesticides and preservatives, may represent practices that compromise food safety.

On the other hand, within the facets of reusing, recycling and regenerating food loss and FMSS in a closed-loop system of FCE, specific food safety implications are also identified. Conventionally used in animal feed and fertilizers, FMSS are increasingly recognized for their potential in the production of materials and compounds, demonstrating the expansive scope of upcycling within the food manufacturing industry[20–22]. Furthermore, the growing interest in converting FMSS into valuable food ingredients, packaging materials, underscores the potential to increase the longevity of these resources while maximizing their value[9]. However, this raises distinct and multifaceted challenges, particularly concerning food safety in the instance where the reintegration of these materials carries the risk of introducing food safety hazard into the food chain[10,11]. The intrinsic variability in foods due to diverse factors, including genetic variation, is further compounded in FMSS generated from secondary food processing that have undergone various food processing. This variability imparts FMSS with diverse properties and hazards prior to their reuse (Table 2).

Table 3 | Definition of key terms in the 'Quad-Modal hazard dynamic' approach

Term	Definition
Introduction	Generation of new food safety hazards during the management of FMSS, including storage, handling, transportation and processing.
Reduction	Reduction involves the decrease or elimination of biological or chemical hazards during processing of FMSS.
Accumulation	Accumulation refers to the build-up of inherent contaminants or pathogens through various stages of the management of FMSS, which can lead to elevated levels of food safety hazards in the final product.
Interaction	Interactions can occur between introduced, reduced, or accumulated biological or chemical hazards in FMSS, potentially leading to adverse health effects.

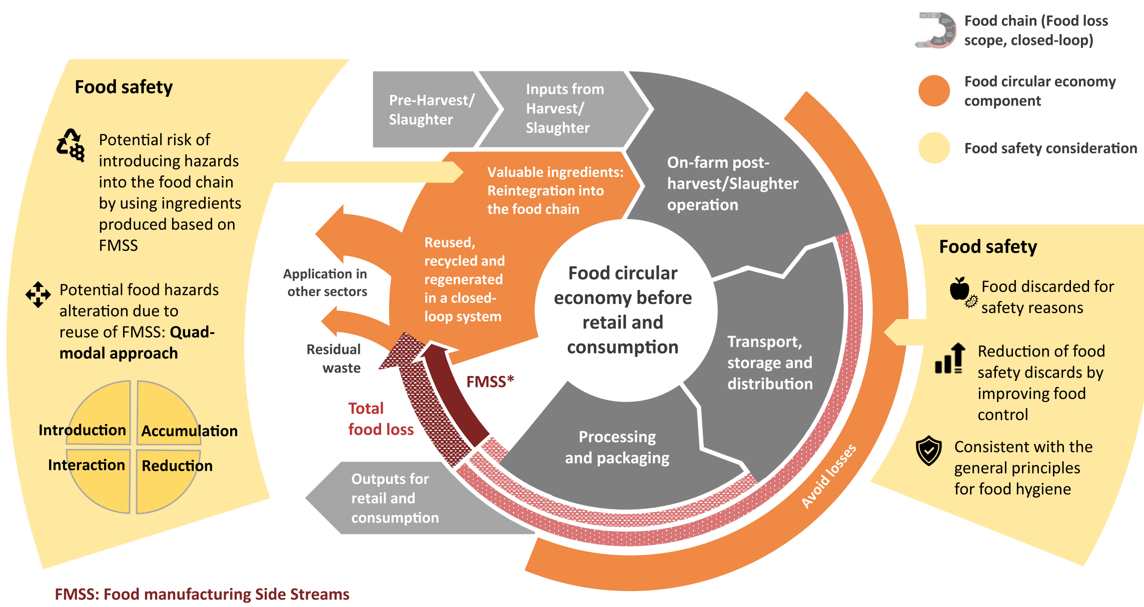

Fig. 1 | Interconnection between food safety, food loss and food manufacturing side streams (FMSS) within the framework of a circular food economy. The diagram illustrates three key components: (1) Food supply chain segment, represented by gray sectors near the center of the circle. The critical food chain stages from which food loss and FMSS (in red tones) originate are highlighted in dark gray tones. (2) The orange sections represent the components of the circular food economy integrated throughout various stages of the food chain, emphasizing the reintegration of valuable ingredients from FMSS into the food chain through closed-loop systems. (3) The yellow sectors denote considerations for food safety within the context of food circular economy.

To effectively mitigate potential food safety risk associated with these cases, it is essential to recognize the potential and varied dynamics in the occurrence and levels of food safety hazards that could happen throughout the stages of transformation of side streams to by-products that will be reintroduced into the food chain. These dynamics would depend on several factors, such as the occurrence and previous levels of hazards in the raw material, raw material characteristics, reprocessing methods, and handling conditions. Each side stream and by-product have distinctive characteristics that influence their specific considerations for its reuse and consumption. Throughout various stages of reprocessing and rehandling, they undergo transformations, including in food hazard aspects, termed the 'quad-modal hazard dynamic approach'. This comprises four key modalities through which food safety hazards can evolve in food circular systems, defined in Table 3.

Figure 1 provides a cohesive illustration of the interconnection between food safety and food loss and FMSS within the framework of a food circular economy. At its core, the diagram represents solely the stages of the food supply chain (highlighted in green tones) where food loss occurs (shown in red tones), and the FMSS are generated. The links with preceding and succeeding stages of the chain are represented in gray. The chain becomes circular via the FCE's closed-loop approach. Encircling this core, the diagram presents the primary components of the food circular economy in orange. This layer is divided into two primary objectives: preventing food losses at all stages of the supply chain, and the reintroduction of reclaimed food loss and FMSS back into the cycle, highlighting the potential to repurpose valuable food ingredients derived. The outermost layer, in yellow, depicts the crucial considerations for food safety pertinent to each component of the FCE, integrating a quad-modal approach for comprehensive coverage.

Case studies: Assessment of food safety hazards in high-volumeFMSS using the 'Quad-Modal hazard dynamics' approach

To illustrate the 'Quad-Modal hazard dynamics' approach to evaluate food safety hazards in food circular systems, we assess selected hazards within three FMSS that have gained significance in the food industry due to its large production quantities. By analyzing these FMSS as case studies, we gain critical insights into the complex nature of food safety hazards present in these materials when reintegrated into circular food system. The focus is on discerning the nuanced interplay of chemical, biological, and physical hazards within these FMSS, given their extensive utilization and the consequent potential for widespread impacts on food safety within FCE.

Seafood side streams

Seafood side streams, encompassing large quantities of unused fish and crustacean parts, are rich in high value nutrients like omega-3 fatty acids and proteins[23,24]. In fish processing, the side streams constitute a considerable portion of the total weight of fish (~50%), comprising unused parts of the fish such as viscera, heads, trimmings, skin, scale, fin, bone, and damaged or unsuitable fish[25]. These seafood side streams are economical sources of useful ingredients for culinary applications[26–28]. However, reutilizing seafood side streams is not without its food safety challenges, and it necessitates an assessment of the associated food safety hazards that may arise from its reintegration within the FCE. Seafood is subject to various food safety hazards, among which chemical hazards are predominant, and seafood side streams that are reprocessed for foods, feed and supplements are no exception[29,30].

Introduction. Biogenic amines (BAs) may be introduced into seafood side streams during improper handling, storage, and processing[29]. Seafood side streams are highly perishable, with their quick spoilage driven largely by processes such as microbial metabolism, autolysis, and lipid oxidation[31]. Factors such as higher temperatures can promote the growth and enzymatic activities of decarboxylase-producing bacteria like *Enterobacteriaceae*, *Pseudomonas*, and lactic acid bacteria, favoring formation of BAs[32]. In addition, during the processing of the seafood side streams, processes like fermentation can result in increased levels of BAs[33]. In a study of Korean fermented foods by Moon et al.[33], elevated levels of histamine, a derivative of histidine identified as a key causative toxin of scombroid poisoning, were found to have increased across all tested fermented food samples[29,33]. The formation of histamine poses as a food hazard as it cannot be easily eliminated due to its thermal stability[34].

Accumulation. The bioaccumulation of heavy metals is particularly pronounced in seafood side streams. Some types of fishmeal produced using fish parts that are unsuitable for human consumption, may be fed to farmed finfish and shellfish, leading to the bioaccumulation of contaminants such as methylmercury (MeHg) in muscle[35]. Fishmeal is also often used as feed for poultry and swine, and can lead to significant mercury accumulation in these livestock, exceeding safety limits[36]. Mercury that is present in the feed may then accumulate further in chicken feathers, a poultry side stream often repurposed into feather meal for livestock and aquaculture, thus perpetuating the cycle of contamination within the closed loop of FCE[37].

Reduction. Depending on the food processing methods utilized, food safety hazards may be reduced in the process, which is a crucial step in ensuring the safe use of seafood side streams. Techniques like ultrasonic cleaning have proven effective in reducing heavy metals and other contaminants in shellfish side streams, enhancing their suitability for various applications, such as in calcium supplements[38,39]. Depending on the technological interventions used for food processing, food safety hazards may be lowered, and hence reducing the need to dispose of waste, aligning with the goals of circular food systems.

Interaction. Besides histamine, the formation of other BAs, notably putrescine and cadaverine, are also closely linked to spoilage of seafood, which can affect the resulting quality of the seafood side streams that would be made into by-products. Putrescine and cadaverine are formed by bacterial decarboxylation of ornithine and lysine, respectively[29]. More importantly, the presence of putrescine and cadaverine can aggravate the toxicity effects of histamine poisoning through synergistic interactions[29]. These BAs have been found to facilitate histamine transport across the intestinal lumen and enhance its absorption, increasing histamine bioavailability, or may inhibit histamine-metabolizing enzymes like diamine oxidase (DAO), leading to reduced histamine breakdown and clearance from the body[40].

Whey from dairy processing

The dairy industry generates an estimated 180 to 190 million tons of whey each year, a valuable side stream utilized as a by-product derived from cheese and casein-based dairy production[41]. Whey constitutes a substantial proportion of the total milk volume and retains a significant amount of nutrients, such as protein, lactose, minerals and vitamins, making it a nutritious and functional resource for various applications in food and beverage products[42,43].

Accumulation. The repercussions of veterinary drug use in dairy production become increasingly evident in the context of whey utilization[44]. The reliance of the dairy industry on heat treatment to ensure the safety of milk products falls short when it comes to antibiotics. Studies report that the extent of heat degradation, a standard process in milk treatment, is insufficient for removing antibiotic residues[45]. This shortfall means that these substances can remain present despite the heat treatment. The correlation between antibiotic levels in milk and its derivatives such as whey and fresh cheese is remarkably direct. Research indicates that the levels of antibiotics in whey and fresh cheese closely mirror those found in the original milk, with as much as 85.9% of these substances being transferred from the milk source to whey[46,47]. This suggests a predictable and consistent contamination of whey when originating from antibiotic-laden milk.

Interaction. The persistence and transfer of antibiotic residues from milk to whey not only concentrate these substances but also elevate the potential risk of fostering antimicrobial resistance (AMR). Moreover, the acquisition of antimicrobial resistance genes (ARGs) by pathogens through horizontal gene transfer poses severe health and environmental risks[48]. For instance, Fraiture et al.'s study highlights this concern, identifying ARGs from *Bacillus subtilis* in a notable percentage of vitamin B2-enriched feed samples[49]. Similarly, the investigation conducted by Lányi et al. into raw milk samples from public markets reveals the alarming presence of various bacterial genetic materials, including complete ARGs[46]. These ARGs have the capacity to compromise the effectiveness of a broad spectrum of antibiotics, including cephalosporin, cephamycin, fluoroquinolone, peptide antibiotics, and tetracycline[46]. The accumulated presence of antibiotic residues in whey, stemming from standard dairy processing practices, emerges as a critical issue. It not only represents a direct threat to food safety but also contributes to the broader, more complex challenge of AMR.

Brewer's spent grain from breweries

Brewer's spent grain (BSG) is a significant side stream of the brewing industry, accounting for about 85% of the solid waste generated, reaching an annual production of 39 million tons worldwide[50]. BSG is composed of various valuable components such as hemicellulose, cellulose, lignin, and proteins[51]. Despite its potential value, BSG presents food safety challenges that need to be addressed. For instance, the prevalence of fungal secondary metabolites, namely mycotoxins, in BSG pose as a hazard that might affect human health, due to their toxicity to cause various health issues. Pereyra et al.[52] evaluated the mycotoxins content in 33 brewer's spent grain samples and found that all the samples are contaminated with fumonisin B1 (FB1) (104 – 145 $\mu g\,kg^{-1}$), with 18% of the samples containing aflatoxin B_1 (AFB_1) at levels between 19 and 44.52 $\mu g\,kg^{-1}$[52].

Introduction. Mycotoxins can also be introduced after its production, due to the fungi contamination. The high moisture and nutritional contents of BSG makes it especially susceptible to microbial growth and spoilage, in particular common fungal species such as Fusarium[53]. This genus is known for producing mycotoxins, including deoxynivalenol (DON) and fumonisins (FBs), which pose significant risks to animal and human health[54–56]. In the study by Penagos-Tabares et al., compounds like Zearalenone (ZEA), T-2, and HT-2 toxins were detected, even though they were found to be below European maximum limits for animal feeds[57,58]. Their persistent presence, however, is a stark reminder of the potential dangers if accumulated. BSG may initially meet acceptable standards for food use, however its microbial profile is subject to rapid alteration post-production, characterized by increases in microaerophilic bacteria and anaerobes[59]. Particularly disturbing are the high levels of Penicillium-derived metabolites, often indicative of post-production contamination during storage, which exacerbate the already serious issue of toxin accumulation[58].

Table 4 | Summary of cases presented and food hazards consideration under 'Quad-Modal hazard dynamic' approach

Case	Hazards Identified	Hazard dynamic case (Quad-modal approach)			
		Introduction	Accumulation	Reduction	Interaction
Seafood side streams	Biogenic amines (BAs)	Introduction of BAs during improper storage and handling or fermentation of seafood side streams	-	-	Aggravated histamine toxicity due to interactions between BAs
	Heavy metals	-	Mercury present in seafood side streams found in fishmeal feed for poultry accumulated in feather meal feed for aquaculture and livestock	Lower heavy metal levels in calcium supplements after ultrasonic cleaning	-
Brewer's spent grain from breweries	Mycotoxins	Post-production contamination of mycotoxin-produced fungi during storage	Mycotoxins absorbed from brewery's raw materials accumulated with newly produced mycotoxins during storage	Fermentation process to reduce the production and concentration of mycotoxins	Combined cytotoxic effects between different mycotoxins presented
Whey from dairy processing	Antibiotic residues	-	Antibiotic residues and antibiotic resistant genes from milk found accumulated in whey	-	-
	Antibiotic-resistant pathogens	-	-	-	Antibiotic residues in whey promote the selection of antibiotic-resistant pathogens

Accumulation. Grains, which serve as the raw materials for the brewery industry, are frequently contaminated with mycotoxins. However, the concentration of mycotoxins in beer is usually reduced as they are primarily absorbed and accumulated in the spent grains during the brewing process[60]. This was also corroborated by another study, in which 60% of the ZEA and 18% of the 15-acetyldeoxynivalenol (15-ADON) presented on the malt grist before the brewing process were found remaining in the spent grains[61]. Cumulatively, the gradual accumulation of mycotoxins in brewer's spent grain, together with the newly produced mycotoxins after BSG production, can escalate to concentrations that pose acute health risks, underscoring the necessity for continuous monitoring and strict control measures in the management of BSG.

Reduction. Interestingly, research indicates that biological detoxification can effectively reduce the production and concentration of mycotoxin. Gomaa et al. demonstrated the ability of lactic acid bacteria, *Lactobacillus brevis*, to reduce the production of aflatoxin B_1 by *Aspergillus flavus* and *Aspergillus parasiticus*, by 96.31% and 90.43%[62]. Luz et al. successfully reduced ochratoxin A (OTA) by 97% and 95% using Lactobacillus *rhamnosus* and *Lactobacillus plantarum*[63]. Several cutting-edge technologies, such as cold plasma, moderate electric field (MEF), pulsed electric field (PEF), ultrasound, and ohmic heating, have shown significant positive outcomes together with fermentation for mycotoxin detoxification, suggesting these technologies may interact synergistically to degrade mycotoxins in food[64].

Interaction. BSG is likely to be co-contaminated by several mycotoxins during complex processing and storage. The interaction between different mycotoxins might result in more severe toxic effects than exposure to individual mycotoxin. The simultaneous presence of, AFB_1 and ZEA, or, AFB_1 and DON, in agricultural products, for example, could be more hepatotoxic than either mycotoxin acting alone[65].

Overall, these case studies of high-volume FMSS demonstrate that while these resources present a valuable opportunity for resource reutilization in circular food systems, they require a good assessment and understanding of the potential food safety hazards arising from food circularity. The 'Quad-Modal hazard dynamics' offers a structured approach to identify, characterize, and therefore able to manage these hazards through a targeted manner, ensuring the safe integration of FMSS into the food value chain while aligning with the principles of a sustainable circular economy.

Food control implications and advancing research on food safety risk in food circular economy: A critical imperative

In the transition towards a circular food economy, aimed at sustainability and resource efficiency, the various aspects of food safety that we have described, particularly the multiple dynamics that food safety hazards could experience, underscore the critical need for a deeper understanding of these phenomena. Based on this, tailoring appropriate approaches to mitigate food safety risks associated with food loss and waste (FLW) across diverse stages of the food supply chain is imperative. These insights, grounded in scientific evidence and a risk-based perspective, are pivotal for developing effective food control strategies to ensure food safety within circular economy frameworks.

As highlighted in previous studies[11–13], food safety challenges inherent in FCE practices remain inadequately understood or addressed, particularly in the reuse of food side streams for food ingredient purposes. While the reuse of these side streams within the food supply chain effectively reduces losses, it also may pose a risk of (re)introducing contaminants into the food stream. Our 'Quad-Modal hazard dynamic' approach aims to illustrate that the occurrence and concentration levels of both new and pre-existing contaminants in raw materials depend largely on the nature and composition of the food Table 4 by-products, the processes employed to transform them into food ingredients, and the hygiene conditions maintained by operators during these processes. These dynamics of food hazards within the closed-loop section of the FCE model contribute to the complexities of ensuring effective food safety control measures.

From a food control standpoint, competent authorities and partners can build up on the insights provided here to develop food control strategies tailored to the needs of more sustainable food systems. Adhering to international risk analysis principles for food safety, hazard assessment investigations must meticulously identify and evaluate these hazard dynamics, with particular attention to potential new hazards. This involves comprehensively understanding the adverse health effects associated with these agents and characterizing the relationship between dosage and the likelihood of adverse effects occurring. However, to advance comprehensive risk-based control measures, other elements of risk assessment and management, as well as other food control aspects. Table 5 provides examples demonstrating how these food safety control elements can integrate the quad-modal approach to understanding the dynamics of food safety hazards, along with other pertinent considerations.

Table 5 | Examples of considerations in food safety control linked to the 'Quad-Modal hazard dynamic' approach and other food safety aspects

Food control element	Examples of considerations
Screening assessment	• Given the wide array of substances that may be found in food side streams and the resulting food ingredients, efficient identification of potential food safety hazards, even those with limited safety data, screening strategies can be used. These strategies can be relied on non-targeted methods in conjunction with toxicity estimation or exposure prediction schemes to prioritize chemicals for further assessment.
Exposure assessment	• Better understanding of how the dynamics of food hazards within the closed-loop section of the FCE model can affect the pathways and levels of exposure incurred by populations of interest under existing conditions. • Explore how management options, including the effects of applied transformation processes, affect existing conditions and resulting exposures.
Risk characterization	• Based on appropriate Hazard Assessment and Exposure Assessment inputs, understand the nature and magnitude of the potential risks associated with the conditions generated within the closed-loop section of the FCE model. • Apply integrated risk-benefit perspectives to find an appropriate balance between options to ensure food safety and promote sustainability.
Risk management	• Apply management options duly based on risk-based evidence and that take into account food safety considerations related to avoid, reuse, recycle and regenerate food loss.
Policy and regulation	• Seek to integrate or align sustainability policies for the promotion of a circular economy in food and food safety regulations to have a consistent legal framework. • Develop risk-based specific regulations to ensure safety of valorized food by-products, particularly those intended to be reinserted into the food supply chain. These regulations should establish provisions that address the dynamics of food hazards within the closed-loop section of the FCE model, as well as the conditions of the transformation processes and detoxification effects of this.
Surveillance and monitoring	• Establish appropriate surveillance and monitoring measures to capture information and take action on the occurrence and levels of priority contaminants within the closed-loop section of the FCE model.
Education and communication	• Appropriate education and communication measures on food safety considerations related to avoid, reuse, recycle and regenerate food loss must be in place with competent authorities and food business operators at different stages of the food chain.
Food hygiene system	• Within the framework of the general principles of food hygiene, and following the applicable regulations, food business operators that use valorized food by-products for food production, when appropriate, must adapt their food hygiene system (including good hygiene practices and HACCP system) to control the significant hazards that could be present. This may include applying hazard analysis of raw materials and other ingredients to prevent the introduction of hazards above acceptable levels. • When appropriate, establish good hygiene practices to manage food loss that will be destined for reuse, recycle and regenerate processes. • In general, all food business operators may consider strengthening their food hygiene systems in order to reduce food loss associated with food safety discards.

Likewise, the scientific community should engage in rigorous research that examines the entire lifecycle of these by-products within circular systems. The research should focus on understanding how processing, storage, and handling in circular systems contribute to the safety profiles of these FMSS. There is a pressing need to develop and validate new methodologies for contaminant detection and quantification, assessing current decontamination techniques, and exploring innovative approaches to manage these food safety hazards. Furthermore, with better understanding of the food safety hazards, research into the integration of advanced food processing technologies like High Pressure Processing (HPP), Pulsed Electric Fields (PEF), and Atmospheric Cold Plasma (ACP) can offer promising technological solutions to minimize waste within food circular systems, through their capabilities of reducing microbiological activity, chemical contaminants, and food allergens in food products[66–71]. These technologies, alongside advanced detection methods like Next-Generation Sequencing (NGS), quantitative Polymerase Chain Reaction (qPCR), utility of stable isotopes, and various spectroscopy techniques, provide comprehensive tools for tracking and monitoring changes in FMSS in the context of food safety[72–77]. The use of biosensors for real-time monitoring and the combination of multiple detection technologies with chemometric and omics approaches, augmented by artificial intelligence, present innovative avenues for detecting food hazards[77–81].

By undertaking this crucial research, the scientific community can provide indispensable insights and guidelines that will aid policymakers, industry stakeholders, and regulatory bodies in harmonizing sustainability goals with uncompromised food safety in circular economy food systems. This alignment is essential for the sustainable and safe growth of our global food systems, ensuring that our pursuit of environmental sustainability goes hand in hand with the protection of public health.

Concluding remarks

This perspective article has examined the interlink between food safety and food circular economy model, with emphasis on the complexities of food hazards dynamic that can occur in the reuse of food manufacturing side streams (FMSS) and their reintegration into the supply food chain.

The transition towards circularity in food systems via the reprocessing of food manufacturing side streams and by-products holds significant promise for waste reduction, resource conservation, and the promotion of more sustainable consumption and production patterns. However, to ensure the success of this transition, it is crucial to thoroughly understand the complexities potential occurrences and harmful alterations of the hazard levels associated with these reprocessing practices. The proposed quad-modal approach addresses these food safety hazards dynamics by describing their potential modalities of introduction, accumulation, reduction, and interaction. This underscores the critical need for a deeper understanding and developing effective management strategies for potential food safety risks to ensure the safety and sustainability of food systems. These strategies should encompass rigorous hazard assessment, but should also address appropriate exposure assessments, risk characterization, and proactive risk management practices. Based on this, the competent authorities must deploy appropriate actions to control food safety, which must be applied within the framework of the food circular economy.

Future research should focus on the compositional changes and risks associated with reprocessing food manufacturing side streams, to develop safer and more efficient processing techniques. The advancement of new detection, monitoring, and analysis technologies will also be essential for assessing and managing risks and ensuring food safety.

As we advance our understanding and implementation of circular food systems, it becomes clear that the goals of environmental sustainability and food safety are not only compatible, but are integral, complementary pillars essential for building a truly sustainable food system. Therefore, we call upon industry stakeholders, policymakers, and researchers to unite in their efforts to innovate on robust solutions that not only advance sustainable food system objectives but also ensure the safety and well-being of consumers. Through such collaborative efforts, we can craft a food system that upholds the principles of sustainability while safeguarding public health, thereby achieving a sustainable future for all.

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Competing interests

The authors declare no competing financial interests.

Additional information

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