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COMPREHENSIVE REVIEW

Addressing the safety of new food sources and production systems

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Abstract

New food sources and production systems (NFPS) are garnering much attention, driven by international trade, changing consumer preferences, potential sustainability benefits, and innovations in climate-resilient food production systems. However, NFPS can introduce new challenges for food safety agencies and food manufacturers. Most food safety hazards linked to new foods have been identified in traditional foods. However, there can be some food safety challenges that are unique to new foods. New food ingredients, inputs, and processes can introduce unexpected contaminants. To realize the full potential of NFPS, there is a need for stakeholders from governments, the food industry, and the research community to collectively work to address and communicate the safety of NFPS products. This review outlines known food safety hazards associated with select NFPS products on the market, namely, plant-derived proteins, seaweeds, jellyfish, insects, microbial proteins, as well as foods derived from cell-based food production, precision fermentation, vertical farming, and 3D food printing. We identify common elements in emerging NFPS regulatory frameworks in various countries/regions. Furthermore, we highlight current efforts in harmonization of terminologies, use of recent scientific tools to fill in food safety knowledge gaps, and international multi-stakeholder collaborations to tackle safety challenges. Although there cannot be a one-size-fits-all approach when it comes to the regulatory oversight for ensuring the safety of NFPS, there is a need to develop consensus-based structured protocols or workflows among stakeholders to

Abbreviations: 3DFP, 3D food printing; Anvisa, Brazilian Health Regulatory Agency; BSE, bovine spongiform encephalopathy; EFSA, European Food Safety Authority; EU, European Union; FAO, Food and Agriculture Organization (of the United Nations); FDA, Food and Drug Administration; FSA, Food Standards Agency (of the United Kingdom); FSANZ, Food Standards Australia New Zealand; FSSAI, Food Safety and Standards Authority of India; GCC, Gulf Cooperation Council; GRAS, Generally Recognized as Safe; HPP, high-pressure processing; LED, light-emitting diode; LPS, lipopolysaccharide; MFDS, Ministry of Food and Drug Safety (of the Republic of Korea); MOH, Ministry of Health; NAM, new approach methodologies; NFPS, new food sources and food production systems; OECD, Organisation for Economic Co-operation and Development; PEF, pulsed electric field; POPs, persistent organic pollutants; PTM, post-translational modification; RuBisCO, ribulose-1,5-bisphosphate carboxylase–oxygenase; SFA, Singapore Food Agency; USA, United States of America; WGS, whole genome sequencing; WHO, World Health Organization (of the United Nations).

facilitate comprehensive, robust, and internationally harmonized approaches. These efforts increase consumers' confidence in the safety of new foods and contribute toward fair practices in the international trade of such foods.

KEYWORDS
food safety, food regulation, new food production systems, new foods, novel foods

1 | INTRODUCTION

The current expansion of international agri-food trade, catalyzed by an increase in multilateral trade agreements, has introduced consumers worldwide to food sources beyond those offered by their traditional or regional diets (Food and Agriculture Organization of the United Nations [FAO], 2022a). Consumers are now increasingly exploring food options that are perceived to be more nutritious or healthful, as well as foods produced more sustainably and not sourced from livestock animals (Li et al., 2021; Spendrup & Hovmalm, 2022; Torán-Pereg et al., 2023). Concurrently, modern technology has led to innovations in food production systems. These innovations include in vitro culture of animal cells for consumption, engineering of microorganisms to produce food ingredients, as well as vertical farming of fruits and vegetables (Benke & Tomkins, 2017; Post et al., 2020; Teng et al., 2021). These new food production systems are underpinned by progress in our understanding of fundamental cellular processes, advances in molecular engineering tools, as well as developments in engineering solutions for large-scale cultivation of cells or organisms in controlled environments (Durand, 2003; Naranjani et al., 2022; Voigt, 2020).

The scope of what food is considered obtained from new food sources and production systems (NFPS) differs among countries and regions. For a specific human population, a food substance can be considered derived from NFPS if it has not been traditionally consumed at a significant level by that population, even if said food substance has a history of safe consumption by a separate population in another region. Other foods are more generally recognized as NFPS. These include foods derived from microorganisms that have not been consumed by any significant human population, as well as animal cells derived from cell culture (also known as cell-based food or cell-cultivated food) (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 2023b). Therefore, products considered new today may become more mainstream in our markets as they find greater acceptance among consumers, whereas other emerging food products continue to be inducted under the scope of NFPS.

Considering the impact that international trade, shifting consumer preferences, and technological innovations have had on the agri-food landscape, NFPS may significantly influence the global food supply in the foreseeable future by diversifying our current food sources (Figure 1). Certain NFPS, through their application as complementary protein sources, can reduce our reliance on proteins derived from livestock animals and may consequently be associated with lower impacts on the environment in terms of carbon footprint, greenhouse gas emissions, and arable land and water use (Green et al., 2022; Poore & Nemecek, 2018).

As the NFPS sector expands, it has been recognized internationally that challenges in bringing NFPS products to the market can manifest in the form of knowledge gaps in safety assessments, as well as uncertainties in regulatory guidelines and terminologies (Figure 1) (FAO & WHO, 2021). Indeed, NFPS has been the subject of recent interest and discussion at the level of the Codex Alimentarius, with member countries, industry, and advocacy groups providing their views (FAO & WHO, 2021, 2023c). Given that foods from NFPS may raise new or unexpected food safety concerns, there is an urgent need for stakeholders in the NFPS ecosystem to have a clear, science-based understanding of the various NFPS products and co-develop approaches to ensure food safety. This is because food safety is a key requirement to gaining consumer trust for such products. In recent years, several regulatory bodies overseeing food safety have initiated public consultations and developed regulatory frameworks to provide guidance to the nascent NFPS ecosystem (Anvisa, 2020; Food Standards Australia New Zealand [FSANZ], 2022; Food Safety and Standards Authority of India [FSSAI], 2017; GCC Standardization Organization, 2023; Health Canada, 2022; Ministry of Food and Drug Safety [MFDS], 2018; National Food Service Israel, 2022; Singapore Food Agency [SFA], 2019; Turck et al., 2016; Witherspoon & Donse, 2023). The goals commonly associated with these efforts include identifying potential food safety risks, facilitating the sharing of risk assessment data and tools, creating a predictable regulatory environment for both regulators and the industry, and shaping consumer perception through communicating evidence-based information. These efforts are timely

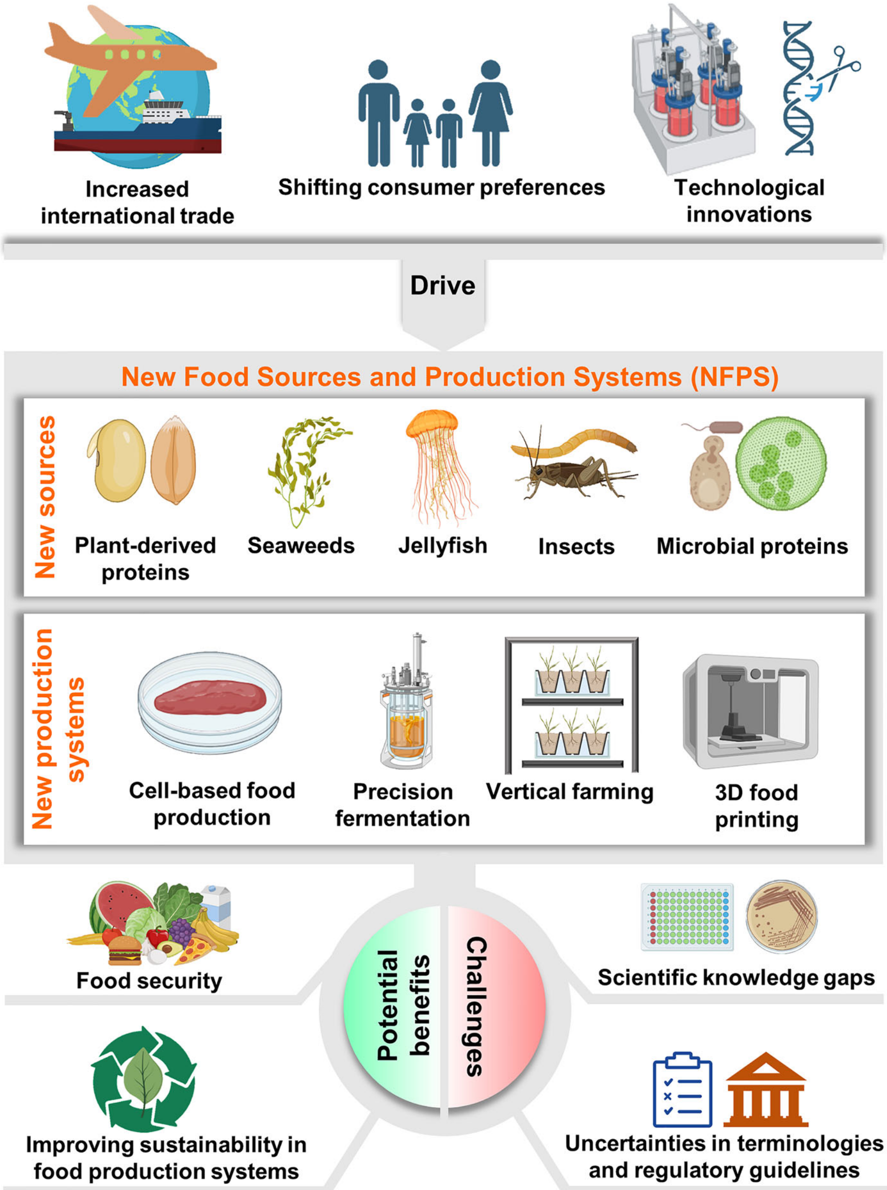

FIGURE 1 Schematic overview of some key drivers that are leading to the development of new food sources and production systems (NFPS). Select categories of NFPS are shown, along with key potential benefits and food safety challenges associated with NFPS.

as various NFPS are already on the market (Table 1), with many more products currently being developed by a plethora of market actors, from start-ups to multinational corporations (Charlebois et al., 2022). This review provides an overview of the food safety hazards associated with select NFPS food products that are already on the market, identifies trends in regulatory approaches taken by regulatory bodies to assess and manage NFPS-associated food safety risks, and outlines possible ways forward for internationally harmonized food safety guidance pertaining to NFPS.

2 | NFPS FOOD SAFETY CONSIDERATIONS

Regulatory bodies, intergovernmental agencies, producers, researchers, and consumers all have a part to play in ensuring the safety of NFPS products. Mapping out hazards associated with NFPS can support food safety risk assessment, management, and communication by said stakeholder groups in the NFPS ecosystem. Therefore, we provide an overview of microbiological, chemical, and physical hazards associated with select NFPS foods as iden-

TABLE 1 New food sources and production systems (NFPS) categories/technologies and examples of products available on the market.

NFPS category/technology	Examples of products	Availability
Plant-derived proteins	Tofu and tempeh, both made from soybeans	Traditionally consumed in East and Southeast Asia but now available in other countries/regions (Guan et al., 2021)
	Soy milk	Available in China for centuries and has been available in Europe and the US since 1950s (Mäkinen et al., 2016)
	Textured vegetable protein (from soy, wheat, and cottonseed, among other protein-rich seeds)	Available in the United States of America (USA) since 1960s, now available globally (Arora et al., 2023)
	Oat milk	Available since 1990s in parts of Europe and the USA and is now more widely available globally (Yu et al., 2023)
	Canola protein isolate	Available in the USA since 2008 (Hills, 2008) and in the European Union (EU) since 2013 (EFSA, 2013)
	Mung bean protein isolate	Available in the EU since 2022 (Southey, 2022)
Seaweeds	*NorPyropia tenera, Pyropia yezoensis* (multiple *Pyropia* species are known as nori)	Traditionally consumed in East Asia and is now available in Western countries/regions (Nisizawa et al., 1987)
	Caulerpa lentillifera, *Caulerpa racemosa* (multiple *Caulerpa* species are known as sea grapes)	Traditionally consumed in East and Southeast Asia and is now available in Western countries/regions (Paul et al., 2014)
	Undaria pinnatifida (wakame)	Traditionally consumed in East and Southeast Asia and is now available in Western countries/regions (Young et al., 2022)
Jellyfish	*Stomolophus meleagris* (cannonball jellyfish)	Traditionally consumed in East Asia and is now available in other countries/regions (Hsieh et al., 2001)
	Rhopilema hispidum, *Rhopilema esculentum*	Traditionally consumed in East Asia and is now available in other countries/regions (Raposo et al., 2022)
	Nemopilema nomurai (Nomura's jellyfish)	Traditionally consumed in parts of Asia and is now available in other countries/regions (Leone et al., 2019)
Insects	*Gryllus similis*, *Gryllus bimaculatus*, *Acheta domesticus* (collectively referred to as crickets) (Magara et al., 2021)	Traditionally consumed in parts of South America, Africa, and Asia (Stork, 2018) *Acheta domesticus* is authorized as food in the EU since 2023 (European Commission, 2023)
	Tenebrio molitor larvae (mealworm)	Traditionally consumed in parts of Asia (Errico et al., 2022) Mealworm larvae are authorized as food in the EU since 2021 (European Commission, 2021)
	Bombyx mori larvae (silkworm)	Traditionally consumed in parts of Asia and newly introduced to Western countries/regions (Wu et al., 2021)
Microbial proteins (proteins obtained from bacteria, fungi, and microalgae)	*Arthrospira platensis, A. maxima, A. fusiformis* (collectively termed *Spirulina*)	Traditionally consumed in parts of South America and Central Africa and is now actively explored as an alternative protein source (Deng & Chow, 2010; Eilam et al., 2023)
	Chlorella vulgaris	Consumed as dietary supplements in Japan since 1950s and is now actively explored as an alternative protein source (Eilam et al., 2023; Görs et al., 2010)
	Fusarium venenatum	Available in the United Kingdom (UK) since 1984 (Wiebe, 2002)
	Chlamydomonas reinhardtii	Available in the USA since 2018 (Fields et al., 2020)
	Fusarium flavolapis	Available in the USA since 2021 (Ho, 2021)
	Hydrogen-oxidizing bacteria (Ercili-Cura, 2020)	Available in Singapore since 2022 (Begum, 2022)

(Continues)

TABLE 1 (Continued)

NFPS category/technology	Examples of products	Availability
Cell-based food production	Chicken cells derived from cell culture	Cell-based chicken products available in Singapore since 2020 (Phua, 2020) and in the USA since 2023 (Wiener-Bronner, 2023)
	Bovine cells derived from cell culture	Cell-based beef products have been approved for sale in Israel since 2024 (Southey, 2024)
Precision fermentation	Chymosin made from bioengineered *Kluyveromyces marxianus*	Available in the USA since 1990 (Flamm, 1991)
	Human milk oligosaccharides (e.g., 2′-fucosyllactose, lacto-*N*-tetraose) made from bioengineered *Escherichia coli*	Available in the USA and Europe since 2015 (Zeuner et al., 2019)
	Soy leghemoglobin made from bioengineered *Komagataella phaffii*	Available in the USA since 2018 (Fraser et al., 2018)
	Beta-lactoglobulin made from bioengineered *Trichoderma reesei*	Available in the USA since 2020 (Watson, 2020) and in Singapore since 2022 (Ettinger, 2022)
	Beta-lactoglobulin made from bioengineered *Komagataella phaffii*	Available in Israel, Singapore, and the USA since 2023, and in Canada since 2024 (Wrobel, 2024)
Vertical farming	Mainly leafy greens and herbs. Currently expanding to also produce fruits and other vegetables (Benke & Tomkins, 2017)	Available in various cities in some countries (e.g., China, France, Germany, India, Japan, Singapore, USA) since 2012 (Al-Kodmany, 2018)
3D food printing	Different food-based materials are utilized, both traditional (cheese, chocolate, icing, dough, and butter) and novel (insect protein powder, animal cell cultures)	Available in the UK since 2016 (Norum, 2016)

tified in the literature. Food safety concerns may arise due to either new hazards or increased levels of known hazards relative to more widely consumed foods. We also wish to highlight that food safety hazards do not necessarily translate to adverse consumer health impacts. This is because hazard identification is only the first step in food safety risk assessment. To further understand the food safety risk arising from a hazard, it would be necessary to characterize the hazard (such as in terms of dose-response effects), determine the dietary exposure to the hazard, and determine the probability and/or severity of potential adverse health effects (FAO & WHO, 2023a; Goldstein, 2005).

2.1 | Food safety hazards associated with new food sources

In this subsection, we provide brief descriptions of five categories of new food sources that are available on the market, namely, plant-derived proteins, seaweed, jellyfish, insects, and microbial proteins. We also describe the food safety hazards associated with each category based on available literature. Hazards that have not been reported but could plausibly be introduced are indicated as "potential." Listing potential hazards can be helpful in raising awareness of possible food safety issues that may arise from new food sources that have yet to be studied extensively in terms of food safety.

2.1.1 | Plant-derived proteins

Plant-derived proteins are obtained from plant materials via chemical and mechanical processing steps that largely remove carbohydrates, lipids, and other nonprotein components, resulting in a mixture with protein as the major component. In recent years, there has been strong consumer interest in utilizing plant-derived proteins as dietary substitutes for animal-derived proteins (Wild et al., 2014). Sources of plant-derived proteins include soybean, mung bean, wheat, chickpeas, pea, jackfruit. A noteworthy recent development in plant-derived proteins is the potential application of RuBisCO (ribulose-1,5-bisphosphate carboxylase–oxygenase) as food (Pearce & Brunke, 2022). RuBisCO, the enzyme responsible for carbon fixation in plant leaves, is thought to be the most abundant protein in leaves, accounting for an estimated 3% of the total mass of leaves, and may therefore be an under-tapped source of plant-based proteins (Bar-On & Milo, 2019). Sources, such as duckweed, sugar beet leaves, mulberry leaves, and alfalfa (lucerne), have emerged as attractive options for extracting RuBisCO (Kobbi et al., 2017; Martin et al., 2019; Nieuwland et al., 2021; Sun, Wu, et al., 2015). Plant-derived proteins, especially those derived from soybean and wheat, have been traditionally consumed in many parts of Asia, especially in areas where vegetarianism is prevalent. However, certain plant-derived proteins are considered new in the West. For example, mung bean protein is considered as a novel food by the European Union (EU) (Turck et al., 2021). A determination on whether a plant-derived protein product is a new or novel food may be made based on the extent of processing as well as increased dietary exposure to certain plant components (including any contaminants that may be present) in the plant protein concentrate compared to the unprocessed plant. However, there is no consensus on the extent or type of processing involved, the increase in dietary exposure, or the extent of protein concentration relative to the source material before a plant-derived protein is considered a new or novel food ingredient.

Food safety hazards in plant-derived proteins can arise from the source plant material in the form of microbiological contaminants as well toxins and allergens naturally produced by the plant. Plant-derived protein production typically involves numerous processing steps, which can increase the risk of introducing pathogenic and toxigenic microorganisms (McClements et al., 2019).

Microbiological hazards

Plant-derived proteins that mimic meat and other animal products generally have high nutrient and moisture content and are therefore susceptible to microbial contamination (Wild et al., 2014). Microbiological hazards can come from the source plant material or can be introduced during processing and handling steps. Ready-to-eat plant-based meat substitutes were found to contain the pathogen *Enterococcus faecium*, whereas vacuum-packed plant-based sausages were found to contain *Clostridium botulinum* (Geeraerts et al., 2020; Pernu et al., 2020). *Listeria monocytogenes* has been detected in plant-based products mimicking cheese in 2023, which led to recalls in the EU (Whitworth, 2023). Both *L. monocytogenes* and *Salmonella enterica* were found to proliferate in plant-based beverages (almond, cashew, and coconut) mimicking dairy at higher rates than in cow's milk at ambient temperature (Bartula et al., 2023). These findings highlight the need to store and handle plant-based food products hygienically (e.g., keeping food in covered containers at 5°C or lower). Some plant-derived proteins undergo heat treatment steps (e.g., extrusion) during their processing, which can inactivate most bacteria (Wild et al., 2014). However, endospore forming bacteria, such as *Bacillus cereus* and *Clostridium* spp., can survive heat treatments at 100–121°C for short periods of time, with the actual time taken to inactivate such bacteria being species and food matrix dependent (Lee et al., 2021). Various methods in inactivating pathogens, including endospore-forming bacteria, without compromising the nutrition and taste of plant-derived proteins are actively being explored (Menta et al., 2022). These include high-pressure processing (HPP), pulsed electric field, and cold plasma.

Chemical hazards

Toxigenic fungi, such as certain *Alternaria, Aspergillus, Diaporthe, Penicillium*, and *Fusarium* species, can contaminate raw plant materials used as a source for various plant-based proteins (Mihalache et al., 2022). A systematic review found that fermented soy-based food can be contaminated with aflatoxins, alternariol, fumonisins, ochratoxin A, T-2 toxin, zearalenone, and among other mycotoxins (Tian et al., 2022). Lupines are susceptible to infestation by the toxigenic fungus *Diaporthe toxica*, which can produce the mycotoxins ochratoxin A and phomopsin A (Kunz et al., 2022). An analysis of soy, oat, rice, and almond beverages revealed that 95% of samples contained at least one mycotoxin species, with enniatin B being the most prevalent (Juan et al., 2022). It should be noted that heat treatments such as roasting and baking can reduce, but not necessarily eliminate, mycotoxins in food (Schrenk et al., 2020).

Some plant species biosynthesize secondary metabolites that may cause adverse health effects in humans. Examples include cyanogenic glycosides in cassava, quinolizidine alkaloids in lupines, and glycoalkaloids in potatoes (Cereda & de Vasconcellos, 2023; Schryvers et al., 2023; Urugo & Tringo, 2023). Food safety risks from plant toxins can be reduced using a variety of processing steps such as washing and roasting (Schrenk et al., 2019).

Certain proteins in popular plant-based protein sources can cause adverse hypersensitivity effects in a small proportion of consumers. These include gluten in wheat, profilin in soybean, and prolamins in peanuts (Hischenhuber et al., 2006; Mueller et al., 2014; Wiederstein et al., 2023). These proteins may not be necessarily inactivated by heat and processing and can therefore pose food safety risks (Hansen et al., 2003; Wiederstein et al., 2023). Exploration of new sources of plant-based proteins could also expose consumers to new allergens. For instance, even though pea is currently not considered a major allergen, allergic reactions, likely resulting from the allergenic proteins Pis s 1 and Pis s 2, have been documented (Taylor et al., 2021). The increasing popularity of pea-derived protein products may warrant a review of pea in existing risk management measures. Taken together, given the vast biosynthetic potential of plants, further research to identify and quantify small molecules toxins and protein allergens in plants that are commonly utilized in making plant-derived proteins can support food safety risk assessment.

Certain food items naturally contain higher levels of radioactivity than others. Two emerging sources of plant-derived proteins, Brazil nuts and lima beans, are known to bioaccumulate radionuclides such as ^{40}K and ^{226}Ra (Adebo, 2023; Parekh et al., 2008; U.S. Nuclear Regulatory Commission [US NRC], 2022). Nonetheless, a person consuming food from a variety of sources is unlikely to be exposed to unhealthy doses of radiation from food.

Physical hazards

Plant-derived proteins typically undergo numerous processing steps, which increases the probability of physical hazards being inadvertently introduced. Small pieces of woods and metal have been found in plant-based protein products, which have led to food recalls (Calvo, 2023; Staff, 2023). A survey of plant-based beverages in Brazil revealed that 23% of products tested had some form of foreign matter (Fioravanti et al., 2024). These include insect fragments and mammalian hair, possibly from rodents. Taken together, these case studies highlight the importance of putting in place food safety monitoring measures, such as X-ray detection systems, to capture foreign matter that can be introduced during critical points during plant-based protein processing (Lim, Lee, et al., 2022). Installation of sieves, magnetic separators, and optical sorters can also help to prevent foreign matter such as seed pits, stones, and metal pieces from ending up in the final product (Payne et al., 2023).

2.1.2 | Seaweeds

Seaweeds, also known as macroalgae, have been traditionally consumed in East Asia, Southeast Asia, and coastal regions in Europe. In addition, seaweeds have a long history of being a source of various food additives, such as gums and hydrocolloids (FAO & WHO, 2022). In more recent times, some seaweed species, such as *Palmaria palmata* (red dulse) and *Fucus vesiculosus* (bladderwrack), have been introduced as a new food source in some European regions. Seaweeds have gained interest internationally as a good source of minerals, especially iodine, proteins, polyunsaturated fatty acids, and dietary fiber (Leandro et al., 2020).

Food safety hazards in seaweeds can arise from environmental contaminants, such as microorganisms, heavy metals, and radionuclides. Allergens and toxins naturally present in certain seaweeds can also be safety concerns.

Microbiological hazards

Microbiological pathogens known to be associated with seaweed, especially uncooked seaweed, include norovirus, *Staphylococcus aureus*, *S. enterica* ser. Typhimurium, and *Escherichia coli* O157:H7 (Løvdal et al., 2021). Seaweeds can also harbor *Vibrio parahaemolyticus*, with higher occurrence in seaweeds harvested from warmer waters (Mahmud et al., 2007). Certain consumers may choose to consume raw seaweed, which can increase health risks from microbiological contaminants (Rogel-Castillo et al., 2023). Processing steps such as dehydration and cooking are likely to reduce microbiological risks from seaweeds.

Chemical hazards

Toxigenic dinoflagellates are known to attach to seaweeds (FAO, 2022b). Dinoflagellates from the genus *Gambierdiscus* have been reported to attach to edible seaweed genera, such as *Polysiphonia* (filamentous red algae), *Dictyota* (brown seaweed), and *Ulva* (sea lettuce) (Rains & Parsons, 2015). *Gambierdiscus* species produce a range of potent neurotoxins, such as ciguatoxins and maitotoxins (Larsson et al., 2018; Stuart et al., 2022). Pinnatoxin-G, a cyclic imine neurotoxin from the dinoflagellate *Vulcanodinium rugosum*, has been reported in *Saccharina latissimi* (sugar kelp) (Banach et al., 2020; Rambla-Alegre et al., 2018).

Allergic reactions to seaweed have been documented, though the causative agents of allergenicity of seaweed have not been well characterized (Garciarena et al., 2022). More research may be warranted in characterizing the presence of toxins and allergens in seaweeds to support comprehensive risk assessments.

Certain edible seaweeds can accumulate heavy metals, including arsenic, cadmium, lead, and mercury, from seawater (Rose et al., 2007). The accumulation propensity differs between individual seaweed species. For example, the concentrations of the inorganic forms of arsenic in hijiki were found to be two orders of magnitude higher than that found in in arame, wakame, kombu, and nori. Nonetheless, soaking seaweed in water can reduce its inorganic arsenic levels. Some seaweeds can biosynthesize diverse natural products, such as kainoids, polycavernosides, and prostaglandin E_2, which can exert toxicological effects (Smit, 2004). The high iodine concentrations in certain seaweeds, such as kombu, can cause thyroid function disorders if such seaweeds are consumed at high levels (Smyth, 2021).

Pesticide residues have been found in seaweeds due to pesticides in agricultural runoff (Banach et al., 2020). Pesticides classes, such as organochlorines, benzoylureas, organophosphates, carbamates, and pyrethroids, have been detected in seaweeds (García-Rodríguez et al., 2012; Lorenzo et al., 2012). Certain pesticides, such as organochlorines, benzoylureas, and pyrethroids, are lipophilic and are likely to bioaccumulate in seaweed, leading to increased food safety risks (Sundhar et al., 2023). Seaweeds grown in waters contaminated with persistent organic pollutants (POPs) can accumulate these contaminants. Polychlorinated dibenzo-*p*-dioxins have been found in edible seaweeds such as *Undaria* and *Ecklonia*, whereas polychlorinated biphenyls have been found to be concentrated in the green algae *Ulva rigida* (Banach et al., 2020; Cheney et al., 2014).

Seaweeds are known for their ability to concentrate radionuclides and have been used as indicators for monitoring marine radioactive contamination (Goddard & Jupp, 2001). For example, the radionuclides ^{226}Ra, ^{228}Ra, and ^{40}K have been detected in *Eucheuma* spp. (Khandaker et al., 2019). Following the Fukushima nuclear accident in 2011, radioactive cesium isotopes (^{134}Cs and ^{137}Cs) have been detected in seaweeds in surrounding waters (Wada et al., 2016). It should be noted that the radionuclide concentrations in seaweeds have been monitored to decrease over time and have been below regulatory limits from 2012 to 2015 (Banach et al., 2020).

Physical hazards

Studies have shown that microplastics in seawater are able to adhere to the surface of seaweeds and can therefore be a potential pathway for ingestion of microplastics (Gutow et al., 2016; Li et al., 2020). Nonetheless, thorough washing should remove most of the surface adhered microplastics.

2.1.3 | Jellyfish

Jellyfish has been traditionally consumed in several Asian and Southeast Asian countries for centuries but are considered new to the Western diet (FAO, 2022b). Edible jellyfish species, such as *Rhopilema esculentum* (flame jellyfish), *Nemopilema nomurai* (Nomura's jellyfish), *Rhizostoma pulmo* (barrel jellyfish), and *Stomolophus meleagris* (cannonball jellyfish), have gained interest as new food sources in the West as they are high in protein and low in fat (Leone et al., 2019; Ranasinghe et al., 2022). Furthermore, certain jellyfish species, such as *Rhopilema* spp. and *Aurelia aurita*, can form large blooms, sometimes triggered by climactic factors, and are therefore perceived by some as a climate-resilient food source (Youssef et al., 2019). However, it is important to refrain from such a perception as not all blooms can be managed by fishing and only a small subset of jellyfish species is edible. Similar to seaweeds, food safety hazards in jellyfish can arise from their biochemical composition and from environmental contaminants in the marine environment.

Microbiological hazards

Fresh jellyfish spoil easily after harvesting and need to be processed quickly to reduce risk of microbiological contamination (FAO, 2022b). Within hours of harvest, jellyfish are typically washed thoroughly with clean water and soaked in a mixture of sodium chloride and alum. This salting step inhibits microbial growth and helps to preserve the jellyfish (Raposo et al., 2022). A study has shown that *E. coli*, *Salmonella* spp., and *L. monocytogenes* were absent from *R. pulmo* that had been washed with sterile seawater and fresh water (Bleve et al., 2019). However, low levels (at around 10^2 CFU/g) of *Staphylococci* were still present. This was attributed to the environment from which the jellyfish samples were harvested. Using 16S rRNA gene sequencing, six genera of bacteria, namely, *Vibrio, Mycoplasma, Ralstonia, Tenacibaculum, Nautella*, and *Acinetobacter*, have been detected in washed but unsalted samples of four jellyfish species, namely, *Aurelia coerulea*, *Cyanea nozakii*, *N. nomurai*, and *R. esculentum* (Peng et al., 2021). Certain species within these genera are known food- or water-borne pathogens. Currently, no viral or fungal species of food safety concern have been found in jellyfish (Raposo et al., 2022).

Chemical hazards

There has been a case report of ciguatoxin poisoning from jellyfish consumption, suggesting jellyfish may be able to harbor toxigenic dinoflagellates (Zlotnick et al., 1995). However, the jellyfish species was not identified so it is unknown if the jellyfish consumed belongs to a species with a history of significant human consumption. It has also been hypothesized that jellyfish may contain the toxins gambierol and brevetoxin produced by dinoflagellates (Cuypers et al., 2007). Nonetheless, more research is needed to link jellyfish consumption with the risk to consumer safety from marine biotoxins.

R. pulmo has been found to bioconcentrate cadmium, lead, and, in particular, arsenic, relative to seawater (Bonaccorsi et al., 2020; Muñoz-Vera et al., 2016). Aluminum-containing food additives are used in jellyfish processing as a firming agent and to increase the shelf life of the jellyfish. These additives have raised food safety concerns due to the high levels of aluminum found in the final product (Bleve et al., 2021; FAO & WHO, 2011). Nevertheless, it has been reported that levels of aluminum can be lower in cooked products compared to raw jellyfish (Raposo et al., 2022). Taken together, these studies highlight the importance of monitoring such chemical contaminants in jellyfish.

Case reports of anaphylaxis caused by ingestion of cooked jellyfish have been reported, though the etiology of allergic reactions caused by ingestion of cooked jellyfish is unclear (Imamura et al., 2013; Suzuki et al., 2017). A separate study reports that individuals who are allergic to crustaceans, cephalopods, or fish may be able to safely consume jellyfish, suggesting the allergenic proteins in jellyfish may be unique (Amaral et al., 2018). There are currently no studies on specific allergens found in jellyfish, which represents a knowledge gap in jellyfish food safety risk assessment.

Physical hazards

The presences of microplastics have been reported in some jellyfish, such as *Cassiopea xamachana* and *Pelagia noctiluca*, which may pose food safety concerns (Iliff et al., 2020). However, the toxicological mechanisms and effects from microplastic ingestion are not well understood, prompting research efforts in this area (Allan et al., 2020).

2.1.4 | Insects

Insects have been part of traditional diets across the world, with an estimated 2000 species consumed (Costa-Neto & Dunkel, 2016; FAO, 2021; Ramos-Elorduy, 2009). Some insect species, such as crickets and mealworms, are considered good sources of protein as they have high digestibility and can fulfill the amino acid requirements of humans (Poelaert et al., 2018). With advances in animal husbandry, adoption of modern Western dietary habits, and rising negative perception of insects as pests in agriculture, there has been a notable decline in entomophagy (FAO, 2013). Nonetheless, insects are still eaten widely in many countries in Central and South America, Africa, and Asia. Insects have recently gained interest in modern Western cultures as they are viewed as a more sustainable source of protein compared to livestock and seafood (Grabowski et al., 2022).

Food safety hazards associated with insects are linked to how they are harvested or produced, what they are reared on, the processing conditions, as well as the insect species itself. Insects produced under controlled hygienic conditions tend to pose fewer food safety risks than those gathered from the wild (FAO, 2021).

Microbiological hazards

Under unhygienic conditions, such as when contaminated feed substrates are used or when insects are harvested from the wild, there can be increased microbiological risks associated with edible insect species. Insects of commercial interest can harbor diverse microbiota, which can include pathogenic microorganisms. A systematic review reported that the microbiota of edible insects can contain bacteria from *Bacillus, Campylobacter, Clostridium, Cronobacter, Escherichia, Listeria, Proteus, Pseudomonas, Salmonella, Serratia, Staphylococcus, Streptococcus, Vibrio*, and *Yersinia*, which are genera associated with known pathogenic bacteria species (Garofalo et al., 2019). Processing steps involving high temperatures, such as roasting, boiling, and frying, can usually reduce microbial loads in insects intended for consumption (Megido et al., 2018). However, endospore-forming bacteria genera, such as *Bacillus*, *Paenibacillus*, *Psychrobacillus*, and *Clostridium*, have been detected in cricket and mealworm powders through metagenomic analyses (Osimani & Aquilanti, 2021). It is likely that these endospore-forming bacteria survived high temperature processing steps to varying extents. The potential of HPP to inactivate endospores in insect-derived food ingredients is currently being explored, as it may have fewer adverse impacts on the food's nutritional profile compared to traditional heating methods (Aganovic et al., 2021).

Some insect species that traditionally consumed can be vectors for parasites. The parasitic protozoa *Toxoplasma gondii*, which can cause toxoplasmosis in immunocompromised individuals, was detected in mealworms (Percipalle et al., 2021). Pathogenic parasites, which include *Cryptosporidium* spp., *Isospora* spp., and Cestoda (tapeworms), have been found in mealworm, cricket, and locusts (Gałęcki & Sokół, 2019). Taken together, these studies highlight the importance of rearing insects under controlled, hygienic conditions to minimize the risk of introducing pathogens and parasites.

Chemical hazards

Insects can harbor fungal species that can produce mycotoxins. For example, *Aspergillus* spp. was detected in crickets, whereas various *Penicillium* species have been associated with ants, bees, and beetles (Nicoletti et al., 2023; Vandeweyer et al., 2018). Aflatoxins have been detected in improperly stored caterpillars and termites due to *Aspergillus flavus* contamination (Kachapulula et al., 2018).

Heavy metals, specifically arsenic, cadmium, and lead, have been identified as food safety concerns in edible insects (FAO, 2021; Schrögel & Wätjen, 2019). There is evidence to suggest that edible insects, both reared and wild, may accumulate POPs, including but not limited to organophosphorus flame retardants, polychlorinated biphenyls, and organochlorine pesticides (FAO, 2021; Poma et al., 2021). Insects reared on plant-based substrates may accumulate pesticides. It has been reported that mealworm larvae can accumulate a range of pesticides (Houbraken et al., 2016). Pesticides that were more lipophilic were taken up to a higher degree, whereas less lipophilic pesticides were excreted more readily.

Food allergy to various insect species due to the allergenic proteins tropomyosin and arginine kinase is well-characterized, as these allergens are evolutionarily conserved and are also present in crustaceans and house dust mites (de Gier & Verhoeckx, 2018). As with other protein-based allergens, thermal processing may not necessarily reduce allergenicity (de Gier & Verhoeckx, 2018). There may also be poorly characterized insect proteins that may carry a risk of de novo sensitization, which can cause food allergies (Remington et al., 2018). Given the diversity of edible insects, elucidating insect allergens may be a useful research endeavor.

Physical hazards

Small body parts, such as legs, husks, and bristles, can present choking hazards if the insect is eaten whole (Bhardwaj et al., 2020). Insects that are processed into powder form are less likely to present such physical hazards.

2.1.5 | Microbial proteins

Microbial proteins, also known as single cell proteins, are derived from certain microalgal, fungal, and bacterial species through biomass fermentation. The result of the fermentation process is an edible biomass that contains approximately 30%–80% w/w protein content, depending on the specific species used (Bertasini et al., 2022). Examples of microbial species used in this process include (Bajić et al., 2022):

- Microalgae: *Chlorella vulgaris*, *Nannochloropsis oculata*, and *Haematococcus pluvialis*
- Fungi: *Fusarium venenatum*, *Aspergillus oryzae*, *Saccharomyces cerevisiae*, *Kluyveromyces marxianus*, and *Neurospora crassa*
- Bacteria: *Methylophilus methylotrophus*, *Rhodobacter capsulatus*, and *Cupriavidus necator*

In a general microbial protein production process, the microorganism of interest is grown in a fermenter or bioreactor with the appropriate nutrient-rich media or substrate. These include simple sugars and food processing side streams. Specific growth conditions can also include light for photosynthetic microalgae and bacteria and hydrogen for hydrogen-oxidizing bacteria (Bajić et al., 2022). The accumulated biomass from the microorganism is removed from the substrate and processed into food products.

Food safety hazards associated with microbial proteins can be introduced via the substrate as well as through fermentation and processing steps. Certain microbial species used as microbial protein sources may also naturally produce hazardous substances.

Microbiological hazards

The same conditions used to grow the desired microorganism can easily support the growth of pathogenic microbial contaminants (Stacey, 2011). Hence, there is a need to control for microbial contamination using sterile inputs and maintaining aseptic conditions during fermentation and processing. To date, no microbial contamination has been reported for a microbial protein product.

Chemical hazards

Certain microorganisms used to produce microbial proteins are known to accumulate or absorb heavy metals. For example, *Chlorella* spp. has been documented to accumulate cadmium and arsenic, mycelia of *Pleurotus ostreatus* (oyster mushroom) can bioconcentrate copper and cobalt, whereas *Aspergillus* and *Fusarium* can act as biosorbents for heavy metals, including cadmium, chromium, and lead (Ghosh et al., 2023; Leong & Chang, 2020; Mohamadhasani & Rahimi, 2022). Hence, it is important to ensure that the growth substrates are monitored for levels of heavy metal contaminants (Berger et al., 2022).

Fungal and bacterial microbial proteins can contain high levels of RNA content, which is metabolized into purines that are further converted into uric acid in humans (Ritala et al., 2017). Hence, microbial proteins may not be suitable for individuals with gout as high consumption of purine-rich foods can exacerbate this medical condition (Nyyssölä et al., 2022).

There have been case reports of individuals demonstrating hypersensitivities to *F. venenatum* mycoprotein, which may be attributed to the 60S acidic ribosomal protein P2 that is conserved in mold species (Hoff et al., 2003; Katona & Kaminski, 2002). If a microorganism with no history of significant human consumption is used to produce microbial proteins, the genetic potential of that organism to produce natural toxins or protein allergens should be considered (Bauman et al., 2021).

A recent trend in microbial protein production is the coculturing two or more microbial species to improve the nutritional content of the final food product (Nyyssölä et al., 2022). Varying modes of interaction between the different organisms in a coculture could result in altered profiles of secondary metabolites produced compared to monocultures and therefore should be carefully evaluated (Sun et al., 2021).

Hazards from food processing side streams

Another trend in microbial protein production is the use of food processing side streams as growth substrates (Salazar-López et al., 2022). While upcycling food processing side streams can bring about environmental benefits, such side streams can potentially introduce an array of microbiological, chemical, and physical hazards into the fermentation process and end up in the resulting biomass to be consumed. These hazards include but are not limited to pathogenic bacteria and viruses, parasites, mycotoxins, heavy metals, pesticides, allergenic proteins, plant and algal toxins, and nanoparticles (James et al., 2022). Due to the diversity and recent adoption of food processing side streams, there are data gaps in how their utilization as nutrient substrates impacts the safety of the microbial protein products (Moshtaghian et al., 2021).

2.2 | Food safety hazards associated with new food production systems

In this subsection, we provide a brief description of four categories of new food production systems, namely, cell-based food production, precision fermentation, vertical farming, and 3D food printing (3DFP). Products from these new food production systems are already on the market. We also describe the food safety hazards associated with each category. As with hazards for new food sources, hazards that have not been reported but could plausibly be introduced are indicated as "potential." Listing potential hazards may be helpful in raising awareness of possible food safety issues that may arise from new food production systems that have yet to be studied extensively due to the very limited number of products on the market.

2.2.1 | Cell-based food production

Cell-based food production (also called cell-cultivated food or cultured meat and seafood production) refers to the in vitro cultivation of animal cells followed by processing into products that resemble conventionally sourced meat (Post et al., 2020). The potential food safety hazards associated with cell-based food have been reviewed and catalogued in a recent publication by FAO and WHO (2023b). A generalized cell-based food production process involves (Stout et al., 2023):

1. sourcing and selection of production cell lines,
2. proliferation in bioreactors, differentiation of cells into desirable cell types (such as muscle and fat cells),
3. harvesting of cellular or tissue mass,
4. and formulation of the cellular or tissue mass into food products through incorporation of texturizers, fillers, and flavorings.

In general, food safety hazards present in cell-based foods are common to some of the existing conventional food products (FAO & WHO, 2023b). While some of the inputs, materials, and equipment used for the cell-based production can be new, the food safety risk assessment methods and risk mitigation measures are similar to those used for other conventionally produced foods.

Microbiological hazards

Potential microbiological hazards could arise from contamination of the culture media by pathogens, which can proliferate quickly in the nutrient-rich culture media (FAO & WHO, 2023b). Pathogens to be monitored should include those associated with the source animal. These include *Salmonella* spp. for chicken and pork, Shiga toxin-producing *E. coli* and *L. monocytogenes* for beef, and *V. parahaemolyticus* for seafood (Hussein & Bollinger, 2005; Rortana et al., 2021; Su & Liu, 2007).

It is also possible that microbial toxins, such as endotoxins and protein-based toxins (e.g., botulinum toxin), may be present in the animal samples sourced during biopsy or introduced at different processing steps through microbiological contamination from common foodborne pathogens such as *E. coli* and *C. botulinum*. These toxins may pose food safety risks if present in the final product and should therefore be controlled for at critical points in the manufacturing process via aseptic handling.

Chemical hazards

Prions, the causative agents of bovine spongiform encephalopathy (BSE) in cattle, may be present in the biopsied tissues of the source animal or in the growth media containing bovine serum. Prions could potentially be propagated during the production process, leading to their presence in end products where they could be pathogenic to both handlers and consumers (Chou et al., 2015). Manufacturers should therefore source animal sera from regions that conduct regular surveillance and are at low risk for BSE.

Currently, cell-based food products are by and large derived from animals long established to be safe for consumption and are not known to have the genetic potential to produce toxins. Nonetheless, there are concerns that genome instability arising from prolonged cellular replication under in vitro environments could cause dysregulation in gene expression, potentially resulting in increased expression of endogenous allergenic proteins relative to conventionally sourced meat (FAO & WHO, 2023b; Soice & Johnston, 2021). Hence, the levels of such allergenic proteins in cell-based meat should be routinely monitored. This may be done at the transcription level or at the protein level via immunoassays and targeted mass spectrometry.

Antimicrobials may be used to prevent contamination by microbiological pathogens at various steps of cell-based food production and would likely be necessary during the isolation of cells or tissue from whole animals (Post et al., 2020). Antimicrobial residues that are present in the final product may pose food safety risks to the consumer (Okocha et al., 2018). Manufacturers should therefore implement steps during cellular proliferation to eliminate or reduce antimicrobial use as far as practicable while maintaining aseptic conditions. Cell-based food production may also involve the use of chemical inputs that are new to food production or processing (FAO & WHO, 2023b; Ong et al., 2021). These inputs include growth factors, pharmacologically active molecules, pH buffers and indicators, surfactants, antifoaming agents, shear protectants. Cell-based food manufacturers will need to carry out risk assessments on each of these inputs to determine if they present significant toxic or allergenic effects.

Physical hazards

Cell-based food production may also involve the use of physical inputs such as scaffolds and microcarriers to emulate the organoleptic properties of meat (Ong et al., 2021). These physical inputs may need to be assessed for choking risks.

2.2.2 | Precision fermentation

Precision fermentation involves the use of genetically engineered microorganisms to produce food substances in a bioreactor, usually using simple starting materials such as sugar and glycerol (Augustin et al., 2023). Chymosin, an enzyme used to coagulate milk, is the first commercial product from precision fermentation and has been deemed safe for use since 1990 by the US Food and Drug Administration (US FDA) (Flamm, 1991). Food substances that can be produced by precision fermentation range from food additives such as vitamins, functional oligosaccharides, and flavoring agents to macronutrients such as proteins and lipids (Teng et al., 2021). Synthetic biology tools are also currently routinely used to engineer microorganisms to produce diverse target molecules at high titers, rates, and yields (Kitano et al., 2023). Current examples of food substances made with precision fermentation include vanillin, limonene, lycopene, soy leghemoglobin, and various human milk oligosaccharides such as 2′-fucosyllactose and lacto-*N*-neotetraose (Alonso-Gutierrez et al., 2013; Fraser et al., 2018; Hansen et al., 2009; Jing et al., 2021; Zeuner et al., 2019). A trend in recent years is the production of proteins that are conventionally derived from animal sources and are intended to be consumed as macronutrients, such as bovine whey protein and egg ovalbumin (Aro et al., 2023).

Precision fermentation shares similarities with biomass fermentation in that microorganisms are grown under controlled conditions, usually in a bioreactor. Although in biomass fermentation the desired product is the microbial biomass, in precision fermentation the product to be consumed is separated and purified away from the microbial biomass through a series of filtration and chromatographic processing steps post fermentation (Augustin et al., 2023).

Microbiological hazards

Hazards associated with precision fermentation can arise from microbial contamination of the nutrient-rich culture media, especially as the use of antimicrobials is strongly discouraged in large-scale production setups due to cost and environmental biosafety reasons (Pruden et al., 2013). Hence, similar to the production of microbial proteins and cell-based food, adherence to sterile inputs and processes, as well as regular monitoring for microbial contamination, are warranted (Teng et al., 2021). Thus far, no incident of microbial contamination of a commercially available product made with precision fermentation has been reported. The microbial strains that are currently widely used in precision fermentation have a history of use in research and bioprocessing (Teng et al., 2021). They have also been characterized at the molecular level to not produce substances that pose significant risks to human health. These include yeasts such as *Saccharomyces cerevisiae, Trichoderma reesei, Komagataella phaffii*, and *Yarrowia lipolytica*, as well as bacteria such as nonpathogenic *E. coli* B and K-12 strains, *Bacillus subtilis*, and *Lactobacillus* species (Teng et al., 2021).

Chemical hazards

Microbial strains used in precision fermentation generally express recombinant proteins, such as enzymes and transporters, to enable them to produce the target food ingredient (Augustin et al., 2023). Risk assessment of ingredients made with precision fermentation tends to incorporate safety consideration of recombinantly expressed proteins as these proteins may not have a history of safe use in food processing (Codex Alimentarius, 2008; FSANZ, 2022; Health Canada, 2022; SFA, 2019). Hence, at an early stage in the microbial strain engineering process, manufacturers should consider the potential of identified recombinant proteins to cause adverse health effects in humans. These proteins can be screened for sequence similarities to known protein allergens or toxins (Goodman et al., 2016).

Although *E. coli* strains used in precision fermentation are nonpathogenic, food safety issues may arise if the product is contaminated with lipopolysaccharide (LPS), also known as endotoxin, from the cell outer membrane (Rietschel et al., 1994). LPS can cause inflammation and autoimmune diseases in sensitive individuals (Chastain & Miller, 2012). Therefore, if *E. coli* is used in precision fermentation, it is important to purify the product to a high degree and analyze the product for endotoxin residues. Genetic engineering efforts have also been undertaken to attenuate LPS biosynthesis in *E. coli* (Mamat et al., 2015).

A recent safety issue raised for discussion is the impact of posttranslational modification (PTM), such as glycosylation, on the allergenicity of recombinant proteins made with precision fermentation (Mullins et al., 2022). This concern stems from the fact that proteins made in animals often have different PTMs compared to those made in microorganisms, which may impact the allergenicity of the protein (Halim et al., 2015). To date, there has not been any report that proteins made with precision fermentation exhibit substantial difference in allergenicity compared to the corresponding animal sourced proteins. Nonetheless, given the potential diversity of proteins that can be made with precision fermentation, the impact of host-specific PTMs on the allergenicity of a protein may warrant further investigation.

2.2.3 | Vertical farming

Vertical farming is a relatively new modality in indoor farming that has gained popularity in recent years due to increasing urbanization coupled with food security concerns (Benke & Tomkins, 2017). Vertical farms increase the use of a given land area for crop growth by stacking food crops in layers or growing them on a vertical surface. Either soil-based or soilless (e.g., hydroponic, aquaponic, and aeroponic) systems may be adopted in vertical farms (FAO, 2022b). By growing crops in controlled environments close to urban and suburban areas, vertical farms can contribute to food supply resiliency in these areas by reducing time and costs in food transportation. Moreover, vertical farms can be designed with a closed-looped irrigation system that significantly reduces water use compared to traditional farms (Avgoustaki & Xydis, 2020). This makes vertical farms attractive options for producing food in areas that also contend with water scarcity (Al-Kodmany, 2018).

Vertical farms are generally compact to maximize space use while being warm and humid to encourage crop growth. Such an environment can be conducive for introduction of various food hazards if safety measures are not put in place.

Microbiological hazards

Microbial contamination of crops can arise from the application of inadequately treated and filtered water. For example, pathogenic *Salmonella* spp. and *Stenotrophomonas maltophilia* were detected in lettuce grown on hydroponics farms that used untreated water (Tham et al., 2021). Although the use of wastewater to grow crops is attractive from an environmental sustainability perspective, the wastewater should be adequately treated and monitored to reduce microbiological contamination risks. Global cases of foodborne outbreaks associated with consumption of crops irrigated with wastewater have been documented (Adegoke et al., 2018). Causative agents include viruses (e.g., norovirus and rotavirus), bacteria (e.g., *Salmonella* spp. and *E. coli* O157), and parasites (e.g., *Giardia duodenalis* and hookworms). A safety consideration in an aquaponics system is the possibility of translocation of pathogens from fish to crops. For example, in an experimental aquaponics set-up, Shiga-toxin producing *E. coli* from fish feces was detected on the root surfaces on vegetables grown in the same system (Wang et al., 2020).

Considering current trends in use of wastewater and closed looped water systems for irrigation in vertical farms, it may be useful to conduct further research on the various modes by which pathogens in vertical farms can be translocated to edible parts of crops (FAO, 2022b). More research can also be directed toward developing water treatment methods (Adegoke et al., 2018). These efforts can support sustainable water use in vertical farms without compromising public health.

Chemical hazards

Despite being indoors, vertical farms can still be affected by pests and farmers may need to apply pesticides (Roberts et al., 2020). Therefore, pesticide residues in vertically farmed crops may need to be monitored, similar to crops grown on traditional farms (Buscaroli et al., 2021). If the soil and water used in vertical farms are sourced from urban and suburban areas, it is important to be aware of prior uses of the land as the soil and water may have high levels of chemical contaminants (Al-Kodmany, 2018; FAO, 2022b). Contaminants of concern include heavy metals (e.g., arsenic, cadmium, and lead), pesticides, and POPs (Md Meftaul et al., 2020; Montaño-López & Biswas, 2021; Namiki et al., 2013).

The lights and installations used in vertical farms can raise food safety concerns as certain materials can introduce hazardous chemicals into the plant growth media or deposit these chemicals onto plant surfaces. For example, mercury vapor released from urethane-based materials used in light emitting diode lamps has been found to deposit on plants (Ng et al., 2023). This highlights the importance of having a comprehensive awareness of safety aspects of inputs and infrastructure used in vertical farms.

Physical hazards
Vertical farms often contain scaffolds and overhead equipment that can deposit hazardous materials onto crops, such as asbestos and microplastics (Buscaroli et al., 2021). Risks arising from deposition of hazardous chemicals and materials onto crops can be reduced by regular maintenance and inspection of installations and equipment. Soil and water sourced from urban areas are likely to contain microplastics that may translocate into edible crop parts (FAO, 2022b). However, the public health impact from this is currently not well understood.

2.2.4 | 3D food printing

3DFP refers to the use of a computer-controlled robotic process to construct solid food layers and fusing these layers together using physical or chemical methods (Sun, Peng, et al., 2015). Various techniques are reported in food printing, including extrusion, sintering, curing, and jet binding (Escalante-Aburto et al., 2021). Although 3D printing itself is not new, having been developed in the 1980s, the technology was applied to food only since 2010s (Baiano, 2022). 3DFP has been employed to create food products that can be precisely customized in terms of appearance, texture, nutrition, and flavor, as well as to manufacture complex or delicate food products that cannot be produced by more conventional food processing technology (Sun, Peng, et al., 2015). Aside from common food ingredients such as flour, chocolate, and sugar, other unconventional materials, including ground insect powder and cultured animal cells, are being explored as "inks" to create food products with diverse characteristics (Handral et al., 2022; Severini, Azzollini et al., 2018).

Microbiological hazards
3D food printers typically contain small parts and tubes that may hinder thorough cleaning, which may lead to microbial buildup within the printer (Agunbiade et al., 2022). For instance, it was found that high levels of bacterial and yeast contamination (4–5 log CFU/g) in 3D printed foods made from blended fruits and vegetables even though all ingredients were washed thoroughly prior to the 3D printing process (Severini, Derossi et al., 2018). This contamination was attributed to the food contact materials in the 3D printer. Extrusion-based 3D printed materials tend to have high microscopic surface roughness that predispose them to microbial attachment and subsequent bacterial biofilm formation (Mitik-Dineva et al., 2009). Studies done on 3D-printed materials used in medical settings revealed that such materials can be easily contaminated by pathogenic biofilm-forming bacteria such as *E. coli, S. aureus*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa* (Hall et al., 2021; Jackson et al., 2023).

Chemical and physical hazards
Food processing side streams that are often discarded or used as animal feed, such as potato peels, okara (soy pulp), and jackfruit seed, are also being explored as "inks" as the 3D printing process has the potential to increase the palatability of these side stream products (Wong et al., 2022). Due consideration should be given to potential risks arising from the use of food processing side streams. For example, potato peels contain significantly higher levels of solanine than the flesh, whereas improperly stored okara can harbor toxigenic microorganisms (Maga & Fitzpatrick, 1980; Wang et al., 2019). In a 3D food printer, it is important to use food grade contact materials that are physically and chemically robust so as to reduce the probability of introducing food safety hazards in the forms of small particle deposition or chemical migration (Formlabs, 2019). In addition, as 3D printing can significantly change the shape and texture of food, caution should be exercised to ensure that the finished food products are not overly hard or sharp, which can present physical hazards (Zhang et al., 2022).

Home-based 3DFP
Currently, 3D printed foods are available only through restaurants and specialized retailers (Agunbiade et al., 2022; Baiano, 2022). Nonetheless, the 3DFP industry is actively working on scalable production of 3D food printers for use at home, with the promise to craft meals with personalized taste and nutrition on demand (Zhu et al., 2023). There would likely be greater variability in how 3D food printers are used at home as compared to restaurants and food processing establishments, with implications for food safety. For example, improper storage of food-based consumables and inadequate cleaning of 3D food printers at home can increase risks of microbiological contamination in the food product. Hence, it may be useful for the 3DFP industry to prepare materials to educate consumers on hygienic practices using home-based 3D food printers.

2.3 | Risk analysis of NFPS

Risk analysis, as defined by the Codex Alimentarius, is an iterative process comprising three closely linked components: risk assessment, risk management, and risk communications (Figure 2) (FAO & WHO, 2023a). This framework is widely implemented by various countries and regions to protect consumer health while facilitating fair practices in international food trade. The risk analysis framework can be applied for all foods, including NFPS. In this subsection, we describe how risk analysis has or can be applied in the context of NFPS, as well as some challenges in applying risk analysis for NFPS.

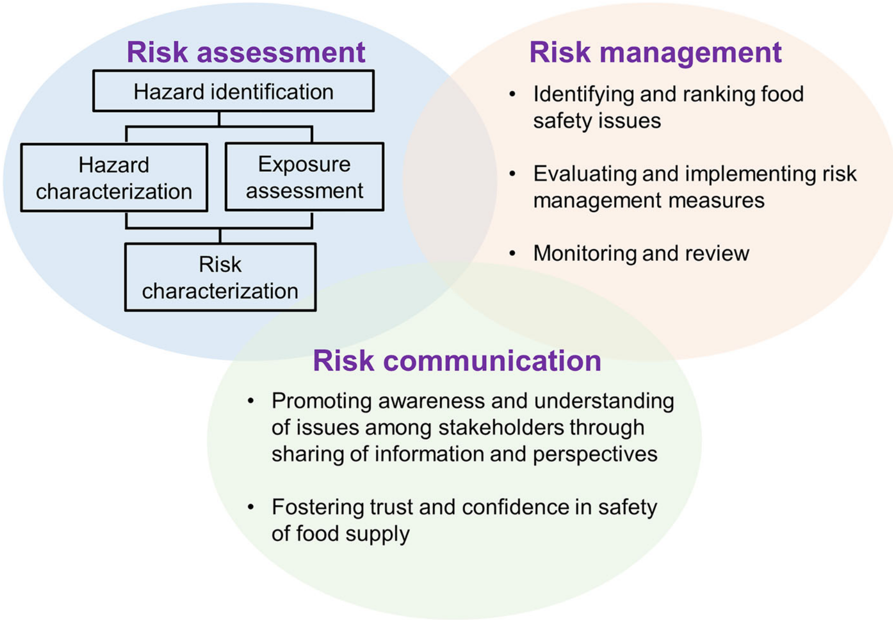

FIGURE 2 The Codex Alimentarius risk analysis framework, consisting of risk assessment, management, and communication (FAO & WHO, 2023a).

2.3.1 | Risk assessment

Risk assessment is a science-based process to describe the health impact of a food or food ingredient quantitatively or qualitatively (FAO & WHO, 2023a). It involves four steps:

- hazard identification
- hazard characterization
- exposure assessment
- risk characterization

Most food safety hazards associated with NFPS have already been identified in foods that are more widely consumed (Tables 2 and 3). However, these hazards may instead be present in new combinations and/or levels, resulting in unexpected dietary exposure. As the NFPS ecosystem is highly dynamic, with new modalities in food sourcing, culturing, and processing constantly being explored, there are knowledge gaps that will require risk assessors to be vigilant. For example, the use of food processing side streams to serve as nutrient sources for edible insects can increase exposure to food safety hazards such as pesticides, POPs, heavy metals, antibiotics, alkaloids, and mycotoxins (Fritsch et al., 2017). Similarly, if food processing side streams are used as the nutrient substrate in biomass and precision fermentation the exposure to hazards, such as microbiological contaminants, natural toxins, heavy metals, dioxins, and pesticides should be considered (Socas-Rodríguez et al., 2021). In cell-based food production, identifying hazards that may be associated with the inputs (e.g., cell lines, growth media, growth factors, and scaffolds) and hazards that can arise from processes (e.g., overexpression of allergenic proteins and microbiological contamination) will bolster the comprehensiveness of the safety assessment (Ong et al., 2021).

Product developers also play an important role in the risk assessment process as they provide critical insights into the production inputs and processes, which can inform the hazard identification process during risk assessment. For hazards that are new to food, such as growth factors used in cell-based food production, there is a need to first characterize the hazards to support risk assessment. This usually involves determining the health impact of a hazard in a dose-dependent fashion (Dybing et al., 2002).

2.3.2 | Risk management

Risk management is a policy-based process that considers risk assessment results, along with other factors, to fulfill dual purposes of protecting consumer health while facilitating trade (FAO & WHO, 2023a). It involves identifying and ranking identified food safety issues, evaluating and implementing risk management measures, as well as monitoring and reviewing of the implemented measures. In the context of NFPS, risk management can manifest in the form of how a country or region regulates specific NFPS categories and products. Regulatory approaches for NFPS can be based on science-based risk assessment, perceptions of the local population, and trade considerations specific to the country or region, among other factors. Sec-

TABLE 2 Food safety hazards identified in products from new food sources.

Category	Hazard		
	Microbiological	Chemical	Physical
Plant-derived proteins	*Enterococcus faecium* (Geeraerts et al., 2020) *Clostridium botulinum* (Pernu et al., 2020) *Listeria monocytogenes* (Bartula et al., 2023; Whitworth, 2023) *Salmonella enterica* (Bartula et al., 2023) *Bacillus cereus* (Wild et al., 2014)	Mycotoxins such as aflatoxins, alternariol, fumonisins, ochratoxin A, T-2 toxin, enniatins and zearalenone from toxigenic *Alternaria, Aspergillus, Diaporthe, Penicillium*, and *Fusarium* species (Augustin Juan et al., 2022; Kunz et al., 2022; Mihalache et al., 2022) Plant toxins such as cyanogenic glycosides, quinolizidine alkaloids, and glycoalkaloids (Cereda & de Vasconcellos, 2023; Schryvers et al., 2023; Urugo & Tringo, 2023) Allergens such as gluten, profilin, and prolamins (Hischenhuber et al., 2006; Mueller et al., 2014; Wiederstein et al., 2023) Radionuclides in Brazil nut and lima beans (US NRC, 2022)	Small wooden parts (Calvo, 2023) Metal shards (Staff, 2023) Insect fragments and mammalian hair (Fioravanti et al., 2024)
Seaweed	Norovirus, *Staphylococcus aureus*, *Salmonella enterica*, *Escherichia coli* O157:H7, *Vibrio* spp. (Løvdal et al., 2021) *Vibrio parahaemolyticus* (Mahmud et al., 2007)	Ciguatoxins, maitotoxins, pinnatoxin-G (Banach et al., 2020; Rains & Parsons, 2015) Allergens (specific causative agents not well characterized) (Garciarena et al., 2022) Inorganic arsenic, cadmium, lead, mercury (Rose et al., 2007) Excessive iodine intake that can cause thyroid function disorders (Smyth, 2021) Kainoids, polycavernosides, and prostaglandin E_2 (Smit, 2004) Pesticide residues (e.g., organochlorines, benzoylureas, organophosphates, carbamates, and pyrethroids) (García-Rodríguez et al., 2012; Lorenzo et al., 2012) Persistent organic pollutants (e.g., dioxins and polychlorinated biphenyls) (Banach et al., 2020; Cheney et al., 2014) Radionuclides (Khandaker et al., 2019; Wada et al., 2016)	Microplastics (Li et al., 2020)
Jellyfish	*Staphylococci* spp. (Bleve et al., 2019) Pathogens from the genera *Vibrio, Mycoplasma, Ralstonia, Tenacibaculum, Nautella, Acinetobacter* (Peng et al., 2021)	Ciguatoxins (Zlotnick et al., 1995) Arsenic, cadmium, lead (Bonaccorsi et al., 2020) Aluminum (Bleve et al., 2021) Allergens (specific causative agents not well characterized) (Imamura et al., 2013; Suzuki et al., 2017)	Microplastics (Iliff et al., 2020)
Insects	*Bacillus, Campylobacter, Clostridium, Cronobacter, Escherichia, Listeria, Proteus, Pseudomonas, Salmonella, Serratia, Staphylococcus, Streptococcus, Vibrio*, and *Yersinia* (Garofalo et al., 2019) Endospore-forming bacteria such as *Bacillus*, *Paenibacillus*, *Psychrobacillus*, and *Clostridium* (Osimani & Aquilanti, 2021) *Toxoplasma gondii* (Percipalle et al., 2021) *Cryptosporidium* spp., *Isospora* spp., and Cestoda (Gałęcki & Sokół, 2019)	Mycotoxins (e.g., aflatoxins) from *Aspergillus* spp. and *Penicillium* spp. (Kachapulula et al., 2018; Nicoletti et al., 2023; Vandeweyer et al., 2018) Arsenic, cadmium, lead (FAO, 2021; Schrögel & Wätjen, 2019) Persistent organic pollutants, such as organophosphorus flame retardants, polychlorinated biphenyls, and organochlorine pesticides (FAO, 2021; Poma et al., 2021) Pesticide residues from plant-based substrates (Houbraken et al., 2016) Known allergens, including tropomyosin and arginine kinase (de Gier & Verhoeckx, 2018) Poorly characterized allergens (Remington et al., 2018)	Small insect parts, such as legs, husks, and bristles (Bhardwaj et al., 2020)

(Continues)

TABLE 2 (Continued)

Category	Hazard		
	Microbiological	Chemical	Physical
Microbial proteins (also known as single cell proteins)	Potential pathogens that can grow in culture media/substrate if aseptic conditions are not maintained (Stacey, 2011) Potential viruses, bacteria, and parasites from food processing side streams (Moshtaghian et al., 2021)	Potential high levels of heavy metals, such as cadmium, arsenic, copper, cobalt, and lead (Ghosh et al., 2023; Leong & Chang, 2020; Mohamadhasani & Rahimi, 2022) High purine content in fungal and bacterial microbial proteins, which can exacerbate gout (Ritala et al., 2017) Fungal allergens, such as 60S acidic ribosomal protein P2 (Katona & Kaminski, 2002) Potential increased production of hazardous metabolites from coculturing (Sun et al., 2021) Potential mycotoxins, heavy metals, pesticides, and allergenic proteins from food processing side streams (Moshtaghian et al., 2021)	Potential nanoparticles from food processing side streams (Moshtaghian et al., 2021)

tion 3 expounds upon the global overview of regulatory frameworks that oversee NFPS. As products from NFPS increasingly gain market share in the global food supply, countries and regions may consider the usefulness in establishing internationally harmonized standards, guidance, and recommendations for specific NFPS categories (FAO & WHO, 2021).

Risk management can also take the form of labels or recommendations for foods that cause adverse health effects in some individuals. This protects the health of vulnerable consumer segments while providing more food choices for most other consumers. For example, allergen labeling was implemented for a specific microbial protein made using *F. venenatum* after a small number of allergic reactions were reported (Finnigan et al., 2019). Allergic reactions to cereals containing gluten, peanuts, soybeans, and tree nuts have been well documented globally (Martínez-Pineda & Yagüe-Ruiz et al., 2022). Therefore, it is crucial that plant-derived protein products made with said plant sources are labeled accordingly. The Codex "Code of Practice on Food Allergen Management for Food Business Operators" provides guidance to food businesses on risk management measures to minimize exposure of major allergens for sensitive individuals (FAO & WHO, 2020). Food labels can also be used beyond allergen warnings. Authorities in France, Norway, Australia, and New Zealand have published recommendations on seaweed intake for individuals that are vulnerable to high dietary intake of iodine (FAO & WHO, 2022). These include pregnant or breastfeeding women and individuals with thyroid dysfunction.

Softer approaches are sometimes adopted in risk management. For example, several food safety agencies hold consultations with food developers to encourage them to consider food safety aspects at an early stage of product development (Health Canada, 2022; MFDS, 2018; National Food Service Israel, 2022; SFA, 2019; US FDA, 2016). These consultations can serve to reduce time and resource burden on both food developers and food safety agencies when developers apply for regulatory evaluation and/or approval.

2.3.3 | Risk communication

Risk communication involves the interactive exchange of information and perspectives among stakeholders in the food chain, including but not limited to governments, industry, academia, and consumers (FAO & WHO, 2023a). Certain NFPS categories, such as microbial proteins and cell-based food, have stirred debate on how such products should be labeled for consumers to make informed decisions (Beach, 2017; Hallman & Hallman, 2021). Therefore, transparent and timely communications to the public are key to ensuring that the food safety aspects associated with NFPS are clearly communicated to consumers. To this end, governmental agencies and advocacy groups have been educating consumers on NFPS, using nontechnical language to convey scientific facts on plant-derived proteins, precision fermentation, microbial proteins, cell-based food, 3DFP, and among other NFPS categories (Good Food Institute [GFI], 2021; SFA, 2023b; Food Standard Agency [UK FSA], 2023; US FDA, 2023c). These efforts serve to engender trust and confidence in the processes and measures taken to ensure the food safety of NFPS.

Risk communication is more than just information dissemination. Effective risk communication ensures that relevant information and perspectives from all stakeholders are incorporated into decision making. The importance of multi-stakeholder discussions to advance food safety aspects of NFPS is discussed further in Section 4.5.

TABLE 3 Food safety hazards identified in products from new food production systems.

Category	Microbiological	Chemical	Physical
Cell-based food production	Potential contamination of nutrient-rich culture media (FAO & WHO, 2023b) Potential pathogens associated with the source animal, e.g., *Salmonella* spp. for chicken and pork, Shiga toxin-producing *Escherichia coli* and *Listeria monocytogenes* for beef, and *Vibrio parahaemolyticus* for seafood (Hussein & Bollinger, 2005; Rortana et al., 2021; Su & Liu, 2007)	Potential prions from bovine sources (Chou et al., 2015) Potentially increased levels of allergenic proteins relative to conventional meat (FAO & WHO, 2023b; Soice & Johnston, 2021) Potential antimicrobial residues (FAO & WHO, 2023b) Potential hazards arising from chemical inputs without history of safe use in food processing, e.g., growth factors, pharmacologically active molecules, pH buffers and indicators, surfactants, antifoaming agents, and shear protectants (FAO & WHO, 2023b; Ong et al., 2021)	Potential scaffolds and microcarriers (FAO & WHO, 2023b)
Precision fermentation	Potential contamination of nutrient-rich culture media (Teng et al., 2021)	Potential allergenicity or toxicity from foreign proteins (Codex Alimentarius, 2008) Potential contamination from *E. coli* lipopolysaccharides (Mamat et al., 2015) Potential allergenicity due to different posttranslational modifications on proteins made with precision fermentation compared to animal sourced proteins (Mullins et al., 2022)	None reported or proposed
Vertical farming	*Salmonella* spp., *E. coli*, *Stenotrophomonas maltophilia* (Tham et al., 2021) Viruses (e.g., norovirus and rotavirus), bacteria (e.g., *Salmonella* spp. and *E. coli* O157) and parasites (e.g., Giardia duodenalis and hookworms) if untreated wastewater is used (Adegoke et al., 2018) Shiga-toxin producing *E. coli* in aquaponics system (Wang et al., 2020)	Potential pesticide residues from intentional pesticide use (Roberts et al., 2020) Potential heavy metals and POPs if contaminated soil is used (Montaño-López & Biswas, 2021; Namiki et al., 2013) Mercury deposition from urethane-based materials in LED lamps (Ng et al., 2023)	Potential deposition of hazardous materials, such as asbestos and microplastics (Buscaroli et al., 2021)
3D food printing	Potential biofilm-forming pathogenic bacteria, such as *E. coli, S. aureus*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa* (Hall et al., 2021; Jackson et al., 2023) Potential microbial contamination if food processing side streams are used (Wang et al., 2019)	Potential hazards if food processing side streams are used (e.g., solanine from potato peels) (Maga & Fitzpatrick et al., 1980) Potential migration of chemicals from food contact materials (Formlabs, 2019)	Potential migration of small particles from food contact materials (Formlabs, 2019) Potential food products that may be too sharp or hard (Zhang et al., 2022)

Abbreviations: LED, light emitting diode; POPs, persistent organic pollutants.

3 | GLOBAL OVERVIEW OF REGULATORY FRAMEWORKS FOR NFPS

NFPS products are usually regulated as part of the national food safety or food production legislation under the remit of the competent authorities responsible for food safety. There is an increasing number of countries and regions that have enacted specific legislation applicable to all or some of the NPFS categories mentioned in this paper. Such legislation typically sets up a system for the authorization or regulation of NPFS that includes requiring the product developer to conduct a food safety risk assessment of such products. Once the competent authority evaluates that the assessment conducted by the product developer sufficiently demonstrates the safety of the product, said product is, depending on the legislative context of the jurisdiction, approved, registered, or notified for use as food.

It should also be noted that globally, regulations for NFPS are just emerging and many countries and regions have yet to install mechanisms or embark on updating existing regulations for regulating NFPS. In addition, the extent to which countries and regions develop regulatory frameworks for NFPS may depend on a variety of considerations beyond food safety. These considerations include trade issues, food security, shifting domestic consumer trends, environmental sustainability, and among others (Andreoli et al., 2021). Nevertheless, food safety remains the foremost consideration in regulatory frameworks for NFPS. Therefore, potential benefits of certain NFPS, such as contribution to sustainable food production and food security, are generally not part of the key considerations by food regulators in evaluating the suitability of an NFPS product for consumption.

3.1 | Scope of NFPS in a regulatory context

Legislation, along with policy documents and guidelines for parties involved, contributes toward a regulatory framework. In recent years, several countries and regions have introduced regulatory frameworks for NFPS. These frameworks are generally intended to capture foods that do not have a history of safe consumption by a human population to a significant degree. Legislation typically includes explicit rules for the authorization, labeling, production, and use of NFPS based on the various requirements and considerations in the food chains of respective jurisdictions. The starting point for legislation is usually to define the scope of foods and productions systems that would fall under the purview of the framework governing NFPS. Such an approach creates regulatory certainty and is key to building trust in NFPS among the food industry and consumers. Elements of what is a new or novel food in various jurisdictions are summarized in Table 4.

Regulators across different jurisdictions have chosen to define the scope of NFPS differently based on each jurisdiction's unique legislative, societal, economic, and dietary contexts. Therefore, the way NFPS food products are regulated in various regions are not harmonized internationally. For example, the European Food Safety Authority (EFSA) and FSANZ define any food that does not have history of human consumption in their respective jurisdictions as "novel." On the other hand, the SFA considers a food to be "novel" if it has both a history of significant human consumption in or outside Singapore. Since the introduction of the "novel food" terminology by EFSA, other competent authorities have also adopted the term "novel food" in their frameworks. Examples include the Brazilian Health Regulatory Agency (Anvisa), FSANZ, FSSAI, Gulf Cooperation Council (GCC) Standardization Organization, Health Canada, Israel's National Food Service, Republic of Korea's MFDS, and SFA (Anvisa, 2020; FSANZ, 2022; FSSAI, 2017; GCC Standardization Organization, 2023; Health Canada, 2022; MFDS, 2018; National Food Service Israel, 2022; SFA, 2019; Turck et al., 2016; Witherspoon & Donse, 2023).

3.2 | Practical learning points gleaned from NFPS products that have undergone the regulatory process

Although regulatory frameworks that address food safety aspects of NFPS have been implemented in some jurisdictions (Table 4), food innovators may still face ambiguities in bringing NFPS products into the market. Food regulatory agencies likewise face challenges in evaluating the safety of certain NFPS products due to unfamiliarity with such products. Nevertheless, in recent years, number NFPS products have been successfully introduced to the market in a safe and lawful manner. In this subsection, we provide practical learning points gleaned from recent examples of NFPS products that have undergone the regulatory process (Table 5). We highlight how regulatory agencies and/or food innovators have addressed safety challenges to ensure the safety of these products for their intended food use. We wish to caveat that some of these learning points may not be widely applicable in the longer term as the NFPS innovation and regulatory landscape is constantly evolving. Hence, stakeholders will need to learn and adapt as the ecosystem progresses and more NFPS products are introduced to consumers.

TABLE 4 Scope of new food sources and production systems (NFPS) in different jurisdictions across the globe.

Jurisdiction	Competent authority	Scope of NFPS/novel foods/new foods
Australia and New Zealand	Food Standard Australia New Zealand	Novel foods are non-traditional foods that means one of the following (FSANZ, 2022): (1) food that does not have a history of human consumption in Australia or New Zealand; (2) a substance derived from food, where that substance does not have a history of human consumption in Australia or New Zealand other than as a component of that food; or any other substance, where that substance, or the source from which it is derived, does not have a history of human consumption as food in Australia or New Zealand
Brazil	Brazilian Health Regulatory Agency (Anvisa)	Novel foods are substances with no history of consumption in the country, or foods containing substances which are already consumed but found at levels much higher than currently observed in foods used in the regular diet (Anvisa, 2020). Novel food and ingredients require premarket approval, which may be renewed every 5 years
Canada	Health Canada and the Canadian Food Inspection Agency (CFIA)	Novel foods refer to one of the following (Health Canada, 2022): 1. a substance, including a microorganism, that does not have a history of safe use as food; 2. food that has been manufactured, prepared, preserved, or packaged by a process that has not been previously applied to that food, and causes the food to undergo a major change; and 3. genetically modified plants, animals, or microorganisms
China	National Center for Food Safety Risk Assessment (CFSA)	Any food that has not been traditionally consumed in China. This includes organisms, substances extracted from organisms, or food ingredients in which the original structure has changed, as well as newly developed food ingredients (Sun, 2015).
European Union	European Food Safety Authority (EFSA)	Any food that was not used for human consumption to a significant degree within the Union before 15 May, 1997 (Turck et al., 2016)
Gulf Cooperation Council	Relevant competent authority overseeing food safety in member state (e.g., Ministry of Public Health in Qatar)	Novel food consists of, is isolated from, or is produced from cell culture or tissue culture derived from animals, plants, microorganisms, fungi, or algae (GCC Standardization Organization, 2023)
India	Food Safety and Standards Authority of India (FSSAI)	Novel foods are those that (FSSAI, 2017): 1. may not have a history of consumption by humans; or 2. may not have any history of consumption of any ingredient used in it or the source from which it is derived; or A food or ingredient that is obtained by using new technology and innovative engineering process. This procedure may change the size, composition, or structure of the food or its ingredients—which may in turn change its nutritional value, metabolism, or level of undesirable substances
Israel	National Food Service (NFS)	Foods that have not been consumed to a significant degree by humans in Israel before 19 February, 2006, when the first Regulation on Novel Food in Israel came into force (National Food Service Israel, 2022). Novel foods can be a newly developed, innovative food, food produced using new technologies and production processes, as well as food which is or has been traditionally eaten outside of Israel
Japan	Food Safety Commission of Japan (FSCJ)	Foods that have no history of safe use or are made using new production processes are required to undergo novel food safety assessment (Food Safety Commission of Japan, 2004)
Singapore	Singapore Food Agency (SFA)	Foods without a history of significant use as food for at least 20 years, whether within or outside Singapore (SFA, 2019)
Republic of Korea	Ministry of Food and Drug Safety (MFDS)	Food ingredients that do not have a history of consumption in Korea (MFDS, 2018)

(Continues)

TABLE 4 (Continued)

Jurisdiction	Competent authority	Scope of NFPS/novel foods/new foods
Thailand	Food and Drug Administration Thailand (FDA Thailand)	Any substance used as food or food ingredients that either has been used widely for human consumption for less than 15 years based on scientific or reliable evidence or has undergone a production process not currently used, where that process gives rise to significant changes in the composition or structure of the food that affect their nutritional value, metabolism, or level of undesirable substance (FDA Thailand, 2016)
United Kingdom of Great Britain and Northern Ireland	Food Standard Agency (UK FSA)	A Novel Food is defined as food that has not been consumed to a significant degree by humans in the UK before 15 May 1997, as defined by UK legislation (UK FSA, 2021)
United States of America	United States Food and Drug Administration (US FDA)	No explicit definition of new or "novel" food. Nonetheless, a new food substance is subject to premarket approval by the US FDA unless it is Generally Recognized as Safe (GRAS) (US FDA, 2016)

4 | ADDRESSING CHALLENGES ON MOVING FORWARD

Implementation of a regulatory framework for NFPS provides a guiding strategy for addressing food safety risks and ensures that food products from NFPS meet possible additional criteria, such as nutritional, consumer choice, religious, and environmental sustainability requirements. However, several challenges that are faced by stakeholders in the NFPS ecosystem will need to be addressed for the sector to move forward. A select few are discussed below.

4.1 | Uncertainties in terminologies and consumer perceptions

There is significant ambiguity surrounding the terminologies used to describe certain NFPS products, with implications for establishing regulatory frameworks by posing complications for labeling as well as how such products are produced, placed on the market, and consumed. Various considerations and motivations, such as sustainability, economic, scientific, cultural aspects, and consumer perception, influence the adoption of different terminologies by different stakeholder groups. Prime examples that have sparked debate are plant-derived proteins that are used as ingredient substitutes for animal-based proteins and cell-based food (FAO & WHO, 2023b; Tziva et al., 2023). According to the EU Court of Justice ruling in 2017, certain terms such as "milk," "cheese," or "yoghurt" cannot be used to label products in which milk has been substituted with plant-based ingredient, even if the plant-based characteristic of the ingredient is indicated on the label (Boukid et al., 2021). Similar discussions are taking place in various countries, for instance in the USA (US FDA, 2023a).

In the area of cell-based food, there is much ongoing discussion on the qualifying terminology that should be used to describe such foods, which include but are not limited to: "cultured," "cell-based," "lab-grown," "cultivated," "clean," and "imitation." Some of these terms carry with them connotations that result in them not being well received by certain groups. For instance, using "clean meat" to describe cell-based food may implicitly cast aspersions on the cleanliness of conventionally sourced meat. On the other hand, the "imitation meat" term would probably not be well received by the cell-based food industry, which may argue that their products are made using real animal cells and are not significantly different from conventionally sourced meat (FAO & WHO, 2023b). In the absence of internationally harmonized terms for new foods such as cell-based foods or plant-derived protein products, there can potentially be significant restrictions and uncertainties in using food commodity terms such as "meat," "fish," "milk," and so forth. In such cases, consumer studies can enrich discussions around terminologies. For instance, a pioneering study on consumer perception of cell-based food by Hallman & Hallman reports that "cell-based seafood" is the best performing term, at least with regard to consumer perception and interest in the USA, to label cell-based products made from fish cells (Hallman & Hallman, 2021).

Food labeling is an essential tool to enable consumers to make informed decisions about their diets. Therefore, it is important to be transparent on the various considerations behind labeling of NFPS products. Engaging stakeholders on terminology discussions on open platforms, in which preferences and objections raised are backed by evidence, will contribute to labels that can inform consumers on food safety aspects, nutrition, ingredients, and conditions of use in a factual manner. Labels can also inform consumers on characteristics that may make NFPS products differ from

TABLE 5 Examples of how safety challenges were addressed for some new food sources and production systems (NFPS) products that have undergone the regulatory process.

NFPS product	Food regulatory agency concerned	Safety challenges	How safety challenges were addressed
Rapeseed protein isolate (FSANZ, 2021a)	FSANZ	1. Concerns of mustard allergen as both mustard and rapeseed belong to the Brassicaceae family 2. Concerns of *Salmonella* spp. and *Bacillus cereus* contamination 3. Presence of antinutrients erucic acid and glucosinolates	1. FSANZ worked with expert bodies to develop a risk communication strategy and materials to inform individuals allergic to mustard (FSANZ, 2021b) 2. Food producer implemented food safety management systems to control for foodborne hazards. *Salmonella* spp. and *B. cereus* contamination risks were screened and the risks were determined to be low 3. Erucic acid intake from rapeseed protein isolate was assessed to not exceed provisional tolerable daily Intake (PTDI) of 7.5 mg/kg bw/day. Glucosinolates intake from rapeseed protein isolate was found to be comparable to the amount resulting from normal daily consumption of *Brassica* vegetables
16 insect species from the orders orthoptera, coleoptera, lepidoptera, scarabaeidae, and hymenoptera (SFA, 2023a)	SFA	1. Insects harvested from the wild may harbor pathogens 2. Some feed substrates for insects may contain high levels of contaminants	SFA set the following import and pre-licensing conditions for insects and insect products: 1. Insects cannot be harvested from the wild. Insects that are intended to be ready-to-eat must have been subject to sufficient heat treatment to inactivate pathogens 2. Manure, decomposing organic material, and materials of ruminant origin must not be used as feed substrates
Fusarium sp. strain flavolapis microbial biomass (Health Canada, 2023)	Health Canada	1. *Fusarium* sp. strain flavolapis is known to produce fumonisins and beauvericin mycotoxins 2. Contamination by pathogens during production 3. Presence of fungal allergens	1. Fumonisins were not detected above analytical limits of detection. Beauvericin was detected but was assessed not to be a health concern 2. Food is manufactured under current good manufacturing practice conditions. Microbial biomass is streamed or cooked prior to consumption 3. *Fusarium* sp. strain flavolapis genome was screened against known allergens. Identified allergens in *Fusarium* sp. strain flavolapis shared significant homology to *Fusarium venenatum*, which has been consumed since 1985. Hence, it was concluded that *Fusarium* sp. strain flavolapis is safe for most consumers, excluding a small number of individuals who are hypersensitive to mold proteins
Chicken cell material from cell culture (US FDA, 2022a; USDA, 2023)	US FDA and US Department of Agriculture (USDA)	1. Introduction of environmental microbial pathogens, including *Mycoplasma* spp., *Listeria monocytogenes*, *Salmonella* serovars, pathogenic *Escherichia coli*, and *Campylobacter* spp. 2. Introduction of prions (causative agents of BSE) from bovine sera 3. Loss of stability in cell lines 4. Use of growth factors during cell proliferation	1. Implementation of sterile production conditions and periodic testing of pathogens at critical control points, such as at cell banking, proliferation, differentiation, and harvesting stages 2. Sourcing bovine sera from BSE-free cow herds 3. Monitoring growth and viability of cell lines at critical control points 4. Using growth factors that are not known to be major food allergens. Using assessments based on scientific data that the growth factors used would likely be denatured by cooking and digested in the gastrointestinal tract

(Continues)

TABLE 5 (Continued)

NFPS product	Food regulatory agency concerned	Safety challenges	How safety challenges were addressed
6′-sialyllactose made with precision fermentation (Turck et al., 2022)	EFSA	1. Product from precision fermentation may not be chemically identical to the conventionally sourced counterpart 2. Residual cells or endotoxins from the production microorganism in the product 3. Potential allergenic potential of proteins newly expressed in production microorganism	1. Comprehensive chemical characterization of the product using liquid chromatography, mass spectrometry, and nuclear magnetic spectroscopy to ensure it is chemically identical to the authentic standard 2. Implementation of purification steps and verification using established methods that neither cells nor endotoxins from the production microorganism are in the product 3. Bioinformatics screening revealed that newly expressed proteins do not bear significant homology to known allergens

Abbreviations: BSE, bovine spongiform encephalopathy; EFSA, European Food Safety Authority; FSANZ, Food Standards Australia New Zealand; SFA, Singapore Food Agency.

other food products in the market. This will empower consumers to make food purchases that are in line with their personal needs and values.

4.2 | Addressing current knowledge gaps on NFPS food safety

There is a limited body of knowledge on the combination and levels of food safety hazards in NFPS compared to foods that have been long history of consumption worldwide. In addition, recent trends in exploring the use of food processing side streams as inputs for insects, microbial proteins, and 3DFP, as well as use of wastewater for vertical farming, introduce further uncertainties that impact food safety (Adegoke et al., 2018; Ojha et al., 2020; Salazar-López et al., 2022; Wong et al., 2022). Addressing knowledge gaps and uncertainties on NFPS food safety aspects would contribute to more scientifically robust and comprehensive risk assessments of NFPS products. This would further support risk management decisions and facilitate risk communication to all stakeholders, including consumers. We summarize pertinent knowledge gaps on food safety aspects of NFPS and provide suggestions on research directions to address these gaps (Table 6).

4.2.1 | New tools to support NFPS risk assessment

Recent advancements in scientific tools can address data gaps within NFPS food safety risk assessment. In this context, we highlight some benefits of incorporating these innovative tools to support NFPS food safety.

Certain proteins in food can cause allergic responses in sensitive individuals, which in some cases may lead to life-threatening situations. Therefore, it is useful to do bioinformatics screening of new food sources, such as insects and new microorganisms used in producing microbial proteins, to identify potential food allergens for food safety risk assessment (López-Pedrouso et al., 2020). Bioinformatics screening for allergens may also be done on microbial hosts used in precision fermentation, looking at both proteins naturally expressed by the host as well as recombinantly expressed proteins. Established web-based tools for predicting protein allergenicity based on similarities to known epitopes include AllergenOnline and AllerCatPro (Goodman et al., 2016; Nguyen et al., 2022).

Many microbial species can biosynthesize a wide array of bioactive substances. A concern with the use of a new microorganism to produce food, either as a processing aid or for direct consumption, is the potential for the microorganism to produce toxins. It is known that the DNA sequences of biosynthetic gene clusters for natural products, including toxins, are generally well-conserved in microorganisms (Bauman et al., 2021). Therefore, whole genome sequencing (WGS) information can be used to determine if a microorganism has the genetic potential to biosynthesize certain small molecule toxins, such as mycotoxins and alkaloids (Gallo & Perrone et al., 2021).

Omics approaches, such as transcriptomics and metagenomics, can help to determine the presence and levels of food safety hazards in a high-throughput fashion. This can enable producers to detect anomalies in hazard levels, more accurately trace hazard sources along the food supply chain, and support evidence-based decision-making in food safety management (Kovac et al., 2017). For example, in cell-based food production, transcriptomics has been proposed to screen for messenger ribonucleic acid transcripts that may be unexpectedly overexpressed in the cell-based food compared to a reference control

TABLE 6 Knowledge gaps relating to new food sources and production systems (NFPS) food safety and suggested research direction to address these gaps.

Knowledge gap	Applicable to:	Suggested research direction to address knowledge gap
There is nascent and limited data on the effectiveness of new processing techniques that can reduce microbiological contamination (e.g., HPP, PEF, and cold plasma) (Alles et al., 2020; Menta et al., 2022)	• Plant-derived proteins • Insects	• Further studies can be done to measure the effectiveness of new processing techniques on various plant-derived protein and insect food matrices. Variables to consider include: effects of food matrices, physical parameters (e.g., pressure, time, and voltage) • Studies can also be done to assess effectiveness of new processing techniques to maintain the sterility of products across the food production chain. Special focus may be placed on endospore-forming bacteria as these are known contaminants in plant-derived proteins and insect product and are resistant to physical stresses such as high temperature and pressure (Sehrawat et al., 2021)
Some NFPS products have not been well studied at genetic and/or biochemical levels. Thus, there may be endogenous toxins and/or allergens that have yet to be identified or have not been sufficiently quantified	• Plant-derived proteins • Seaweeds • Jellyfish • Insects • Microbial proteins • Cell-based food production • Precision fermentation	• Whole-genome sequencing of organisms used directly as or used to produce food. Subsequent bioinformatics analysis of genomic data to identify DNA sequences that potentially encode for allergens or toxin-producing enzymes (Bauman et al., 2021; Nguyen et al., 2022) • Biochemical detection and quantification of putative toxins and allergens in organisms • Toxicological studies on newly identified toxins and allergens
Lack of standard methods for quantifying microplastics in food matrices and lack of harmonization in approaches in studying toxicology of ingested microplastics (Mohamed Nor et al., 2021; Sridhar et al., 2022)	• Seaweeds • Jellyfish • Vertical farming	• Developing standard methods for separating, measuring, categorizing, and quantifying various types of microplastics found in food (Emecheta et al., 2022) • Developing unified approaches for studying toxicological effects of microplastics. Parameters to consider include chemical composition, particle size, biodistribution, and among others (Kadac-Czapska et al., 2023; Koelmans et al., 2023)
Lack of hazard characterization data on chemical inputs that are new to food production	• Cell-based food production	• Comprehensive toxicological studies of new inputs used in cell-based food production. Examples include but are not limited to: growth factors, pharmacologically active molecules, pH buffers, surfactants, antifoaming agents, and shear protectants. Studies may include toxicodynamics (e.g., genotoxicity, effects on cells, tissues, and organs) and toxicokinetics (i.e., absorption, distribution, metabolism, and excretion behavior)
Uncharacterized food safety implications of recombinant proteins that have different PTMs from the conventionally-sourced counterpart	• Precision fermentation	• Studies on allergenicity potential and digestive fates of recombinant proteins compared to conventionally-source counterparts • Metabolic engineering of microbial hosts to enable these hosts to produce recombinant proteins with PTMs closer to conventionally sourced counterparts (Dupuis et al., 2023)
Nascent data on exposure to contaminants in food processing side streams	• Insects • Microbial proteins • 3DFP	• Investigations of uptake of microbiological, chemical, and microplastic contaminants in food processing side streams into the food product. Parameters to consider may include type of food processing side stream (e.g., peels, pomace, spent grains, and seafood processing residuals), species/genus-specific uptake (for insects and microbial proteins), effectiveness of various processing steps to reduce microbiological loads, and among others
Nascent data on exposure to contaminants in wastewater	• Vertical farming	• Investigations of uptake of microbiological, chemical, and microplastic contaminants in wastewater into the edible parts of the plant. Parameters to consider may include types of plants, types of contaminants, sources of wastewater, soil-based vs. hydroponics systems, and among others

Abbreviations: 3DFP, 3D food printing; HPP, high-pressure processing; PEF, pulsed electric field; PTM, posttranslational modification.

(FAO & WHO, 2023b). Overexpressed transcripts that encode for allergenic proteins can be identified for targeted monitoring in the cell-based food product to determine if they present increased food safety risks. Using metagenomics, it is possible to explore multiple microbial communities and genes of interest directly from food samples without isolating individual bacterial species, potentially reducing analysis turnaround time (Billington et al., 2022; Ko et al., 2022). Although the application of metagenomics in food safety is still in its early stages, it offers immense opportunities for determining the presence or the emergence of pathogenic microorganisms based on changes observed in the microbial community.

4.2.2 | Regulatory acceptance of new risk assessment tools

Initial steps have been made in regulatory acceptance of new risk assessment tools for NFPS. For example, on allergenicity assessment of a new protein, novel food guidelines put forth by FSANZ, Health Canada, and SFA recommend that sequence and structural homology to known allergens, determined via bioinformatics approaches, can be a starting point in assessing the allergenic potential of the new protein (FSANZ, 2022; Health Canada, 2022; SFA, 2019). As part of EFSA's consideration on whether a microorganism should be accorded the qualified presumption of safety status for use in food, WGS data is utilized to assess if the microorganism has the genetic capacity to cause infections or potentially produce toxins (Koutsoumanis et al., 2023). This can facilitate the assessment on the use of new microorganisms in innovations in food production and processing systems.

The use of animal models in toxicology studies has traditionally been viewed as the "gold standard" among regulatory agencies for predicting potential adverse health effects of substances in humans (Swaters et al., 2022). In recent years, however, the use of animal models in regulatory toxicology has been criticized as an inaccurate and inconsistent predictor for humans, in addition to raising animal welfare concerns (Hartung & Daston, 2009; Van Norman et al., 2019). Several food safety agencies, including EFSA, Heath Canada, SFA, and US FDA, have taken steps toward advancing nonanimal testing methods, which include but are not limited to the use of relevant new approach methodologies (NAM) (Fitzpatrick, 2020; Lim, Hughes, et al., 2022; Miccoli et al., 2022; Stucki et al., 2022). These methodologies are aimed at next-generation risk assessment through integrated approaches to testing and assessments, more defined methods for data interpretation, as well as performance-based evaluation of test methods. They include in silico, in chemico, in vitro, and ex vivo methods (Bhuller et al., 2021; Escher et al., 2022; Miccoli et al., 2022; Stucki et al., 2022). Advocates of nonanimal testing methods reason that, compared to animal models, these methods can provide a better understanding of the biochemical and cellular mechanisms by which a substance exerts its toxic effects in humans. However, there is yet to be an international consensus on the extent to which new risk assessment tools can replace or complement animal testing due to the difficulties in addressing complex toxicological endpoints in NAM implementation (Stucki et al., 2022). The new food safety challenges introduced by NFPS may therefore provide opportunities for in-depth discussions on new risk assessment tools through international platforms.

4.3 | Challenges in information sharing

Hundreds of commercial entities around the world, from start-ups to multinational corporations, are currently developing innovative NFPS products, particularly microbial proteins, cell-based food, and food ingredients made with precision fermentation (Boukid & Gagaoua et al., 2022). In this highly competitive environment, it may seem to go against business sense for a company to publicly share proprietary information on its products (Chitale et al., 2022). However, if a company is not transparent in communicating characteristics of its products to consumers, misinformation and falsehood may seep into the information lacuna.

For NFPS products strongly tied to innovation and intellectual property, it can be challenging to find the right balance in sharing enough information to build consumer trust on the safety of the products while protecting proprietary information. For instance, microbial protein producers may be reluctant to share the exact microbial species or strain they are using and cell-based food companies may not wish to disclose details of their inputs and processes (Ercili-Cura, 2020; US FDA, 2022a). For food ingredients made with precision fermentation, there are current debates on the level of information that should be indicated on the product label, particularly the fact that such ingredients are generally made with genetically engineered microorganisms (Poinski, 2022).

4.4 | Recommendations on stakeholder engagements to address NFPS safety challenges

To realize the potential of NFPS in contributing to sustainable and climate-resilient food production, it is important

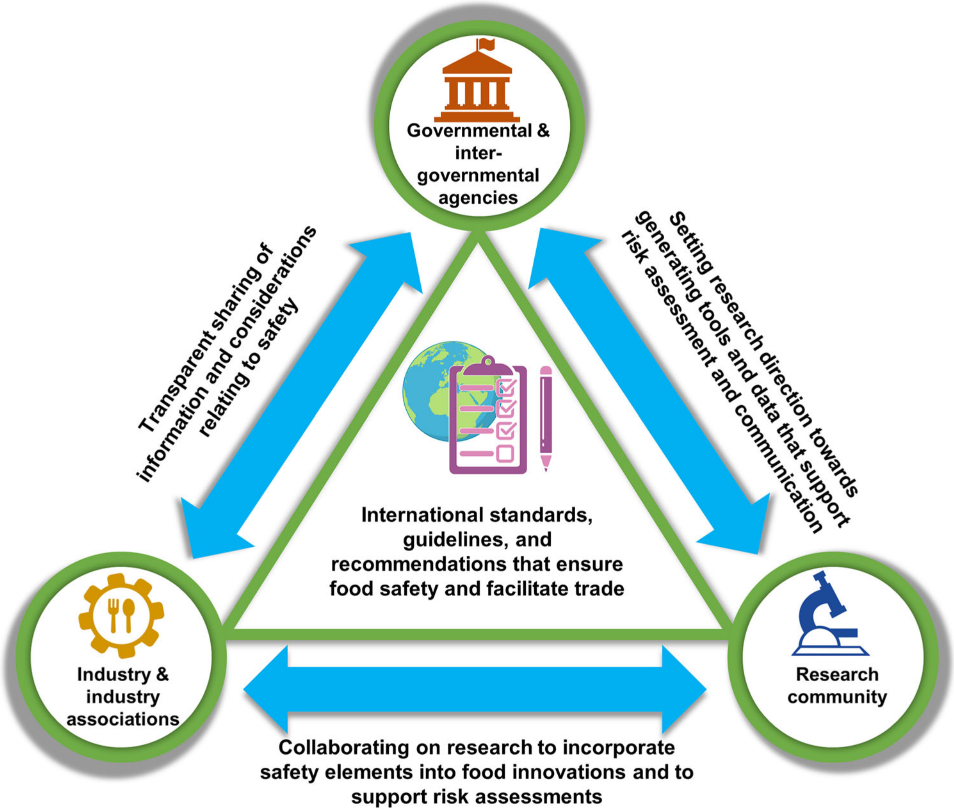

FIGURE 3 Schematic showing how collaboration between key stakeholder groups can support the development of international standards, guidelines, and recommendations for new food sources and production systems (NFPS) products.

that various stakeholder groups continuously engage with each other to address the safety challenges pertaining to NFPS and to communicate the message of safety to consumers. This allows regulations and safety guidance to keep pace with innovations in the NFPS sector, thereby facilitating the translation of NFPS products onto the market. In this subsection, we provide recommendations on how three key stakeholder groups, governmental and intergovernmental agencies, the industry, and the research community, can work together to develop international standards, guidelines, and recommendations that ensure the food safety of NFPS while facilitating international trade (Figure 3).

4.4.1 | Engagements between governmental agencies and the industry

A predictable regulatory environment that facilitates the lawful entry of NFPS products within a jurisdiction is beneficial for the industry as it reduces time and resources spent in managing uncertainty. Transparent regulations and regulatory guidance that are consistently applied across countries and regions can bolster confidence in the safety of NFPS products and reduce duplicative work done by food safety competent authorities and the industry. Toward such a goal, it is important that the industry is transparent with competent authorities on various aspects of their products that may impact safety. These aspects can include the source of the NFPS product, any inputs and processes used in the production, and hazards identified in the product. With regard to information on inputs and processes that may be proprietary and which individual companies may be unwilling to disclose voluntarily, industry associations can aid in identifying common elements used by most companies within a particular NFPS category. Industry associations can then work toward sharing this set of knowledge with competent authorities across countries and regions (Mridul, 2023). Such efforts can enable competent authorities to collectively evaluate and reach broad consensus on the safety of inputs and processes common to a NFPS category, thereby reducing time and resources expended in conducting safety assessments and processing regulatory submissions for similar products.

Competent authorities may find it helpful to take a consultative approach with the industry to gain awareness of the latest innovations and trends in the NFPS sector. This can contribute toward the development of regulatory frameworks that can accommodate current NFPS products

(Table 4) and allow authorities to be anticipative rather than reactive toward emerging products. Intergovernmental agencies, such as FAO, WHO, and the Organisation for Economic Co-operation and Development (OECD), are actively working on guidance documents for safety assessments of NFPS that reflect consensus views from experts in member countries and the industry (FAO, 2023; FAO & WHO, 2023b; OECD, 2023). These documents can serve as resources for countries and regions that are in early stages of developing regulatory approaches for NFPS. Collectively, these resources can contribute toward fair and transparent practices in international trade of NFPS products.

4.4.2 | Engagements between governmental agencies and research community

As detailed in Table 6, there are existing data gaps for some food safety hazards associated with certain NFPS products, such as allergens in jellyfish and seaweed. These gaps may raise public health concerns. Therefore, governments may work with the research community to generate data and tools that support risk assessment of NFPS products. For example, Israel MOH, US FDA, UK FSA, and SFA are funding research projects that focus on food safety of NFPS products (Ben-David, 2022; Quadram Institute, 2022; SFA, 2023c; US FDA, 2023b).

Researchers can also support governments in risk communication by conducting studies on consumer perceptions on specific NFPS categories. To illustrate, studies on perceptions of various consumer groups across regions toward new foods have revealed that food safety is a primary concern for insects and cell-based food but is less of a concern for plant-derived proteins and seaweed (Onwezen et al., 2021). It has also been reported that consumers who view cell-based food as unnatural tend to have a lower risk tolerance for cell-based food as compared to conventionally sourced meat (Siegrist & Sütterlin, 2017). According to studies, to gain consumer trust on new foods and new food technologies, it is not sufficient to see consumers as mere receivers of scientific knowledge (in what is known as a Deficit Model) (Kasza et al., 2022). Instead, given the complexity of information available, consumers generally depend on the assessments of other agents along the food chain to enable them to make informed decisions (Siegrist & Hartmann, 2020). Therefore, it is important for these agents, which include food manufacturers, to be transparent to build trust. Taken together, these studies can help governmental agencies tailor their messaging, anticipate public sentiments, as well as prepare risk management and communication strategies in response to these sentiments.

4.4.3 | Engagements between the industry and the research community

Toward the collective aim of sustainable food systems, numerous industry-academia research partnerships have emerged in recent years to develop new protein-rich food products that are "alternative" to products derived from livestock animals (FAO, 2018, 2022b; GFI, 2023). Examples include proteins derived from plants and seaweeds, microbial proteins, cell-based food, and proteins made with precision fermentation. The success of new food products is contingent on them being safe to consume. Hence, it may be useful to think about food safety aspects at an early stage of research and development. Industry can share their "real-world" experience on safety challenges with research partners to provide clear research directions. For instance, developing tools for real-time monitoring of pathogens in bioreactors and the environment can be useful for maintaining the safety of NFPS products that are prone to microbiological contamination during production, such as microbial proteins, cell-based food, and crops grown in vertical farms (Heins et al., 2022; Nnachi et al., 2022). For NFPS categories where genetic engineering may be used, such as precision fermentation and cell-based food production, industry and researchers may consider developing antibiotic-free selection methods to circumvent public health and environmental safety concerns during safety assessment and regulatory evaluation (Mignon et al., 2015).

Industry and the research community may also find it useful to embark on projects to fill in data gaps to support risk assessments. To illustrate, new food production systems sometimes involve the use of chemical inputs that do not have an established history of use in food production and processing (Table 3). These new chemical inputs often do not have sufficient toxicological data to support food safety risk assessments (Ong et al., 2021). It may therefore be useful for a company using a new chemical input to work with toxicologists to assess the safety of said chemical for its intended food use.

4.5 | Multi-stakeholder discussions to advance food safety aspects of NFPS

As FAO and the WHO highlighted NFPS as a crosscutting and emerging area, the Codex Alimentarius Commission has held discussions with Codex members to gather views and further information (Codex Alimentarius Commission, 2022). Various workshops and publications by the two United Nations agencies, as well as by different national authorities, have facilitated the sharing of perspectives and knowledge between stakeholders in governments, academia, and industry (EFSA, 2023; FAO, 2020, 2023; FAO & WHO, 2022, 2023b; SFA, 2019). Although some countries and regions have the capacity to address issues arising from the fast-evolving NFPS ecosystem, low- and middle-income countries and regions often have limited resources to adequately conduct food safety risk assessments and implement food safety management systems for NFPS. It is therefore important to encourage greater transparency in knowledge exchange between countries and regions already actively evaluating products from NFPS, and those that are in the early stages of developing policies and regulatory approaches for NFPS.

Sharing views and experiences from diverse stakeholders on product development, risk assessment, regulatory frameworks, nomenclature, and risk communication will foster an inclusive international debate on the safety of NFPS. This can create a predictable and collaborative environment that streamlines regulatory processes while upholding food safety. For instance, the US FDA has completed premarket consultations for two cell-based food products and made public the submissions from the cell-based food developers (select sections containing trade secrets are redacted) and responses from the FDA that reflect their safety assessment thinking and approach (US FDA, 2022b). The completed premarket consultations should be helpful in informing other cell-based food developers of safety issues that they need to consider. Although the conclusions of these processes do not imply regulatory approvals, they signify that the agency had no further questions at that time about the safety assessments and conclusions put forth by the developers. Looking forward, co-development of science-based risk assessments for NFPS through information sharing should set the stage for international regulatory harmonization, facilitating trade while increasing consumers' confidence in food products from NFPS.

5 | CONCLUDING REMARKS

As our agri-food systems transform, NFPS can play an important role in the realization of sustainable and resilient systems. Today, a litany of new foods is entering the retail space, bolstered by rapid advances in innovation and an increased emphasis by the food industry on streamlining the entry of such products into the market. Driven by consumers who are demanding agri-food systems pay closer attention to environmental sustainability, nutritional adequacy, and affordability of new foods while ensuring safety, the NFPS space is expected to grow, leading to further food supply chain diversification. Therefore, the global food safety community must keep pace with these rapid developments to safeguard consumer health while facilitating international trade.

As new ingredients, inputs, and production systems are explored, the safety profile of the NFPS products can be altered through unintentional introduction of microbiological, chemical, or physical contaminants. It is therefore important to identify and characterize food safety hazards linked to new foods, leveraging available cutting-edge technologies and innovative tools. As new food sources, production systems and processing technologies are further explored, advances in digital analytic platforms and machine learning capabilities will continue provide tools to collect, integrate, and analyze data across food chains. Informed utilization of this data can drive better prediction, assessment, and management of food safety risks from a systems perspective. In addition, it may be increasingly more challenging to manage food safety hazards with global stressors such as climate change and supply chain disruptions, making it important to put appropriate food safety guidelines in place as well as encourage the use of forward-thinking approaches to safeguard our food sources and production systems of tomorrow (FAO, 2020, 2022b).

Given the heterogeneity of new foods, there cannot be one single approach when it comes to food safety risk assessments. However, there is still a need for stakeholders along the food chain to co-develop structured protocols or workflows toward comprehensive assessments that are based on current scientific knowledge. As risk assessments inform policymakers to make evidence-based food safety risk management decisions, it is vital that regulatory bodies keep up with new food innovation and production methods. With the development of regulatory frameworks for new foods proceeding at varying paces in different jurisdictions, future directions for global harmonization can only be established through continued transparency in sharing of information.

Food safety is a joint responsibility. Active and transparent communication through public and private collaboration is crucial not only to better prepare industries and governments but also to maximize the effectiveness of relevant safety assurance programs. Establishing an adequate level of control for NPFS is a complex task that must be based on scientific evidence, using a risk-based approach, through multidisciplinary and multisectoral work.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DISCLAIMER

The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations or of the Singapore Food Agency.

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