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A Systematic Review of Food Safety Risks in Plant and Seaweeds as Emerging Alernative Protein Sources

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Abstract

Alternative plant and seaweed protein sources other than soy and pea have gained significant interest as sustainable replacements of animal proteins in the last decades. However, despite a large food safety literature base, there are concerns about their food safety risks. The current study aims to synthesize the existing knowledge and gaps on safety risks associated with brewers' spent grain (BSG), grapes, hazelnuts, potatoes, pumpkins, and seaweed. A systematic review between 2003 and 2023 was conducted in the PubMed database to identify microbial, chemical, mycotoxins, heavy metals, and allergenic risks in the key commodities. The records obtained were exported into an online reference management platform, screened by inclusion and exclusion search strings, and the duplicates were removed. Finally, two reviewers assessed the eligibility of the full-text articles. The findings demonstrated that 9127 papers were identified, and 1639 of them were left for eligibility assessment. The reviewers finally included 144 articles. Amongst the commodities, the most safety studies were on grapes, with 55 papers, followed by potatoes (n=38), seaweed (n=21), hazelnuts (n=19), pumpkin (n=9), and BSG (n=2), respectively. Based on the risk type, heavy metals were the most studied ones, with 49 papers, followed by mycotoxins (n=31), microbial risks (n=23), chemical contaminants (n=21), and allergenic risks (n=20), respectively. To meet the growing need for plant and seaweed proteins, their food safety aspects should be extensively studied to deliver safe, healthy, and affordable substitutes based on robust safety standards.

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Introduction

The protein demand for the existing 7.3 billion inhabitants in the world is about 202 million tonnes per annum. A surplus of 2.3 billion more people, from mainly developing countries, by 2050 will severely impact the demand for protein. Currently, ~50% of the protein supplied globally is met by plant sources (Toujgani et al., 2023). Plant-based protein sources requirevless land, water, and energy (65 to 98%) while producing 84% less Greenhouse Gas (GHG) emissions, relative to conventional animal protein sources. Thus, the increasing demand for plant and seaweed protein sources has gained significant attraction due to health benefits in diet, increased consumer recognition of ecological sustainability, ethical and welfare issues of animals, and positive consumer view of protein-dense nutrition (Shabir et al., 2023; Wali et al., 2024). The global plant-based protein market is expected to increase from 10.3 billion dollars in 2020 to 15.6 billion dollars by 2026 (Zhang et al., 2022). The latest developments have brought financial investment, accelerated innovation and expanding market for a

Table 1. The production amount, protein content, byproducts and waste streams of this study's plant-based protein sources

Commodity	Global Production (MT)	Protein Content (%)	Byproducts and Waste Streams	Key Insights	Reference(s)
BSG	36.4	26-30 (hordein, gluten, globulin, and albumin)	Residues from brewing processes (~85% of total brewing waste)	High in proteins with physicochemical properties suitable for nutritional use.	Nyhan et al. (2023); Wen et al., (2019)
Hazelnuts	1.1	Skins: ~38; Defatted cake: ~48; Shells: ~3	Skins (~2.5% weight), shells (~36-39%), husks, and defatted cake	Hazelnut byproducts offer significant protein valorization potential	Nicoletti et al. (2022); Zhao et al. (2023)
Potatoes	300	~3	Organic waste: 16-25% of weight during processing (~44M tonnes)	Wasted potatoes and processing byproducts are substantial and can be valorized for proteins.	Chauhan et al. (2023); SavFood (2022)
Pumpkins	28	Seed flour: 36.5-51%; Seeds: ~48%	Waste/biomass: 3.1-4.4%; Peels: 2.6-16%; Pulp: 72-76%	High protein content in seeds and seed flour makes pumpkins valuable for a circular bioeconomy.	Gibbens (2022); Gavril et al. (2024)
Algae (Seaweed & Microalgae)	Seaweed: 358,000 tonnes (2019); Microalgae: 56.5k tonnes (2019)	Brown algae: 24 g/100g; Green algae: 32.7 g/100g; Red algae: 50 g/100g	Microalgae: Spirulina, Chlorella; Seaweeds: Brown, Green, Red	Spirulina and Chlorella (GRAS by FDA/EFSA); promising protein sources	Zhang et al. (2022); Ashour and Omran (2022); Medeiros et al. (2024)

sustainable protein and circular food system transition (Simon et al., 2024).

Research on plant and seaweed proteins has mainly focused on functionality, processing, industrial application, and side-stream valorization (Banach et al., 2023). However, their food safety risks have received less attention at different stages (Flint et al., 2023). Potential safety risks in plant and seaweed proteins have generally been described as: "*no indication*", "*general or potential risk*", "*knowledge gap*", "*rarely occurred*", and "*technological gap"* (Lang and Barling, 2013). For instance, spoilage bacteria and pathogens may differ from animal origin, there is not sufficient evidence in the frequency of mycotoxins, allergens, anti-nutrients, polyaromatic hydrocarbons (PAH), and heavy metal contaminants (Kumar et al., 2022; López-Pedrouso et al., 2023).

The food and agricultural industries discard remarkable quantities of biomass streams (Tufail et al., 2022). Extracting upcycled plant and seaweed proteins from raw materials otherwise destined to become food loss and waste (FLW) can enhance the sustainability of the entire food supply chain, reducing environmental burdens (Baca-Bocanegra et al., 2021). Hence, within the scope of a project "IPSUS-Climate-smart food innovation using plant and seaweed proteins from upcycled sources" (https://ipsus.org/en/) supported by EU Horizon 2020 ERA-Nets SUSFOOD2 and FOSC, six plant and seaweed commodities including BSG, grapes, hazelnuts, potatoes, pumpkins, and seaweed were selected to deliver upcycled plant and seaweed protein-based meat alternatives and dairy-free cheese prototypes. The production amount, protein content, byproducts, and waste streams, together with key insights, are tabulated in Table 1.

Despite their potential, food safety risks associated with the key plant and seaweed protein sources have not been extensively investigated. Unlike animal-based sources, plant-based sources may potentially introduce a broad range of safety risks for alternative proteins, considered as 'novel foods' require special authorization process to ensure that they do not pose health risks. This systematic review aims to synthesize evidence on the food safety risks associated with six emerging plant protein sources (BSG, grapes, hazelnuts, potatoes, pumpkins, and seaweed) to identify the critical gaps of safety risks and guide the future research of novel foods.

Material and Methods

Search strategy

A systematic literature search was conducted using PubMed from January 2003 to December 2023. The search included "keywords" related to safety risks in the key commodities, such as:

- "Brewers Spent Grain" OR "Grapes" OR "Hazelnuts" OR "Potatoes" OR "Pumpkin" OR "Seaweeds"
- AND "Food Safety" OR "Food Hazard" OR "Microbial Risks" OR "Chemical Contaminants" OR "Mycotoxins" OR "Heavy Metals" OR "Allergens"

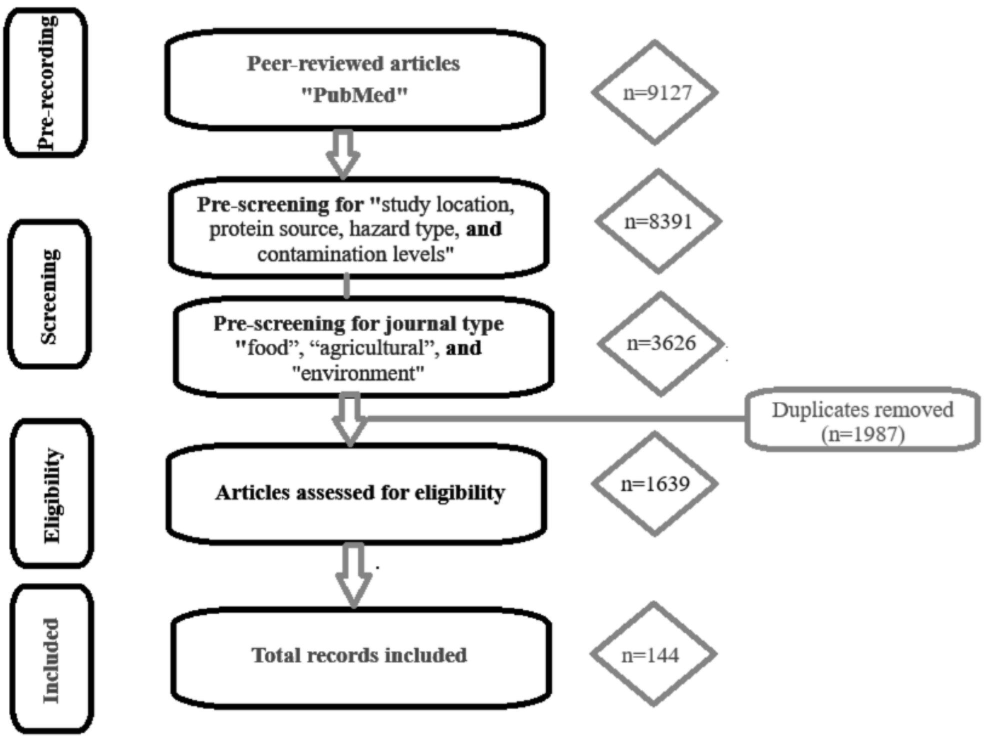

Figure 1. Systematic review stages and results

Inclusions and exclusion criteria

Studies were included if they: (1)were published in English; (2)focused on safety risks in the key commodities; and (3)provided quantitative data. Non-English papers, animal studies, clinical trials, non-peer-reviewed sources, and graduate studies were excluded.

Data extraction and analysis

The pre-records obtained from the PubMed database were exported into an online reference management platform (https://www.rayyan.ai) and initially screened for study location, protein source, risk type, and contamination levels. After that, the pre-screened data were filtered based on the journal title with the words “food”, “agricultural”, and "environment", and duplicates were excluded. Finally, two reviewers independently screened studies for eligibility first based on titles and abstracts, and then on the full-texts, discussing and resolving of conflicting decisions, as well as assessing how well they agreed (Nussbaumer-Streit et al., 2023).

Results and Discussion

Overview of included studies

A total of 9,127 studies were identified, of which 144 met the eligibility criteria. The most frequently studied commodity was grapes (55 studies), followed by potatoes (38), seaweeds (21), hazelnuts (19), pumpkins (9), and BSG (2) (Figure 1). Based on risk type characteristics, heavy metals were the most examined risk (49 studies), followed by mycotoxins (31), microbial risks (23), chemical contaminants (21), and allergenic risks (20) (Figure 2).

Plant protein sources generally depend on soy and pea (Lin et al., 2023). Therefore, exploiting opportunities for extracting protein from different plants and seaweed is paramount to integrating sustainability, in line with the framework the United Nations (UN) Decade of Action and the Second International Conference on Nutrition in 2014 (FAO, 2024; IPSUS, 2025). However, 51% of outbreak-associated illnessesin the United States of America (USA) were traced to plant foods over 10 years, higher than animal

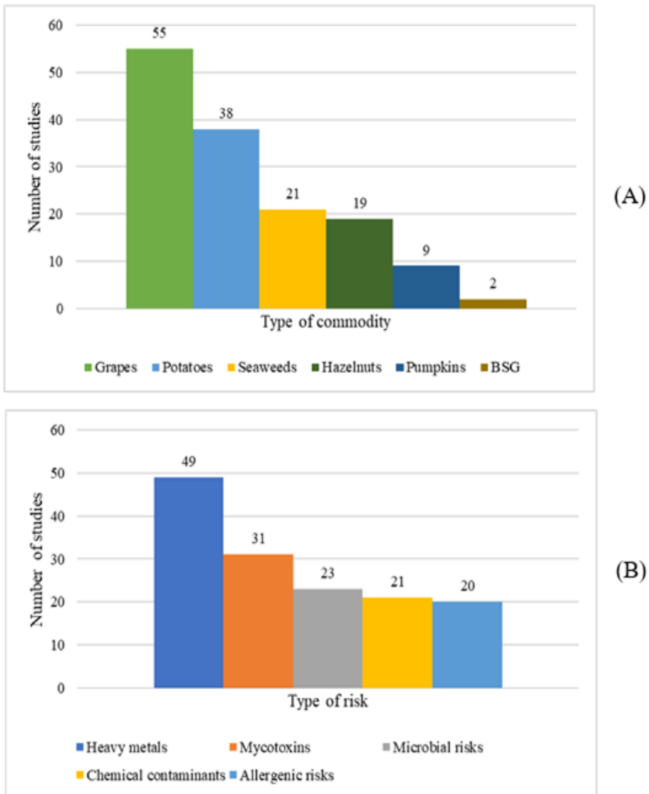

Figure 2. Systematic review results based on key commodities and risk type: (A) Based on type of commodity and (B) based on type of risk

Table 2. Papers reporting heavy metal contaminants

Commodity	Heavy metal	Level (mg/kg)	Reference(s)
BSG	n/a	n/a	n/a
Grapes	Cu	0.462	Olalla (2004)
	Cu	7.54-11.32	García-Esparza et al. (2006)
	Al, Cu, Pb	0.074, 0.0125, 0.0116	Correia et al. (2006)
	Pb, Cu	0.012-0.359, 0.770-4.706	Calisir and Akman (2007)
	Cu, Pb	0.25, 0.07	Vystavna et al. (2017)
	Ni, Cu, Cr, Mn, Cd, Pb, As	3.75-5.22, 0.10-0.27, 9.22-77.8, 0.07-0.30, 0.02-0.07, 0.24-0.37, 0.25-0.26	Li et al. (2018)
	Mn	2.381	Jung et al. (2019)
	Mn, Cr, Pb	0.0913-0.0743, 0.00144-0.00328, 0.0482	Pérez Cid et al. (2019)
	Cd, Pb	0.01, 0.009	Rusin et al. (2021)
	Al, Pb, Mn	0–0.090	Han et al. (2023)
Hazelnuts and hazelnut products	Cu	16.2-32.2	Simsek and Aykut (2007)
	Cr, Mn, Ni, Cu, Pb	7-10, 177-580, 5-35, 90-152, 3-9	Çevik et al. (2009)
	Mn, Zn, Cu, Pb, Cd	0.00013, 0.00115, 0.00005, 0.00001, 0.00457	Mendil et al. (2009)
	Cd, Pb	0.000067-0.000183, 0.000078-0.00021	Arpadjan et al. (2013)
	Mn	0.0126	Erdemir and Gucer (2014)
	As, Cd, Cu, Hg	0.0789, 0.0055, 0.0143, 0.1046	Moreda-Piñeiro et al. (2016)
Potatoes and potato products	Cd, Pb	0.50, 3.19	Antonious and Snyder (2007
	Co, As, Hg, Cr	0.2-0.51, 0.82-2.05, 0.33-0.90, 0.12-0.17	Jonnalagadda et al. (2008)
	As, Cr	1.50-7.50, 23.31-33.84	Karim et al. (2008)
	Zn, Cu, Mn	1.044–3.603, 0.111-1.761, 0.198-1.023	Mansour et al. (2009)
	Pb, Cd, Cu, Zn	0.199, 0.086, 0.534, 5.11	Marković et al. (2010)
	As, Cd, Cr, Cu, Ni, Pb, Zn	0.46–12.3, 0.08–4.4, 6.9–28.6, 0.58–20.04, 0.14–29.6, 0.21–13.3, 0.25–55.7	Cheraghi et al. (2013)
	Pb, Cd, Zn, Cu, Co, Ni	0.02, 0.02, 7.11, 0.75, 0.55 0.25	Ferrante et al. (2013)
	Cd, Pb	0.01, 0.014	Luis et al. (2014)
	As, Cd, Co, Cr, Cu, Hg, Ni, Pb	6.1, 0.5, 0.5, 0.2, 14.2, 0.004, 6.3, 3.2	Briki et al. (2015)
	Cd	0.0-2.65	Huang et al. (2015)
	Cu, Mn, Zn	4.39-4.609, 8.118-8.262, 10.96-11.81	Gąsiorowska et al. (2018)
	Cd	0.26-0.94	Ye et al. (2020)
	Cd, Pb	0.07-0.28, 0.10-0.50	Huang et al. (2020)
	Zn, Cu, Pb, Cr, Ni	2.73, 0.675, 0.027, 0.072, 0.055	Shi et al. (2022)
	Cd, Pb, Ni	0.03, 0.01, 2.5	Antonious et al. (2010)
Pumpkin	Pb, Cd, Cr, Cu, Ni	1.36, 0.27, 0.36, 1.36, 64.25	Galal et al. (2016)
	Cd, Co, Cu	0.0041, 0.002, 0.0282	Moreda-Piñeiro et al. (2016)
	Al, Ar, Cd, Pb	4.25–93.12, 0.001–0.104, 0.015–0.420, 0.003–0.100	Antoine et al. (2017)
	Hg, As, Cd, Pb, Cr, Mn, Co, Zn	0.015, 0.728, 0.382, 0.227, 0.850, 27.227, 0.525, 6.438	Guo et al. (2023)
Seaweeds	As, Pb, Cd	0.031-149, 0.050-12.1, 0.003-3.55	Almela et al. (2006)

products (Rizzo et al., 2021). Unlike animal products, potential food safety risks in plant protein sources must be considered through harvesting, processing, and storage. According to the Institute of Food Technologists (IFT), safety risks associated with plant and seaweed sources, as well as their proteins, are microbial (*Salmonella* spp., *Bacillus* (*B.*) *cereus*, *Clostridium* (*C.*) *perfringens*, *Enterococcus* (*E.*) *faecium* and *Enterobacteriaceae* spp.), allergens, heavy metal contaminants, pesticides, and mycotoxins (aflatoxins) (IFT, 2024). The recent systematic review showed that the key plants and seaweed may potentially pose safety risks for the protein extraction, indicating the need for further scientific evidence and regulatory-centric strategy to comply with the "*do no significant harm*" principles of the EU's Regulations 2015/2283 and 2020/852, European Green Deal 2019, and UN FAO/WHO Codexis.

Heavy metal contaminants

The recent systematic review showed that heavy metals including cadmium (Cd) (0.003 to 4.4 mg/kg), lead (Pb), mercury (Hg), and arsenic (As) (0.03 to 6.9 mg/kg) have been detected above the international safety limits in potatoes, grapes, pumpkin and seaweeds, especially in seaweeds due to marine pollution. However, BSG showed no recorded heavy metal contamination (Table 2).

Heavy metals pose toxic threats to the human body after long-term exposure in high amounts Heavy metals As, Pb, Hg, and Cd, are prioritized for monitoring and reduction. (Scutarașu et al., 2023). The European Union (EU) 2021/1323 of the Commission, which

Table 3. Papers reporting mycotoxin characteristics

Commodity	Mycotoxin	Level (μg/kg)	Reference
BSG	AF B1	19–44.52	Gonzalez Pereyra et al. (2011)
Grapes	AF B1	52800, 0.64	El Khoury et al. (2006); Feizy et al. (2012)
	AF B2	0.10-81.26	Zhang et al. (2018)
	OTA	2-24.5, 1920-1954.6, 40000, 6-32, 400-13300, 34.2-602.5, 2-17, >2, 10-22, 0.12-20.28, 0.20, 1.15-2.04, 0.03-0.62, 1.4-9.2, 0.99, 0.1, 2.98, 159990, 0.5, 0.10-81.26	Magnoli et al. (2003); Bau et al. (2005); El Khoury at al. (2006); Leong et al. (2006); Atoui et al. (2007); Solfrizzo et al. (2008); Díaz et al. (2009); Lucchetta et al. (2010); Feizy et al. (2012); Peraica et al. (2010); Ponsone et al. (2010); Akdeniz et al. (2013); Terra et al. (2013); Tosun et al. (2014); Zhang et al. (2014); García-Cela et al. (2015); Heshmati et al. (2015); Freire et al. (2018); Yusefi et al. (2018); Zhang et al. (2018)
	PAT	1.86-3.53, 53.9	Poapolathep et al. (2017); Hussain et al. (2020)
	PCA, MPA, CPA, FB1, ZEN	0.10-81.26	Zhang et al. (2018)
	FB2, FB4	1660-2531	Perera et al. (2021)
Hazelnuts and hazelnut products	TAF	0.44-3.18, 0.02-78.98, 0.14-0.64, 5600-616000, 0.0-11.3, 0.0000106-0.0000107	Ozay et al. (2008); Baltaci et al. (2012); Prelle et al. (2012); Ekinci et al. (2014); Kabak (2]016); Şen and Civil. (2022)
	PAT, ERG	5600-616000	Ekinci et al. (2014)
Potatoes and potato products	Chaetoglobosin A & C, Communesin A & B, Patulin & Citrinin	n.d.	Andersen & Thrane (2006)
Pumpkin	n/a	n/a	n/a
Seaweeds	n/a	n/a	n/a

modified Regulation (EC) 1881/2006 have set up limits for Cd (0.04 in cereal-based foods, 0.10 in cereals, and 0.05-0.2 mg/kg in vegetables), for Pb (0.20 in cereals and 0.02 mg/kg in cereal-based foods), for As (0.02 mg/kg in infant formulas and special medical foods, and 0.10 to 0.30 mg/kg in cereals and cereal-based products), and for Hg (0.01 mg/kg in various cereals and foods) (Rubio et al., 2023; FAO, 2024a).

Cd is a serious toxicant in the urinary and respiratory systems of the human body and is easily absorbed by plants (Wang et al., 2019), especially potatoes (Scutarașu et al., 2023). Similarly, As, Hg and Pb are associated with carcinogenesis, neurotoxicity, nephrotoxicity and reproductive issues when taken in excess quantities (Bandara et al., 2020). Naturally, the heavy metal contaminants detected in the key plant and seaweed sources pose a severe risk for their protein extracts than non-plant protein sources. For instance, the Clean Label Project (cleanlabelproject.org) reported that Pb, Hg, Cd and As were present in 53 plant protein powders, and 75% had significant concentrations of Pb in one serving (Clean Label Project, 2024). In addition, wastewater might cause pumpkins, hazelnut byproducts (shell and skin), and potatoes to interact with Pb and Cd (Karim et al., 2023). In algae and seaweed products commercially availableed in Spain, the levels of Cd, Pb, Hg, and As ranged between 0.017 and 64.7 mg/kg, and a level of 0.017 mg/kg were detected in Asian and European products (Besada et al., 2008). According to the European Food Safety Authority (EFSA), consuming 5 g of dehydrated seaweed per day may contribute to the tolerable weekly intake of Cd by 22.7% (EFSA, 2023). Overall, the key plants and seaweed contaminated with heavy metal contaminants may provoke potential safety and health risks with their protein extracts to be used for manufacturing meat analogues and dairy free products.

Mycotoxin contamination

This systematic review exhibited that nycotoxin contamination was predominantly reported with ochratoxin A (OTA) in grapes (0.03 μg/kg to 159.9 mg/kg) and total aflatoxin (TAF) (10.6 μg/kg to 5.6 mg/kg) in hazelnuts. BSG contained detectable aflatoxin B1 (AFB1) (19 to 44.52 μg/kg). No mycotoxins were reported in seaweed and pumpkin (Table 3). OTA

Table 4. Papers reporting microbial characteristics

Commodity	Microorganisms	Level (CFU/g)	Reference(s)
BSG	n/a	n/a	n/a
Grapes	TAMB, TAB, yeast, mould, *Massilia, Pantoea, Pseudomonas, Halomonas, Corynebacterium, Bacillus, Anaerococcus, Acinetobacter*	7- 11, 63- 65, n.d.	Kou et al. (2007); Augustine et al. (2013); Xu et al. (2022)
Hazelnuts and hazelnut products	*E. coli*	n.d., 38	Little et al. (2009); Feng et al. (2018)
	Salmonella	0.75	Zhang et al. (2021)
Potatoes and potato products	*C. botulinum*	<1	Del Torre et al. (2004)
	TAB	<30, 20-67	Montville and Schaffner (2004); Manani et al. (2006)
	Salmonella	53-56	DiPersio et al. (2005)
	L. monocytogenes	<60, 20-30	Pérez-Díaz et al. (2008); Szymczak and Dąbrowski (2015)
	B. cereus	10^3, 1×10^2-7×10^2	King et al. (2007); Fangio et al. (2010)
	B. weihenstephanensis	<3	Samapundo et al. (2011)
	B. cytotoxicus	<200	Contzen et al. (2014)
	S. aureus	10^7	Baumgartner et al. (2014)
	Yeasts, moulds	12 – 26	Malavi et al. (2021)
Pumpkin	*Acinetobacter, Arthrobacter, Bacillus, Enterobacter, Erwinia, Klebsiella, Pantoea, Pseudoclavibacter, Pseudomonas, Serratia, Staphylococcus, Weissella, Enterobacteriaceae*	5.6×10^2-1.6×10^6	Baruzzi et al. (2012)
Seaweeds	*V. parahaemolyticus*	0.03-4.6	Mahmud et al. (2007)
	TAB	44-78	Choi et al. (2014)
	E. coli, E. coli 157:H7, *L. monocytogenes, V. parahaemolyticus*	50.1-68.4	Swinscoe et al. (2020)
	Undaria pinnatifida, Palmaria palmata, Arthrospira platensis, Porphyra spp., *Laminaria* spp., *Hizikia fusiformis*, *Ulva* spp.	22.3-55.8	Martelli et al. (2021)

is a carcinogenic, genotoxic, immunotoxic, and hepatotoxic mycotoxin for humans (Group 2B), which is produced by some fungal species belonging to the genera *Aspergillus* (*A.*) and *Penicillium* (*P.*) (Chen et al., 2018). The EFSA has reported its tolerable weekly intake as 120 ng/kg body weight (Freire et al., 2020)

The recent work showed that total AF (TAF) contamination was reported in hazelnuts (5.6 mg/kg), and with AFB1 in BSG (44.52 µg/kg). According to FAO, almost 25% of the global food crop is contaminated with mycotoxins (rBiopharm, 2022). All foods for human consumption should not contain more than 10 µg/kg of TAF, of which AFB1 needs to be lower than 5 µg/kg (FAO, 2024b). AFs are hazardous, toxic, stable and resistant mycotoxins, notably produced by *A. flavus* and *A. parasiticus*. Based on lethal dose values (LD50), AFB1 is the most (geno)toxic metabolite linked to acute hepatitis, liver cancer, immune and reproductive system disorders, and blood-forming stem cell dysfunction (Samimi et al., 2024). AFM1 is a significant metabolite of AFB1 in humans and animals. In the literature, other surveys also reported higher concentrations of TAF (6.55 µg/kg) and AFB1 (78.98 µg/kg) in hazelnuts (Baltaci et al., 2012). Based on these factsi the proteins extracted from these commodities could be contaminated with mycotoxins. Thus, in literature, several studies also detected high concentrations ofAFB1 and OTA in soy protein (Bramante, 2024), in pea, chickpea, lupin, and seitan proteins (Mihalache et al., 2023), and in spirulina, chlorella and kelp (r-Biopharm, 2020). However, AF and OTA are stable toxicants which cannot easily be eliminated with standard thermal methods (Galluzzo et al., 2024). In addition, ultra-processing plant proteins may cause the released of mycotoxins from or bound to matrix components, forming degraded or modified products with unknown toxicokinetic and toxicodynamic characteristics (Pavicich et al., 2024). Thus, monitoring mycotoxins in plant and seaweed as well as their protein extracts during harvesting, extraction and ultra-processing is very important for the consumer health.

Microbial risks

The recent survey demonstrated that pathogenic bacteria (*Salmonella* spp., and *Staphylococcus* (*S.*) *aureus*), hygenic indicators (*Listeria* (*L.*) *monocytogenes*, and *Escherichia* (*E.*) *coli*), and other

Table 5. Papers reporting chemical contaminant characteristics

Commodity	Chemical	Level (mg/kg)	Reference(s)
BSG	Acrylamide & hydroxymethylfurfural (HMF)	0.00537-606.9	Jozinović et al. (2019)
Grapes	Paraffins; flufenoxuron-lufenuron-pyriproxyfen & fenoxycarb; imazalil-prochloraz & thiabendazole; pyrimethanil-boscalid-fenhexamid-cyprodinil & azoxystrobi; chlorpyrifos-Iprodione; carbendazim, chlorpyrifos, dithiocarbamates, iprodione & thiophanate methyl; thiabendazole & Thiophanate- methyl 2-aminobenzimidazole; pyraclostrobin, dimethomorph, cymoxanil, cyazofamid, cyazofamid & CCIM; atrazine, propiconazole, cyhalothrin-L, myclobutanil, cyfluthrin, cypermethrin, difenoconazole, imidacloprid, acetamiprid, chlorpyrifos & thiophanate-methyl, azole pesticides, strobin, benzimidazole, organophosphorus, pyrethroid pesticides, nicotinoid	43-247; 0.14-0.45; 0.0047-0.0072, n.d.; 0.010-0.1; 0.0094-0.135; 0.01-5.86; 49920-72540; <1.36; 0.002-12.285	Fiorini et al. (2008); Payá et al. (2013); Xu et al. (2015); Mutengwe et al. (2016); Esteve-Turrillas et al. (2016); Varela-Martínez et al. (2018); Bouagga et al. (2019); Lu et al. (2019); Yang et al. (2019); Hamzawy (2022)
Hazelnuts and hazelnut products	n/a	n/a	n/a
Potatoes and potato products	Acrylamide	0.0023-0.0186; 0.106-4.630; 0.244-1.688; 0.329; 0.01	Knol et al. (2008),;Becalski et al. (2010); Boroushaki et al. (2010); Mesias et al. (2020); Yang et al. (2021)
	Endosulfan-sulfate, tetradifon, fenbuconazole & others	0.0000125-0.001	Park et al. (2011)
	4-hydroxy-2-hexenal & 4-hydroxy2-nonenal	n.d.	Ma et al. (2019)
Pumpkin	Nitrate-N	281.02	Prasad and Chetty (2011)
Seaweeds	PAH & AHC	110-32000	Soares et al. (2021)
	Acrylic acid	n.d.	Kim et al. (2022)

microorganisms *Bacillus* (*B.*) *cereus*, *C. Botulinum*, total aerobic bacteria (TAB), mould and yeast were detected in multiple commodities. Especially, potatoes exhibited the highest microbial risks with *Salmonella* spp. (53 to 56 CFU/25 g, *L. monocytogenes* (<60 CFU/25 g), *B. cereus* ($7*10^2$ to 10^3 CFU/g), and *S. aureus* (10^7 CFU/g), respectively (Table 4).

According to the Food Safety Authority of Ireland (FSAI) (2020) and Canadian Food Inspection Agency (CFIA) (2025), *L. monocytogenes* and *Salmonella* should be absent in 25 g while *E. coli* and *S. aureus* should be less than 10 and 20 CFU/g, respectively (FSAI, 2020; CFIA, 2025).

Bacillus is a common microbial risk in potatoes. It produces diverse biologically active metabolites, causing high resistance to biofertilizers, biofungicides, heat, desiccation, organic solvents, and ultraviolet (UV) irradiation (Purgatorio et al., 2024). Potatoes also generate moist waste, which may lead to pathogenic illnesses (Chauhan et al., 2023). *Bacillus* and *Clostridium* species are frequently detected in peas (Kyrylenko et al., 2023), as well asn fungi, yeast, and bacteria on grape (Sindrod et al., 2023), *E. coli*, coliforms, *S. aureus,* and *Salmonella*, and fungi (*Aspergillus* spp.) in hazelnuts and hazelnut products (Spagnuolo et al., 2023), fungi in pumpkin (Silva et al., 2022), and *Bacillus* spp., *Vibrio* spp., *E. coli*, and *L. monocytogenes* in algae and seaweeds (Swinscoe et al., 2020; Martelli et al., 2021). However, not only the existence of microbial species, virulence factors and resistant-encoding gene transfer are also considered potential safety risks (Geeraerts et al., 2020). Overall, our data suggest that the key commodities in the review pose significant microbial risks for their protein extracts if sanitation and hygiene are not maintained well at extraction, manufacturing and storage stages.

Chemical contaminants

In this systematic review, chemical contaminants – *pesticides*, *polycyclic aromatic hydrocarbons* (PAH), and *bisphenols*- were frequently detected in the focal commodities. Potatoes contain high acrylamide levels (0.0023 to 4.630 mg/kg), a known carcinogen while seaweeds were found to accumulate high levels of PAHs (110 to 32000 mg/kg) (Table 5).

About 3 million tons of pesticides per year are used for agricultural operations globally, posing a severe threat with neural and kidney damage, congenital disabilities, reproductive problems, and cancer (Rather et al., 2017). PAHs are persistent organic pollutants from fossil fuel combustion, motor vehicles' exhaust emissions, and coke and asphalt production (Ailijiang et al., 2022). PAHs serve as

Table 6. Papers reporting allergenic characteristics

Commodity	Allergen	Level	Reference
BSG	n/a	n/a	n/a
Grapes	*Vit v 1*	n.d.; 0.15-0.88 g.mL^{-1}	Schad et al. (2005); Asero et al. (2007); Vassilopoulou et al. (2007); Wigand et al. (2009)
	N-glycans	30 g.mL^{-1}	Gonzalez-Quintela et al. (2011)
	β-1,3-glucanase & Harpin binding protein	n.d.	Rossin et al. (2015)
	Ethanolamine, ethylamine, putrescine and cadaverine	0.51-24.29 μg.g^{-1}	Moncalvo et al. (2016)
	Profilin, NAD(P)H dehydrogenase, triosephosphate isomerase, glyceraldehyde- 3phosphate dehydrogenase and beta-galactosidase	n.d.	González Mahave et al. (2022)
Hazelnuts and hazelnut products	*Cor a 1, Cor a 2, Cor a 8, Cor a 9, Cor a 11, Cor a 14*	n.d.; 34%, 60% & 73% of samples	Hansen et al. (2003); Flinterman et al. (2008); Platteau et al (2011); Caffarelli et al. (2021)
Potatoes and potato products	Latex	n.d.	Asero et al. (2007)
	Patatin	n.d.	Lattová et al. (2015)
	Sola t 1, Sola t 3, Sola t 4	n.d.	Kobayashi et al. (2021)
	Patatin	n.d.	Gelley et al. (2022)
Pumpkin	Lipid Transfer Protein	n.d.	Rodríguez-Jiménez et al. (2010)
	Skin prick test	1 mm-histamine wheal diameter; negative	Gawryjołek et al. (2021)
Seaweeds	Phlorotannins	n.d.	Barbosa et al. (2018)

potential carcinogens and mutagens (Sampaio et al., 2021). Currently, the maximum levels in foods are specified in Commission Regulation (EU) No. 835/2011 of 19 August 2011 for benzo[a]pyrene and ΣPAH4 (benzo[a]pyrene, benz[a]anthracene, benzo[b]fluoranthene and chrysene), that is 1 µg/kg of the sum of BaP and ΣPAH4 for processed cereal-based foods (Zelinkova and Wenzl, 2015). Moreover, naphthalene, fluorene, pyrene, anthracene, benzo[b]fluoranthene, benzo[a]pyrene, chrysene and acenaphthene have been included in the priority list of pollutants by the U.S. Environmental Protection Agency (EPA) (Borah and Deka, 2024). . In literature, several works reported benzo[a]pyrene (538–873 µg/kg) and PAH (2323-3423 µg/kg) in spirulina (Muys et al., 2019), and bisphenol (1.85 to 18.17 µg/kg) in oat and soy (Rebellato et al., 2023). In summary, our systematic review indicated that the mitigation with chemical contaminants in the key commodities, even of their protein extracts, needs the control and investigation of their modes of formation for effective regulation and reduction in their impact on human health, which aligns with the UN Sustainable Development Goals (SDGs) by 2030.

Allergenic risks

The recent review demonstrated that hazelnuts had the highest allergenic potential, with *Cor a 1* (34%), *Cor a 9* (60%) and *Cor a 14* (73%) proteins found in most samples, while no *Cor a 2*, *Cor a 8*, *Cor a 9*, or *Cor a 11* were detected. Regarding grapes, *Vit v* (0.15-0.88 g/mL) was one of the most identified allergenic risks. None of patatin, *Sola t 1*, *Sola t 3*, and *Sola t 4* was found in potatoes, and only one pumpkin study reported histamine (1 mm with a skin prick test). Besides, no allergenic proteins were detected in BSG, making it a promising alternative protein source (Table 6).

Food allergy is an IgE-mediated immunological response to specific proteins. It is currently estimated to affect 2% of adults and 8% of children in developed countries (Li et al., 2024). Of foodborne allergens, 70% are of plant origin (Tekiner et al., 2020). The relevant data on allergens can be retrieved from the WHO and International Union of Immunological Societies (IUIS) Allergen Nomenclature Subcommittee (http://allergen.org/) (Li et al., 2025). Safety prediction should be conducted by comparing the aminoacid sequences of a novel protein against identified allergens. However, the current allergen sequence databases cannot perform robust safety assessments (Malila et al., 2024). The transition to a plant-based diet may trigger allergic symptoms (Präger et al., 2023). Therefore, technology's multimodal action should challenge how to reduce allergenic risks in plant and seaweeds (Su et al., 2024). Moreover, using *in vitro* and *in silico* techniques such as quantitative structure-activity relationship analysis, physiologically based toxicokinetic modelling and Threshold of Toxicological Concern can be utilized to predict the allergenic risks by combining genetics, transcriptomics, proteomics, metabolomics and bioinformatics with toxicological data, rather than animal-based experiments (De Boer and Bast, 2017; EFSA Scientific Committee, 2019). Overall, foodborne allergenicity is generally considered a clinical issue. However, it requires multidimensional and multidisciplinary collaboration amongst food, nutritional and life sciences for the risk assessment of emerging plant and seaweed protein sources as a part of the food circular system.

Conclusion and future directions

In this systematic review, we evaluated the food safety risks associated with six key plants and seaweed. The results demonstrated that to meet the safe, healthy, and affordable protein substitutes rather than animal-based sources, further research is needed to provide the robust safety standards at all stages of harvesting, extraction, processing, manufacturing, and storage, due to due to insufficient knowledge and data of food safety with the emerging plant- and seaweed protein sources. Safety is a non-negotiable requirement, and food scares can undermine the concept's viability. Overall, it is urgent to design a methodology that uses sustainability, food safety, and a regulatory-centric strategy, which complies with the principles of the "*do no significant harm principle*" of Regulation (EU) No 2020/852, European Green Deal (EGD)2019, EUs Regulation 2015/2283, and UN FAO/WHO Codexis. Besides, At the policy level, it is important to relax strict regulations to accommodate innovative and biotechnological development to mitigate with the safety risks at each level.

Disclosure statement

None to declare.

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