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Review article

Food safety issues associated with sesame seed value chains: Current status and future perspectives

Amarachukwu Anyogu [a,1,*], Yinka M. Somorin [b,c,1], Abigail Oluseye Oladipo [a], Saki Raheem [d]

[a] Food Safety and Security, School of Biomedical Sciences, University of West London, London, W5 5RF, United Kingdom
[b] University of Glasgow, Glasgow, G12 8QQ, United Kingdom
[c] Department of Biological Science, Ajayi Crowther University, Oyo, Nigeria
[d] School of Life Sciences, University of Westminster, London, W1W 6UW, United Kingdom

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ABSTRACT

Sesame (*Sesamum indicum*) is an oilseed crop which is increasingly recognised as a functional food by consumers due to its nutritional and nutraceutical components. Consequently, global demand for sesame has increased significantly over the last three decades. Sesame is an important export crop in producing countries, contributing to their socio-economic development. However, in recent years, major foodborne incidents have been associated with imported sesame seeds and products made with these seeds. Foodborne hazards are a potential risk to consumer health and hinder international trade due to border rejections and increased import controls. An insight into the routes of contamination of these hazards across the value chain and factors affecting persistence may lead to more focused intervention and prevention strategies. It was observed that *Salmonella* is a significant microbial hazard in imported sesame seeds and has been associated with several global outbreaks. Sesame is mainly cultivated in the tropical and subtropical regions of Africa and Asia by smallholder farmers. Agricultural and manufacturing practices during harvesting, storage, and processing before export may allow for the contamination of sesame seeds with *Salmonella*. However, only a few studies collect data on the microbiological quality of sesame across the value chain in producing countries. In addition, the presence of mycotoxins and pesticides above regulatory limits in sesame seeds is a growing concern. Eliminating foodborne hazards in the sesame value chain requires urgent attention from researchers, producers, processors, and regulators and suggestions for improving the safety of these foods are discussed.

1. Introduction

Sesame (*Sesamum indicum*) is an ancient oilseed crop mainly cultivated for its edible seeds from which oil is produced [1]. Sesame seeds comprise up to 60 % oil, the highest content of all major oilseed crops [2,3]. Sesame is a functional food as it is a source of nutritional and nutraceutical components. Sesame oil is a rich source of polyunsaturated fatty acids (PUFA), such as oleic and linolenic acids [4,5]. Sesame is also an excellent source of proteins, carbohydrates, vitamins, and minerals, including phosphorus, manganese,

* Corresponding author.
E-mail address: amara.anyogu@uwl.ac.uk (A. Anyogu).
[1] These two authors contributed equally to this work.

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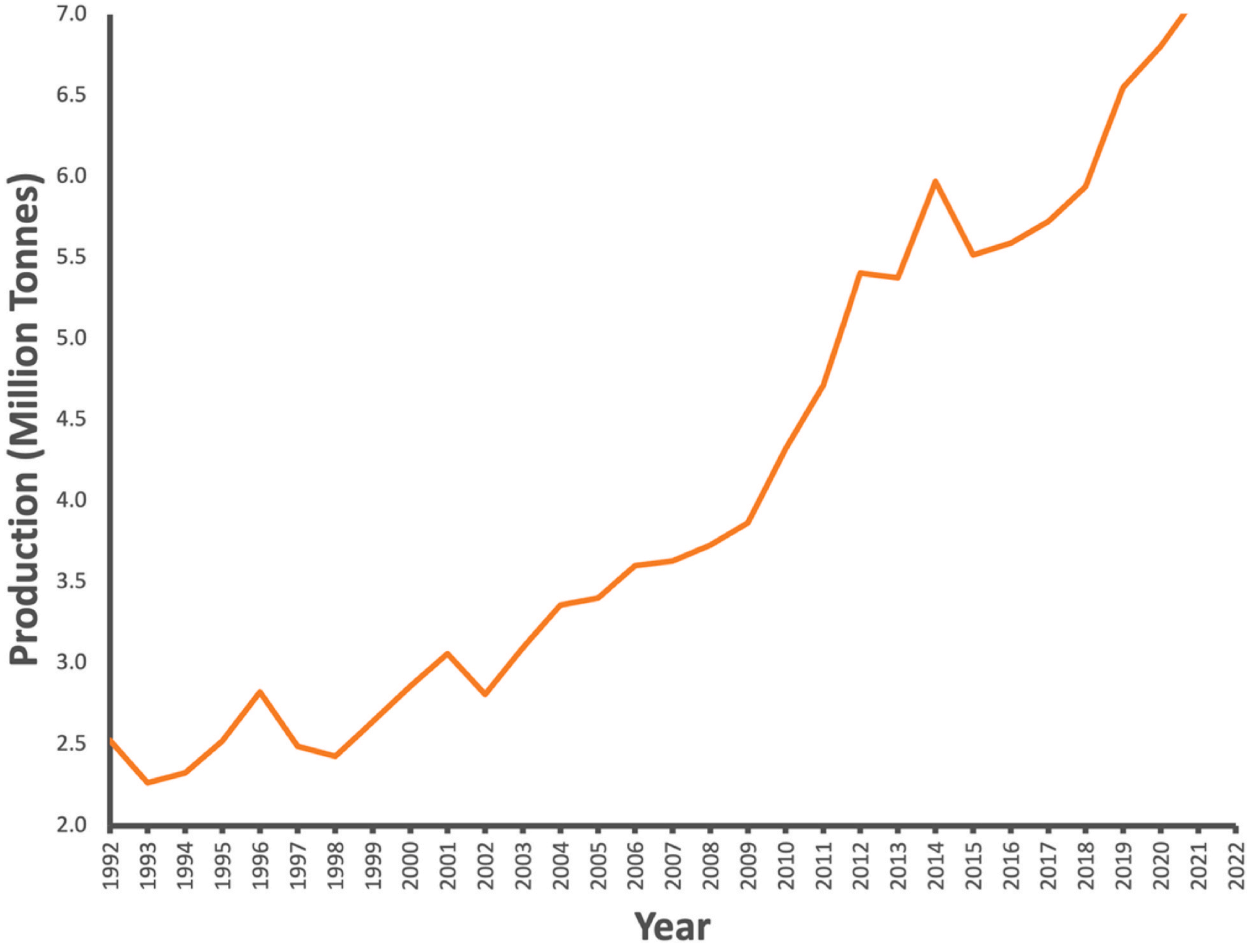

Fig. 1. Global production of sesame seed between 1992 and 2022. Source: Food and Agriculture Organisation Statistical Databases [30].

copper, and iron [6]. Recent studies have reported that sesame is an important natural food source of phytosterols (3–8 mg/g), melatonin (0.04–298.62 ng/g) and tocopherols (530–1000 mg/kg) [7–9]. In addition, lignans such as sesamin, sesamol, sesamolin, and sesaminol are another major group of bioactive compounds found in sesame [9]. These components are associated with various biological and pharmacological activities, including antioxidant, anti-inflammatory, cardioprotective, anticancer and anti-neurodegenerative effects [10].

Consequently, sesame has diverse uses across the food, cosmetic and pharmaceutic industries, and increased demand is driving the growth of the sesame market. The mainstreaming of indigenous foods and ingredients such as *hummus, tahini,* and *halva*, particularly in Western diets, have contributed to the increasing demand for sesame seeds [11]. Sesame oil has pleasant sensorial characteristics, and the presence of antioxidants confers increased resistance to rancidity compared to other oils [4,6]. In addition, different applications of sesame include soap and cosmetic production and as a delivery vehicle for fat-soluble drugs [12,13].

The top producers of sesame are in Africa and Asia, where sesame significantly contributes to the local economy through job creation and foreign exchange revenue [1,14]. However, microbial and chemical hazards in this commodity constitute a significant barrier to the global trade of sesame seeds [15,16]. *Salmonella* spp. and mycotoxin contamination are frequently reported in sesame and sesame-based products. *Salmonella* spp. and mycotoxins were the most significant hazards in the "nuts, nut products and seeds" category in foods exported into the European Union (EU) in 2018 and 2019 [17]. Recent reports have also highlighted the scale of *Salmonella* contamination in sesame imported into the EU [16,18]. In addition, outbreaks of salmonellosis associated with sesame and sesame-related products have been reported worldwide [19–21]. Sesame seeds contaminated with mycotoxins have been observed at different stages of the value chain, suggesting this is a widespread problem [22,23]. Pesticides are also an emerging concern. In September 2020, sesame seeds contaminated with ethylene oxide were reported to the EU's Rapid Alert System for Food and Feed (RASFF). This major incident led to several recalls and withdrawals of sesame-containing foods across Europe [24]. Sesame seeds often serve as ingredients in a wide variety of products. Therefore, the presence of hazards in sesame can have severe and widespread health and economic consequences.

Sesame can be exposed to various contaminants at all stages of the value chain. Poor agricultural practices during cultivation, harvesting and storage can allow for microbial and chemical contamination of sesame seeds [25]. Furthermore, the warm and humid

Table 1
Major producing countries of sesame seeds.

S/N	Country	Production Quantity (tonnes)	Exports (tonnes)	Export to production ratio (%)	Export value (USD million)
1	Sudan	1,231,701	356,643	29	509
2	India	788,740	234,458	30	422
3	Myanmar	760,926	101,565	13	144
4	United Republic of Tanzania	700,000	120,987	17	144
5	China	872,795	90,208	10	202
6	Nigeria	450,000	297,022	66	331
7	Burkina Faso	208,796	58,858	28	68
8	Chad	201,913	69,749	35	102
9	Central African Republic	190,917	115	0.06	0.01
10	Ethiopia	180,000	107,719	60	183

ND - No data available.
Source: Food and Agriculture Organisation Statistical Databases. Data for 2022 [30].

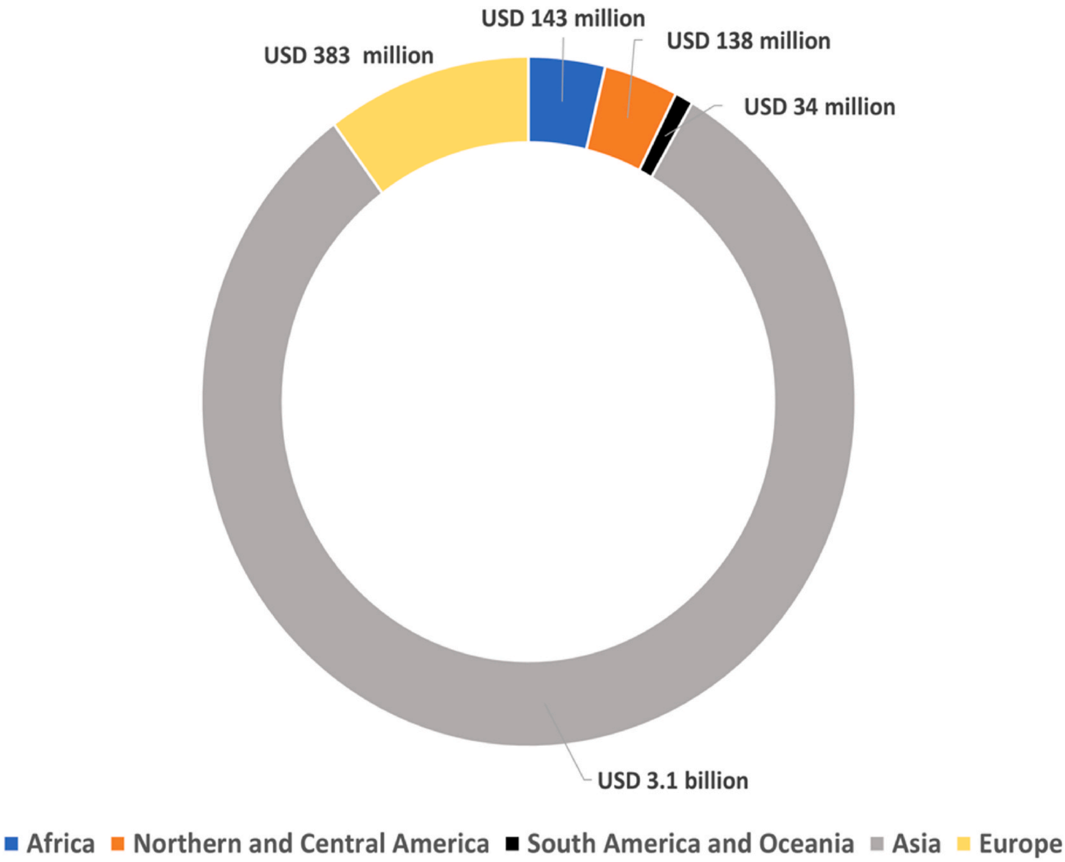

Fig. 2. Major importers of sesame seeds. Data represent import values (USD million) in 2022. Source: Food and Agriculture Organisation Statistical Databases [30].

conditions characteristic of tropical and subtropical regions where sesame is grown may also create an optimal environment for the growth of foodborne pathogens or the production of microbial toxins, further exacerbating the problem [22].

Several reviews discussing sesame have been published. However, these mainly focus on single aspects such as nutritional or nutraceutical components [4,9,26] or economic value [1,27] to producing countries. Olaimat et al. [28] reviewed the microbial safety of oil-based food products but focused on foodborne pathogens. However, no comprehensive overview of microbial and chemical contamination is focused explicitly on sesame and sesame-based products. Therefore, this review is necessary to summarise current knowledge on the safety of sesame-based foods. It also highlights data gaps for future research and suggests interventions to strengthen the sesame value chain.

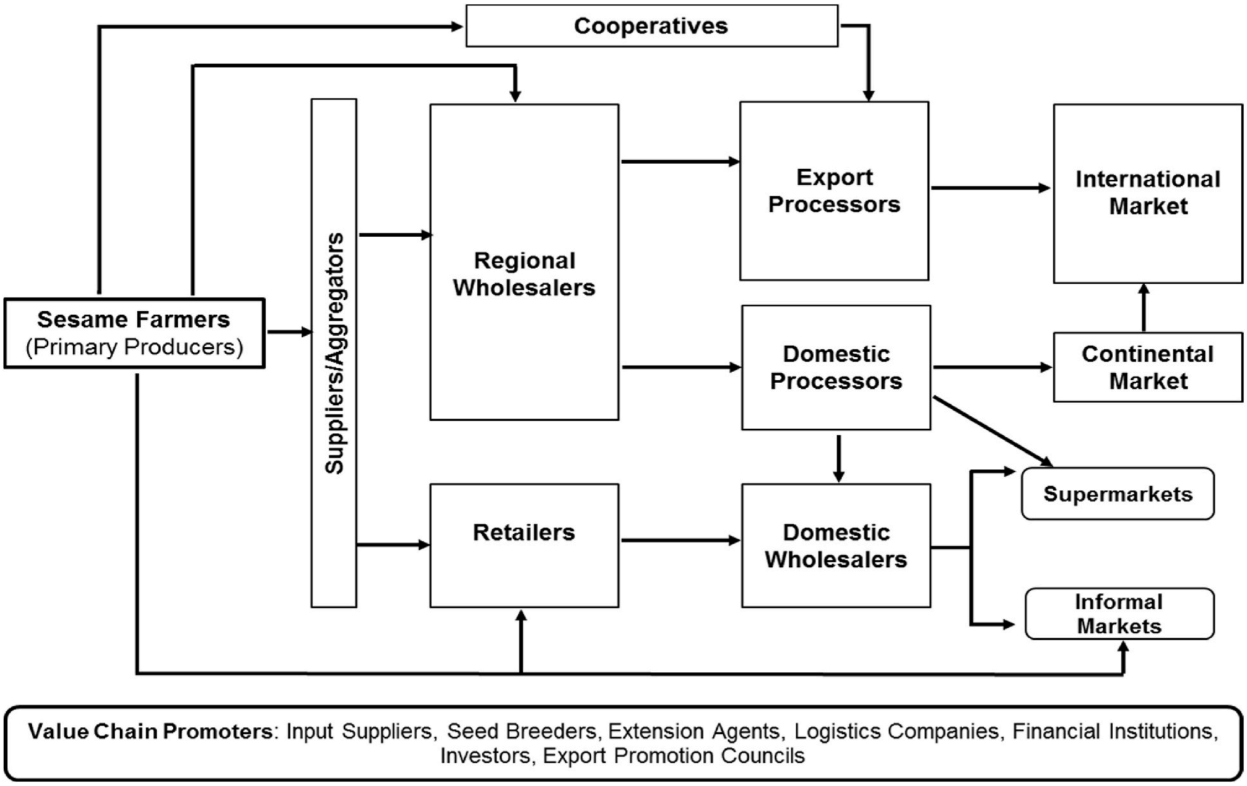

Fig. 3. The sesame supply chain identifying major agents.

2. The global sesame seed market and value chain

Sesame is a highly valued crop worldwide because of its various uses for its seeds and oil in the food, nutraceutical, and pharmaceutical industries. Increased consumer awareness of sesame's health benefits, changing consumption patterns, and a growing population have increased the demand for sesame [27].

The sesame market is projected to grow at a compound annual growth rate of 2.6 % to USD 8.7 billion by 2029 [29]. Global sesame seed production exceeded 7 million tonnes in 2022, an increase of almost 200 % over the last three decades (Fig. 1). Africa and Asia produce over 95 % of the world's supply of sesame. In 2022, the highest producing countries were Sudan, India, Myanmar, the United Republic of Tanzania, and China, accounting for over 60 % of global production (Table 1).

In producing countries, sesame is gaining recognition as a high-value export crop. Over 2.0 million tonnes of unprocessed sesame seeds, valued at USD 3 billion, were traded globally in 2022 [30]. In Nigeria, almost 70 % of domestic sesame production was exported in 2022 (Table 1), and sesame seeds are the third most valuable export product after cocoa and herbs [31]. In addition, Ethiopia, Chad, and India exported 60 %, 35 %, and 30 % of their cultivated sesame in 2022 (Table 1). Asia and Europe are the primary destinations for sesame seeds (Fig. 2). China, Turkey, and Japan are the largest importers of sesame seeds, accounting for about 56 % (almost 1.2 million tonnes) of global imports, valued at nearly USD 1.9 billion [30]. The European Union (EU) is also a growing market for imported sesame seeds primarily used in the food industry to supplement local production [11]. Consequently, sesame is gaining attention as a priority crop, and increasing production has become the focus of many national and international efforts [1,13,32,33].

The supply chain connecting sesame producers with consumers is global and complex (Fig. 3). In major producing regions, sesame is grown predominantly by smallholder farmers, with a minor contribution from a few large-scale farmers. Producers sell individually or through cooperative unions to wholesalers, the principal actors in the sesame value chain. Exporters purchase the bulk of the seeds, while smaller amounts are sold to processors and local retailers [31,32,34]. Several constraints to the value chain in many low and middle-income sesame-producing countries include access to high-yielding and well-adapted cultivars, seed supply systems, and credit. In addition, there is limited use of modern agricultural production technologies, post-harvest crop management infrastructure and systems [14,35,36]. Sesame value chains are poorly organised in the world's major producing regions. They are, therefore, more vulnerable to foodborne hazards that may pose health risks to consumers.

3. *Salmonella* and other microbial hazards in sesame seeds and associated products

Sesame seeds and sesame seed products such as *tahini* (sesame paste) and *halva* are classified as low water activity (a_w) foods (a_w <

Table 2
Microbial hazards in sesame seeds and sesame-based products.

Microorganism	Product(s)	Sample collection point	Country (Country of origin)[a]	Prevalence (n/N)[b]	Analytical method	Reference
Salmonella spp. *S.* Montevideo, *S.* Stanleyville, *S.* Tilene	Sesame seeds	Retail	Italy (Nigeria)	3/36	Conventional	[46]
Salmonella spp.	Sesame seeds	Retail	Mexico (U)	12/100	Conventional	[47]
Salmonella spp.	Sesame seeds	Point of export	Burkina Faso	95/359	Conventional	[48]
Salmonella spp.	Sesame seeds	Point of import	United States of America (U)	20/177	Conventional	[49]
Salmonella spp.	Sesame seeds	Point of import	United States of America (U)	23/233	Conventional	[50]
Salmonella Offa, *Salmonella* Tennesee	Sesame seeds	Retail	Germany (U)	2/16	Conventional	[51]
Salmonella Typhimurium DT104	*Tahini*	Retail	Germany (Turkey)	1/12	Conventional	
Salmonella Typhimurium DT104, *Salmonella* Poona	Halvah	Retail	Germany (Turkey)	8/71	Conventional	
Thermotolerant coliforms	Sesame seeds, Sesame-based snacks	Retail	Burkina Faso	32/75	Conventional	[52]
Microorganism	Product(s)	Sample collection point	Country (Country of origin)[c]	Prevalence (n/N)[b]	Analytical method	Reference
Salmonella spp. *Escherichia coli*	Sesame seeds	Retail	United Kingdom (U)	13/771 8/771	Conventional	[53]
Salmonella enterica subspecies enterica serotype (11:z41: e,n,z15)	Sesame spread	Retail, Household	Germany, Luxembourg (Sudan)	ND	Conventional, Whole Genome sequencing	[20]
	Sesame seeds	Processor	Germany (Nigeria)	ND		
	Sushi containing sesame	Processor	United Kingdom (U)	ND		
Salmonella *Escherichia coli*	Tahini	Retail	Lebanon	7/42 18/42	Conventional	[54]
Bacillus cereus	Sesame seeds	Retail	Japan (U)	1/6	MALDI TOF-MS	[55]
Bacillus spp.	Sesame seeds	Retail	United States of America (India, China, Mexico, Unknown)	6/10	16S rRNA amplicon sequencing	[56]

ND: Not Documented.
[a] Brackets indicate the country where samples were collected. Where no brackets are used, the country where samples were collected was the same as the country of origin of the seeds. (U): Undeclared country of origin.
[b] n/N: n, number of contaminated samples; N, Total number of samples.
[c] Country where samples were collected. Where no brackets are used, the country where samples were collected was the same as the country of origin of the seeds. (U): Undeclared country of origin.

0.70) that typically have an extended shelf life of several months [28]. Low a_w does not support the growth of pathogenic and spoilage bacteria [37]. Therefore, these foods are usually considered microbiologically safe. However, factors influencing pathogen survival in low a_w foods are poorly understood and vary among foods [38]. The oil content of sesame-based foods may protect some pathogens from preservative measures such as heat treatment and gamma irradiation during processing [39,40].

There have been several reports of imported sesame-based foods contaminated with pathogenic bacteria, notably *Salmonella,* with severe consequences, including border rejections, product recalls, and foodborne outbreaks [16,20]. Many of these products are purchased as ready-to-eat (RTE) products without a further inactivation step. Therefore, their safety is of paramount importance.

Salmonella has emerged as a significant hazard in sesame seeds and sesame-based products (Table 2) and is becoming increasingly recognised as a source of outbreaks [41]. A notable example was the 2016–2017 outbreak of salmonellosis, with 47 confirmed cases across five European countries. The causative agent was identified as a novel *Salmonella enterica* subspecies *enterica* serotype (11: z41: e,n,z15). A traceback investigation implicated sesame paste produced in Greece and sesame seeds imported from Nigeria as the vehicles of transmission [20]. More recently, the European Food Safety Authority (EFSA) reported an outbreak associated with sesame-containing products (*halva* and *tahini*) imported from Syria. In total, 135 confirmed cases from five European countries (Denmark, Germany, Netherlands, Norway, Sweden), Canada and the United States of America were infected with six *Salmonella enterica* serotypes between January 2019 and October 2021 [42]. Other outbreaks of salmonellosis linked to sesame-based foods have been reported in New Zealand [43], Australia [21,43], the United States of America [19,44], and Canada [45].

It is important to note that all these outbreaks have involved imported sesame products or raw materials, highlighting the role of the supply chain in the transmission of this microbial hazard. *Salmonella* is recognised as a significant hazard in sesame seeds imported from Africa into the EU. Fifty-six percent (56 %) of the notifications in the RASFF database arising from pathogenic organisms in foods imported into the EU between 2009 and 2019 were due to *Salmonella*-contaminated sesame seeds [16]. Similarly, *Salmonella* contamination was frequently observed in sesame seeds exported into Europe from the Asia-Pacific region between 2000 and 2020 [18]. Van Doren et al. [49] observed that almost 10 % of 229 shipments of sesame seeds imported into the United States of America within a six-month period were contaminated with *Salmonella*. Conversely, Zhang et al. [57] did not detect *Salmonella* in 527 samples of imported sesame seeds collected from retail establishments in the United States of America between 2013 and 2014. In addition, Compaore et al. [48] noted that 27 % of 359 sesame samples intended for export from Burkina Faso over a 10-year period were contaminated with *Salmonella*.

Consequently, RTE sesame seeds and associated products are regarded as high-risk foods and have been subjected to increased official controls in several countries at various times [58,59]. These findings have significant implications for producers, particularly in low- and middle-income countries, where sesame is an essential source of foreign revenue and jobs contributing to socioeconomic development [34].

The prevalence of pathogenic and indicator bacteria in retailed sesame seeds and products made from sesame has also been investigated. Willis et al. [53] studied the prevalence of *Salmonella* and *Escherichia coli* in 771 sesame seed samples collected from retail outlets in the United Kingdom. They reported 1.7 % and 1 % prevalence rates for *Salmonella* and *E. coli,* respectively. Juarez-Arana et al. [47] also observed that 12 % of sesame seeds sold in Mexican markets were contaminated with *Salmonella*. Alaouie et al. [54] also reported the presence of *Salmonella* and *E. coli* in 47 % and 43 % respectively, of *tahini* samples collected in Lebanese markets.

Contamination with enteric pathogens such as *Salmonella* is an indication of unhygienic practices during food production and storage. Sesame seeds are susceptible to microbial hazards from contaminated soil, irrigation water, livestock, equipment surfaces and human handling [25,60]. *Salmonella* can persist in soil for extended periods and be transferred to water and cultivated crops [61]. Post-harvest handling is a significant challenge in many sesame-producing countries. An important post-harvest treatment of sesame seeds is drying to reduce the moisture content of seeds and prevent spoilage during storage. In several producing countries, this process usually occurs on the farm, under the sun, or in the open, exposing sesame seeds to hazards in the farm environment [14,36]. Potential sources of enteric pathogens include contaminated aerosols or dust, manure and animal droppings, and the harvest stage, which are increasingly considered critical for *Salmonella* contamination [48,51]. Many sesame-based products such as *halva* and *tahini* undergo further processing, e.g., cooking or the addition of sugar, which should inhibit the growth of pathogens like *Salmonella*. Therefore, cross-contamination from food handlers is also a possible source of contamination where good manufacturing practices are not utilised.

Other pathogenic or indicator bacteria have been linked to products from sesame seeds. *Tahini* contaminated with *Listeria monocytogenes* has been recalled from retail outlets in New Zealand [62], and other *Listeria* species have been isolated from *hummus* [63]. In addition, survival challenge studies have shown that *L. monocytogenes* can survive in sesame seed products under various environmental conditions and should be considered a safety concern [64,65]. *Bacillus* spp. including *B. cereus,* has also been linked to retailed sesame seeds [56,55]. Compaore et al. [52] evaluated the sanitary quality of sesame seeds and sesame based RTE foods in Burkina Faso. Although they did not detect any pathogenic *Escherichia coli* or *Salmonella* in the 75 samples collected, more than 30 % of the samples did not meet the microbiological criteria for dehydrated products.

Food safety remains a significant global public health challenge. The World Health Organisation (WHO) estimates that 1 in 10 people fall ill, and over 400,000 people, mainly under the age of 5, die each year after eating contaminated food [66]. The role of food as a vehicle for the transmission of biological hazards is well documented, and in an increasingly complex and global food chain, safeguarding the health of consumers, both domestic and international, remains a crucial goal. *Salmonella* outbreaks linked to sesame are a significant public health concern. Results from large-scale surveillance studies suggest that the prevalence of pathogenic organisms in sesame is low [49,50]. However, there are only a few of these studies and surveillance data from producing countries is sparse. Many sesame-based foods are sold as RTE with a long shelf life, which may put consumers' health at risk [46].

Furthermore, more information must be provided on the microbiological quality and safety of raw and processed sesame marketed for domestic consumption in producing countries. Most reports on microbial hazards and foodborne outbreaks linked to sesame are from importing countries [48]. In addition, very few studies investigate the whole supply chain to assess and evaluate critical control points to reduce contamination (Table 2). These are significant research gaps that require further investigation.

4. Chemical hazards in sesame seeds

4.1. Mycotoxins

Mycotoxins are toxic secondary metabolites of fungal species mainly belonging to the genera *Aspergillus*, *Fusarium* and *Penicillium*. These natural contaminants of food and feed are a growing public health concern, especially in low and middle-income countries [67–70]. The most widely recognised classes of mycotoxins of concern are aflatoxins (AF), ochratoxin A (OTA), fumonisins, deoxynivalenol (DON) and other trichothecenes, and zearalenone (ZEA) [71–73].

Aspergillus flavus and *A. parasiticus* are the primary producers of aflatoxins [74]. Aflatoxin B_1 (AFB_1) is considered the most toxic and has been classified as a Group 1 carcinogen by the International Agency for Research on Cancer [76]. Contamination with multiple mycotoxins occurs frequently and can lead to severe health problems for consumers as the cytotoxic effects can impair the function of several organs, such as the liver and kidney, as well as the immune and nervous systems [77,78]. Chronic exposure to mycotoxins has also been associated with childhood stunting [79,80].

The frequent isolation of fungal species which have the potential to produce mycotoxins, particularly during the storage of sesame seeds, is a cause for concern. *Aspergillus flavus* and *Fusarium* spp. were reported as the dominant fungi in retailed sesame seeds in

Table
3Occurrence and contamination level of mycotoxins in sesame seeds and sesame-based products.

Sesame product	Mycotoxin type[a]	Samples (N)	Positive samples (n)	Number of samples > MTL[b]	Mean (μg/kg)	Range (μg/kg)	Analytical method[c]	Country	Reference
Harvested seeds	AFB_1	100	92	24	21.6	1.2–60	TLC	Pakistan	[82]
Stored seeds	AFB_1	100	99	80	30.6	15–60			
Seeds	AF	46	23	7	13.67	0.79–60.5	Scanning densitometer	Nigeria	[81]
Seeds	AFB_1	182	33	9	1.62		HPLC	Iran	[96]
Seeds (Black)	AF	955	203			0.2–16	TLC	Myanmar	[87]
Seeds (White)	AF	110	35			0.3–7			
Seeds	AF	30	10	5	2.95	0.9–61.8	ELISA	Uganda	[97]
	OTA	30	26	1	1.45	0.1–3.1			
	DON	30	21		194.4	0.8–955.3			
Seeds	AFB_1	96	96	96	6.36	3.95–11.75	HPLC	Nigeria	[98]
Seeds	AF	59	7	5	16.9	0.29–88.5	LC-MS/MS	Nigeria	[94]
	FB_1	59	4		13.0	5.60–24.0			
Seeds	DON	17	15		28	8–76	LC-MS/MS	Nigeria	[84]
Seeds	AFB_1	24	3		3.6	0.4–7.2	LC-MS/MS	Nigeria	[22]
	FB_1	24	5		17.3	7.3–26.7			
	DON	24	14		78.3	28–171			
Sesame product	Mycotoxin type[a]	Samples (n)	Positive samples	Number of samples > MTL[b]	Mean (μg/kg)	Range (μg/kg)	Analytical method[c]	Country	Reference
Seeds	AF	40	22	15	1.95		HPLC	Iran	[99]
Tahini	AF	40	18	14	1.10				
Tahini halva	AF	40	13	11	0.72				
Seeds	AF	269	136	8	1.43	0.4–48.18	HPLC	Iran	[93]
Seeds, Tahini, Tahini halva, Sesame bars	AFB_1	30	23	8		0.1–8.6	HPLC	Greece	[100]
Paste	AFB_1	100	37	12	4.31	0.39–20.45	Fluorimetry, LC	China	[101]
	AF			9	6.75	0.54–56.89			
Seeds	OTA	19	19	13	8.14	1.90–15.66	HPLC	Nigeria	[102]
Seeds	AFB_1	200	10	10	1.44	0.84–2.17	LC-MS/MS	Thailand	[23]
	BEA		35		8.89	1.39–37.8			
Seeds	AFB_1	8	7		0.90	0.54–1.82	ELISA	Malaysia	[103]
Seeds	AFB_1	28	25	25	33.7		HPLC	Egypt	[104]
Tahini	AFB_1	117	39	25	6.55	0.2–238.1	HPLC	Egypt	[105]
Seeds	AFB_1	47	5			0.6–2.4	HPTLC	Japan	[92]

(−): Data not available.
[a] **AF**: Total Aflatoxin; **AFB_1:** Aflatoxin B_1; **BEA**: Beauvericin; **DON**: Deoxynivalenol; **FB_1**: Fumonisin B_1; **OTA**: Ochratoxin A.
[b] **MTL**: Maximum Tolerable Limit based on European Commission (EC, 2006) regulations for Total AF (4 μg/kg), AFB_1 (2 μg/kg), OTA (5 μg/kg).
[c] **HPLC**: High-Performance Liquid chromatography; **HPTLC**: High-Performance Thin Layer Chromatography; **LC**: Liquid chromatography; **MS**: Mass spectrophotometry; **TLC**: Thin Layer Chromatography.

Nigeria [81]. Ajmal et al. [82] reported an increase in the prevalence of *Aspergillus flavus* and the concentration of aflatoxins during the storage of sesame seeds.

Sesame seeds are susceptible to fungal contamination at different stages of production and processing. The farm environment can be a source of fungal spores. Post-harvest storage of sesame seeds is common as sesame cultivation is seasonal, and storage provides supply between harvests or before seeds can be exported [35,83]. The storage period can range from a few weeks to several months [84]. Harvested produce is usually stored in non-hermetic packaging and non-climate-controlled facilities, which can support microbial growth. Temperature and water activity are the major extrinsic factors influencing fungal growth and mycotoxin production in food [85,86]. Storage at high humidity may increase water activity. Many sesame-producing countries are in tropical regions, and the warmer temperatures may provide suitable conditions for any fungal spores in the seeds to germinate during storage, thus producing mycotoxins [82,87,88].

Exposure to mycotoxins in food and feed is a major issue for human and animal health, nutrition, and the food trade [89]. International, regional, and national agencies have set maximum tolerable limits (MTLs) for mycotoxins in food to mitigate dietary exposure to mycotoxins and safeguard public health. For example, the European Commission has maximum levels for AFB_1, total aflatoxins and ochratoxin A at 2, 4 and 5 μg/kg, respectively [90], while the United States Food and Drug Administration (U.S. FDA) recommends a maximum limit of 20 μg/kg for aflatoxins in foods intended for human consumption [91].

Several studies have reported a low prevalence of mycotoxins in sesame (Table 3). Ezekiel et al. [84] demonstrated that no detectable aflatoxins or fumonisins were present in sesame seeds collected from farmers (stored for less than 30 days after harvest) in Nigeria. These seeds also complied with international standards for regulated mycotoxins. These data corroborate results by Pongpraket et al. [23], where only 2 out of 200 (1 %) samples of retailed sesame seeds in Thailand were above the European Commission (EC) regulatory limits for aflatoxins. Tabata et al. [92] observed aflatoxins in 5 of 47 (10.6 %) sesame samples in Japan, noting concentrations of AFB_1 between 0.6 and 2.4 μg/kg. Similarly, Hosseininia et al. [93] observed that 50 % of 269 samples from five shipments of sesame seeds imported into Iran contained less than 1 μg/kg of total aflatoxins. Esan et al. [94] reported a prevalence of 12 % and 7 % for total aflatoxins and Fumonisin B_1, respectively, in sesame samples collected from retail markets in Nigeria. Ochratoxin A (OTA) was not detected in any of the samples in the study. It should be noted that in most of these studies, only specific mycotoxins were investigated. The full spectrum of mycotoxins and fungal metabolites in food products must be determined to accurately assess dietary mycotoxin exposure from consuming such foods. Furthermore, consuming foods contaminated with multiple mycotoxins, even at low concentrations over a prolonged period, may pose a health risk due to the possible synergistic effects of metabolite combinations [72,95].

An analysis of aflatoxin contamination in sesame seeds in this report has shown that contaminated samples at the retail or household level regularly exceed regulatory limits (Table 3). Elaigwu et al. [98] observed concentrations of AFB_1 above 2 μg/kg in all sesame seed samples (n = 96) collected in Nigeria. Heshmati et al. [99] reported that 25 % of sesame seeds from the Iranian market were contaminated with AFB_1 above the EC ML. In the same study, 18 % and 15 % of *tahini* and *tahini-halva* samples, respectively, were above the EC ML for AFB_1. Overall, 38 %, 35 % and 11 % of the sesame seeds, *tahini,* and *tahini-halva* samples contained total aflatoxins above the EC limit. A study in China investigating the occurrence of aflatoxins in sesame paste collected from both small-scale and industrial manufacturers noted that 37 % of the samples were contaminated with AFB_1. The maximum AFB_1 concentration recorded was 20.45 μg/kg, and 12 % of samples had concentrations above 2 μg/kg [101]. Echodu et al. [97] observed that 13 % of sesame seed samples collected from households in Northern Uganda exceeded the EC ML for aflatoxins. In *tahini* samples from Egypt, 21 % exceeded the Egyptian ML of 2 μg/kg [105].

Ochratoxin has been demonstrated to be genotoxic and carcinogenic in animals with the kidney as the primary target organ, and it is classified as a Group 2B possible carcinogen [106,107]. There are few reports of OTA contamination of sesame seeds. Makun et al. [102] investigated the prevalence of OTA in sesame samples from Nigeria. They reported that all sesame seed samples in their study (n = 19) were contaminated with OTA, and EC limits were exceeded in 13 % of the samples. This contrasts with Echodu et al. [97], where only 3 % of collected samples had OTA concentrations exceeding EC limits.

Only a few major producing countries have set regulatory limits for mycotoxins, specifically for sesame seeds and products, and where these exist, focus on international trade [108]. In addition to potential risks to consumer health, mycotoxin contamination of sesame seeds could have severe economic consequences due to border rejections and recalls.

4.2. Pesticides

Controlling the growth of microorganisms and pests in sesame is critical for improving food quality and safety. Some previously used biological control methods for reducing microbial hazards in harvested sesame include irradiation, fumigation with carbon dioxide (CO_2) or propylene oxide, and the addition of salts [25,109]. Furthermore, plant protection products, such as pesticides, are used at different stages of cultivation to reduce post-harvest losses due to pest infestation and pathogens. However, there is growing concern about the potential adverse effects of pesticide residues on consumers and the environment [110,111].

Recently, global attention was drawn to the issue of pesticide contamination due to consumer exposure to ethylene oxide after its detection in sesame seeds imported into Europe from India in 2020 [112]. The use of ethylene oxide as a plant protection product is not approved in the EU as it has been classified as a Group 1 carcinogen [113]. However, ethylene oxide was detected at over 1000 times the maximum residue level (MRL) of 0.05 mg/kg [114,115]. This incident led to an unprecedented recall and withdrawal of sesame-based foods across the Member States and non-EU Member States [24]. As a result, new legislation has been implemented to increase import controls on sesame originating from India [15].

Between January 2020 and March 2024, there were 419 notifications regarding pesticide residues in sesame seeds in the EU RASFF system. Most of the notifications concerned sesame seeds originating from India (349, 83.3 %). The main contaminant was ethylene oxide (312 out of 349) and its derivatives, 2-chloroethanol, chlorate and iprobenfos. There have been reduced notifications from India since 2020 (262 notifications in 2020, 78 notifications in 2021, 8 notifications in 2022 and 1 notification in 2023). This is probably because of the increased frequency of checks and import control by importing countries. As of April 2024, there are only 5 notifications regarding pesticide residues in sesame seeds entering the EU for 2024. Four of the notifications were from Nigeria, with Chlorpyrifos (more than two times the MRL) and Chlorate (more than 8 times the MRL) reported in sesame seeds from Nigeria [116].

Some pesticide residues, including lindane, chlorpyriphos, and metalaxyl, have been observed in sesame seeds and oil [117,118]. Pesticide residues are not only found in the sesame seeds but could also be carried over into the processed products. For example, ethylene oxide was detected in caramelised nuts made with sesame seeds from Nigeria [119], in baking mixes made with sesame seeds from India [120], in spice mixes made with sesame seeds from India [121] and in bread baking mixes made with sesame seeds from India [122]. A residue of ethylene oxide, 2-chloroethane, was also detected in baking mixes made with sesame seeds from Nigeria [123].

The presence and persistence of pesticides in sesame seeds and their products raise the urgent need for research and development of alternative pest control strategies. This will eliminate the need to use these unsafe chemicals in foods. Furthermore, there have been repeated notifications of ethylene oxide in sesame seeds imported into the EU. This suggests a need for continuous monitoring and surveillance of these chemicals in sesame seeds and their products. This is particularly important in producing countries for which there is limited data.

4.3. Allergens

Sesame allergy is a growing concern as it triggers hypersensitivities that lead to symptoms including vomiting, diarrhoea, contact dermatitis and systematic anaphylaxis [124,125]. Sesame allergens have been classified into three major groups: lipid, protein, and unknown allergens [126]. Protein allergens are classified into eight groups, *Ses i* 1 to *Ses i* 8 and are associated with IgE-mediated immediate hypersensitivity reactions. Lipid allergens initiate both immediate (seeds) and delayed (oil) hypersensitivity reactions [127].

Reports on the prevalence of sesame allergies globally vary widely from about 0.1 % to 0.8 %, as this depends on how much sesame is consumed within the local diet [125,128,129]. Sesame has been recognised as a source of food allergens in the Middle East, where it is used extensively in the diet. Sesame ranked third as the most common food allergy after eggs and milk in Israeli children [126]. A study in Saudi Arabia noted that sesame was the third most common cause of anaphylaxis, accounting for 15 % of cases prescribed antihistamines over a 2-year period [130]. In Turkey, an estimated 20 % of children with food allergies are allergic to sesame [131]. However, sesame allergies are reported in several other parts of the world. For example, although sesame-induced anaphylaxis rates were reported to be higher in the Middle East than in North America [132], sesame allergy is a substantial burden in the United States. An estimated 0.49 % of the population report a current sesame allergy, and 17 % of children with an IgE-mediated food allergy are estimated to have a sesame allergy [133,134]. Consequently, it is thought that the burden of sesame allergies may be higher than reported [135].

Several countries have established regulatory food labelling on products containing sesame to protect consumers and reduce the risk of unintentional exposure to sesame allergens. Since 2023, it has been required by law in the United States to label sesame as an allergen on food and dietary supplement packaging. This requirement also exists in the European Union, Canada, Australia, New Zealand, and other parts of the world [136]. In addition, a joint FAO-WHO Expert Committee recommended that sesame be considered a priority allergen [137].

There is scarce information on the prevalence of sesame allergies and their regulation in many sesame-producing countries worldwide, particularly those in Africa. This could be because sesame seeds are produced for export rather than local consumption. However, it has also been noted that there are significant data gaps on food allergens in many low-resource countries that bear a significant burden of other food-related challenges, e.g., malnutrition [138].

As observed with microbial hazards, there is limited information on the prevalence and human health risks of chemical hazards in sesame seeds and sesame-based products. Inadequate food safety and quality regulatory and monitoring systems and a lack of public awareness are important limitations in many producing countries [87,97]. To address this critical food safety issue, a better understanding of the routes of contamination of sesame seeds and routine surveillance in producing countries is required. This will serve as a baseline for developing evidence-based strategies for risk assessment and identifying intervention strategies to reduce exposure to these hazards.

5. Discussion and recommendations

Sesame seeds have high economic value and immense potential in enabling producing countries to achieve Sustainable Development Goals focused on poverty alleviation and food security. Sesame is mainly grown as an export crop in producing countries, providing employment and income for producers and processors. While the global sesame market is anticipated to grow [139], compliance with food safety regulations remains a significant barrier to the international trade of sesame seeds. Some major hazards affecting the sesame seed trade identified in this review include *Salmonella* mycotoxins and pesticide residues.

Currently, there is a limited understanding of which stages of sesame production and processing are most vulnerable to contamination. Many studies investigating the occurrence of hazards in sesame focus on the storage and retail stages of the value chain. During production, contaminants can be introduced through pollution from the farm environment, the use of contaminated soil amendments, irrigation water and pesticide use [140]. Further contamination could occur due to poor harvesting, drying, storage and transportation practices and unhygienic conditions during the processing and retail stages [98,141].

There is a dearth of data from sesame-producing countries describing the link between local agricultural practices, particularly at the pre-harvest stage, and the occurrence of microbial and chemical hazards in sesame. Although some good agricultural practices have been recommended to improve the quality of sesame seeds [142], systematic investigations are needed to identify the critical points where contamination occurs in the value chain. This information is important to better target control strategies to minimise the contamination of sesame. This will contribute to food security for many smallholder farmers in producing countries and overall food safety for consumers.

Research could also focus on infrastructural interventions such as alternative drying procedures and hermetic technologies for seed storage [142,143]. In humid climates, in addition to drying, seeds need to be packed in moisture-proof packaging to prevent rehydration [144]. Hermetic technologies such as the Purdue Improved Crop Storage [145] and Super Grain Pro [146] are moisture-proof and prevent oxygen from getting into the seeds. Microorganisms and pests require oxygen for respiration; therefore, oxygen concentrations are reduced to concentrations which cannot support their growth [144]. This is particularly important as conditions that support fungal growth will lead to mycotoxin contamination. In addition, better pest control reduces the need for the use and abuse of pesticides. Consequently, hermetic packaging has been promoted in many low-resource, tropical countries to reduce post-harvest losses of several crops [147,148]. There are relatively few studies exploring the use of hermetic packaging for sesame seed storage

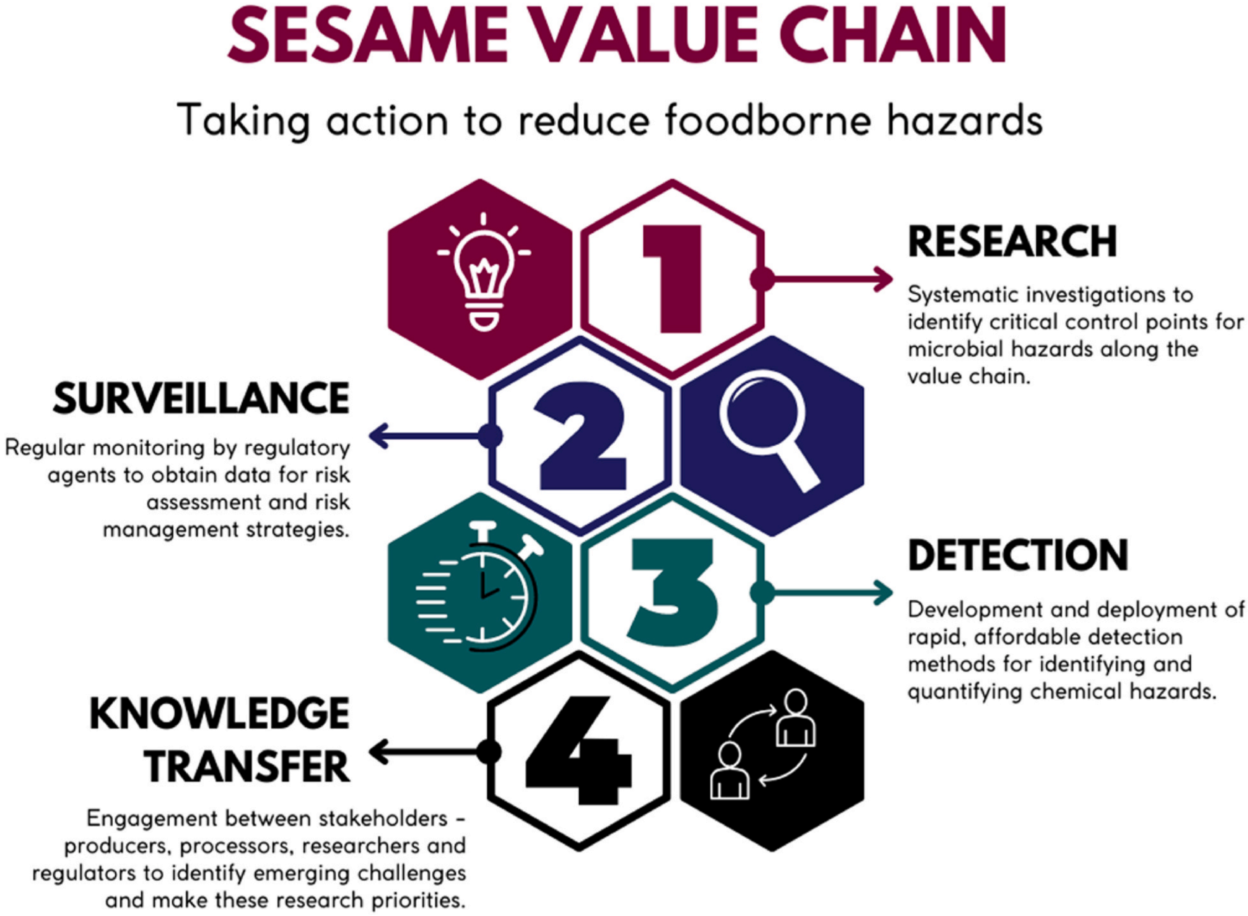

Fig. 4. Recommendations for reducing microbial and chemical hazards in the sesame value chain.

that focus on microbial hazards [143]. Sesame seeds stored in hermetic bags had lower levels of fungal infestation and mycotoxins compared to standard packaging in polypropylene and jute bags over a six-month storage period [149]. The effect of environmental factors, storage periods and affordable packaging technologies on sesame safety and quality is an important research priority in producing countries.

Regular surveillance is required to detect contamination sources and measure the effectiveness of mitigation strategies for mycotoxin contamination. For pesticides in sesame seeds, there is a need to conduct a risk assessment of their presence in sesame seeds and how these are carried over to sesame-based products. Furthermore, it is essential to develop and employ novel rapid detection methods for determining contaminants across the value chain to mitigate post-harvest and economic losses where possible. Alternative pest management strategies, which are sustainable and environmentally-friendly, should be developed and deployed to avoid using unapproved pesticides in the sesame seed value chain.

The safety of sesame seeds for domestic consumption must also be prioritised as a research need in producing countries. Knowledge transfer between researchers, producers, and processors of sesame seeds on food safety is essential. This will give producers and processors the knowledge and tools to produce sesame seeds that meet the food safety requirements for local consumption and the international market. Researchers should regularly network with stakeholders in the sesame seeds value chain to identify emerging food safety challenges and make these research priorities for action (Fig. 4).

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Data availability

All data to support the conclusions in this review have been provided in the manuscript.

CRediT authorship contribution statement

Amarachukwu Anyogu: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Conceptualization. **Yinka M. Somorin:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Abigail Oluseye Oladipo:** Writing – original draft. **Saki Raheem:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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