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

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

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33 **Research Highlights**

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- Foodborne hazards are a major barrier to the global trade of sesame seeds.

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- *Salmonella* and mycotoxins are major hazards in imported sesame seeds.

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- Pesticide contamination of sesame is an emerging concern.

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- Limited knowledge of hazards in sesame seeds for domestic consumption.

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- The safety of sesame along the value chain is an urgent research priority.

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75 **ABSTRACT**

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

97 **Keywords:** Food safety, mycotoxins, pesticides, *Salmonella*, *Sesamum indicum*, value  
98 chain

99 **1. Introduction**

100 Sesame (*Sesamum indicum*) is an ancient oilseed crop mainly cultivated for its edible  
101 seeds from which oil is produced [1]. Sesame seeds comprise up to 60% oil, the highest  
102 content of all major oilseed crops [2,3]. Sesame is a functional food as it is a source of  
103 nutritional and nutraceutical components. Sesame oil is a rich source of  
104 polyunsaturated fatty acids (PUFA), such as oleic and linolenic acids [4, 5]. Sesame is  
105 also an excellent source of proteins, carbohydrates, vitamins, and minerals, including  
106 phosphorus, manganese, copper, and iron [6]. Recent studies have reported that  
107 sesame is an important natural food source of phytosterols (3 – 8 mg/g), melatonin  
108 (0.04 to 298.62 ng/g) and tocopherols (530 – 1000 mg/kg) [7 - 9]. In addition, lignans  
109 such as sesamin, sesamol, sesamolin, and sesaminol are another major group of  
110 bioactive compounds found in sesame [9]. These components are associated with  
111 various biological and pharmacological activities, including antioxidant, anti-  
112 inflammatory, cardioprotective, anticancer and anti-neurodegenerative effects [10].  
113 Consequently, sesame has diverse uses across the food, cosmetic and pharmaceutic  
114 industries, and increased demand is driving the growth of the sesame market. The  
115 mainstreaming of indigenous foods and ingredients such as *hummus*, *tahini*, and *halva*,  
116 particularly in Western diets, have contributed to the increasing demand for sesame  
117 seeds [11]. Sesame oil has pleasant sensorial characteristics, and the presence of  
118 antioxidants confers increased resistance to rancidity compared to other oils [4, 6]. In  
119 addition, different applications of sesame include soap and cosmetic production and  
120 as a delivery vehicle for fat-soluble drugs [12, 13].  
121 The top producers of sesame are in Africa and Asia, where sesame significantly  
122 contributes to the local economy through job creation and foreign exchange revenue [1,

123 14]. However, microbial and chemical hazards in this commodity constitute a  
124 significant barrier to the global trade of sesame seeds [15, 16]. *Salmonella* spp. and  
125 mycotoxin contamination are frequently reported in sesame and sesame-based  
126 products. *Salmonella* spp. and mycotoxins were the most significant hazards in the  
127 “nuts, nut products and seeds” category in foods exported into the European Union  
128 (EU) in 2018 and 2019 [17]. Recent reports have also highlighted the scale of  
129 *Salmonella* contamination in sesame imported into the EU [16, 18]. In addition,  
130 outbreaks of salmonellosis associated with sesame and sesame-related products have  
131 been reported worldwide [19 - 21]. Sesame seeds contaminated with mycotoxins have  
132 been observed at different stages of the value chain, suggesting this is a widespread  
133 problem [22, 23]. Pesticides are also an emerging concern. In September 2020, sesame  
134 seeds contaminated with ethylene oxide were reported to the EU’s Rapid Alert System  
135 for Food and Feed (RASFF). This major incident led to several recalls and withdrawals of  
136 sesame-containing foods across Europe [24]. Sesame seeds often serve as ingredients  
137 in a wide variety of products. Therefore, the presence of hazards in sesame can have  
138 severe and widespread health and economic consequences.

139 Sesame can be exposed to various contaminants at all stages of the value chain. Poor  
140 agricultural practices during cultivation, harvesting and storage can allow for microbial  
141 and chemical contamination of sesame seeds [25]. Furthermore, the warm and humid  
142 conditions characteristic of tropical and subtropical regions where sesame is grown  
143 may also create an optimal environment for the growth of foodborne pathogens or the  
144 production of microbial toxins, further exacerbating the problem [22].

145 Several reviews discussing sesame have been published. However, these mainly focus  
146 on single aspects such as nutritional or nutraceutical components [4, 9, 26] or

147 economic value [1, 27] to producing countries. Olaimat et al. [28] reviewed the  
148 microbial safety of oil-based food products but focused on foodborne pathogens.  
149 However, no comprehensive overview of microbial and chemical contamination is  
150 focused explicitly on sesame and sesame-based products. Therefore, this review is  
151 necessary to summarise current knowledge on the safety of sesame-based foods. It  
152 also highlights data gaps for future research and suggests interventions to strengthen  
153 the sesame value chain.

## 154 **2. The global sesame seed market and value chain**

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

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

165 In producing countries, sesame is gaining recognition as a high-value export crop. Over  
166 2.0 million tonnes of unprocessed sesame seeds, valued at USD 3 billion, were traded  
167 globally in 2022 [30]. In Nigeria, almost 70% of domestic sesame production was  
168 exported in 2022 (Table 1), and sesame seeds are the third most valuable export  
169 product after cocoa and herbs [31]. In addition, Ethiopia, Chad, and India exported  
170 60%, 35%, and 30% of their cultivated sesame in 2022 (Table 1). Asia and Europe are

171 the primary destinations for sesame seeds (Figure 2). China, Turkey, and Japan are the  
172 largest importers of sesame seeds, accounting for about 56% (almost 1.2 million  
173 tonnes) of global imports, valued at nearly USD 1.9 billion [30]. The European Union  
174 (EU) is also a growing market for imported sesame seeds primarily used in the food  
175 industry to supplement local production [11]. Consequently, sesame is gaining  
176 attention as a priority crop, and increasing production has become the focus of many  
177 national and international efforts [1, 13, 32, 33].

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

### 190 **3. *Salmonella* and other microbial hazards in sesame seeds and associated** 191 **products**

192 Sesame seeds and sesame seed products such as *tahini* (sesame paste) and *halva* are  
193 classified as low water activity ( $a_w$ ) foods ( $a_w < 0.70$ ) that typically have an extended  
194 shelf life of several months [28]. Low  $a_w$  does not support the growth of pathogenic and

195 spoilage bacteria [37]. Therefore, these foods are usually considered microbiologically  
196 safe. However, factors influencing pathogen survival in low  $a_w$  foods are poorly  
197 understood and vary among foods [38]. The oil content of sesame-based foods may  
198 protect some pathogens from preservative measures such as heat treatment and  
199 gamma irradiation during processing [39, 40].

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

204 Therefore, their safety is of paramount importance.

205 *Salmonella* has emerged as a significant hazard in sesame seeds and sesame-based  
206 products (Table 2) and is becoming increasingly recognised as a source of outbreaks  
207 [41]. A notable example was the 2016-2017 outbreak of salmonellosis, with 47

208 confirmed cases across five European countries. The causative agent was identified as  
209 a novel *Salmonella enterica* subspecies *enterica* serotype (11: z41: e,n,z15). A

210 traceback investigation implicated sesame paste produced in Greece and sesame  
211 seeds imported from Nigeria as the vehicles of transmission [20]. More recently, the

212 European Food Safety Authority (EFSA) reported an outbreak associated with sesame-  
213 containing products (*halva* and *tahini*) imported from Syria. In total, 135 confirmed

214 cases from five European countries (Denmark, Germany, Netherlands, Norway,

215 Sweden), Canada and the United States of America were infected with six *Salmonella*  
216 *enterica* serotypes between January 2019 and October 2021 [42]. Other outbreaks of

217 salmonellosis linked to sesame-based foods have been reported in New Zealand [43],

218 Australia [21, 43], the United States of America [19, 44], and Canada [45].

219 It is important to note that all these outbreaks have involved imported sesame products  
220 or raw materials, highlighting the role of the supply chain in the transmission of this  
221 microbial hazard. *Salmonella* is recognised as a significant hazard in sesame seeds  
222 imported from Africa into the EU. Fifty-six percent (56%) of the notifications in the  
223 RASFF database arising from pathogenic organisms in foods imported into the EU  
224 between 2009 and 2019 were due to *Salmonella*-contaminated sesame seeds [16].  
225 Similarly, *Salmonella* contamination was frequently observed in sesame seeds  
226 exported into Europe from the Asia-Pacific region between 2000 and 2020 [18]. Van  
227 Doren et al. [46] observed that almost 10% of 229 shipments of sesame seeds imported  
228 into the United States of America within a six-month period were contaminated with  
229 *Salmonella*. Conversely, Zhang et al. [47] did not detect *Salmonella* in 527 samples of  
230 imported sesame seeds collected from retail establishments in the United States of  
231 America between 2013 and 2014. In addition, Compaore et al. [48] noted that 27% of  
232 359 sesame samples intended for export from Burkina Faso over a 10-year period were  
233 contaminated with *Salmonella*.

234 Consequently, RTE sesame seeds and associated products are regarded as high-risk  
235 foods and have been subjected to increased official controls in several countries at  
236 various times [49, 50]. These findings have significant implications for producers,  
237 particularly in low- and middle-income countries, where sesame is an essential source  
238 of foreign revenue and jobs contributing to socioeconomic development [34].

239 The prevalence of pathogenic and indicator bacteria in retailed sesame seeds and  
240 products made from sesame has also been investigated. Willis et al. [51] studied the  
241 prevalence of *Salmonella* and *Escherichia coli* in 771 sesame seed samples collected  
242 from retail outlets in the United Kingdom. They reported 1.7% and 1% prevalence rates

243 for *Salmonella* and *E. coli*, respectively. Juarez-Arana et al. [52] also observed that 12%  
244 of sesame seeds sold in Mexican markets were contaminated with *Salmonella*. Alaouie  
245 et al. [53] also reported the presence of *Salmonella* and *E. coli* in 47% and 43%  
246 respectively, of *tahini* samples collected in Lebanese markets.

247 Contamination with enteric pathogens such as *Salmonella* is an indication of  
248 unhygienic practices during food production and storage. Sesame seeds are  
249 susceptible to microbial hazards from contaminated soil, irrigation water, livestock,  
250 equipment surfaces and human handling [25, 54]. *Salmonella* can persist in soil for  
251 extended periods and be transferred to water and cultivated crops [55]. Post-harvest  
252 handling is a significant challenge in many sesame-producing countries. An important  
253 post-harvest treatment of sesame seeds is drying to reduce the moisture content of  
254 seeds and prevent spoilage during storage. In several producing countries, this process  
255 usually occurs on the farm, under the sun, or in the open, exposing sesame seeds to  
256 hazards in the farm environment [14, 36]. Potential sources of enteric pathogens  
257 include contaminated aerosols or dust, manure and animal droppings, and the harvest  
258 stage, which are increasingly considered critical for *Salmonella* contamination [48, 56].  
259 Many sesame-based products such as *halva* and *tahini* undergo further processing,  
260 e.g., cooking or the addition of sugar, which should inhibit the growth of pathogens like  
261 *Salmonella*. Therefore, cross-contamination from food handlers is also a possible  
262 source of contamination where good manufacturing practices are not utilised.

263 Other pathogenic or indicator bacteria have been linked to products from sesame  
264 seeds. *Tahini* contaminated with *Listeria monocytogenes* has been recalled from retail  
265 outlets in New Zealand [57], and other *Listeria* species have been isolated from  
266 *hummus* [58]. In addition, survival challenge studies have shown that *L.*

267 *monocytogenes* can survive in sesame seed products under various environmental  
268 conditions and should be considered a safety concern [59, 60]. *Bacillus* spp. including  
269 *B. cereus*, has also been linked to retailed sesame seeds [61, 62]. Compaore et al. [63]  
270 evaluated the sanitary quality of sesame seeds and sesame based RTE foods in Burkina  
271 Faso. Although they did not detect any pathogenic *Escherichia coli* or *Salmonella* in the  
272 75 samples collected, more than 30% of the samples did not meet the microbiological  
273 criteria for dehydrated products.

274 Food safety remains a significant global public health challenge. The World Health  
275 Organisation (WHO) estimates that 1 in 10 people fall ill, and over 400,000 people,  
276 mainly under the age of 5, die each year after eating contaminated food [64]. The role of  
277 food as a vehicle for the transmission of biological hazards is well documented, and in  
278 an increasingly complex and global food chain, safeguarding the health of consumers,  
279 both domestic and international, remains a crucial goal. *Salmonella* outbreaks linked  
280 to sesame are a significant public health concern. Results from large-scale surveillance  
281 studies suggest that the prevalence of pathogenic organisms in sesame is low [46, 65].  
282 However, there are only a few of these studies and surveillance data from producing  
283 countries is sparse. Many sesame-based foods are sold as RTE with a long shelf life,  
284 which may put consumers' health at risk [66].

285 Furthermore, more information must be provided on the microbiological quality and  
286 safety of raw and processed sesame marketed for domestic consumption in producing  
287 countries. Most reports on microbial hazards and foodborne outbreaks linked to  
288 sesame are from importing countries [48]. In addition, very few studies investigate the  
289 whole supply chain to assess and evaluate critical control points to reduce

290 contamination (Table 2). These are significant research gaps that require further  
291 investigation.

## 292 **4. Chemical Hazards in Sesame Seeds**

### 293 **4.1 Mycotoxins**

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

300 *Aspergillus flavus* and *A. parasiticus* are the primary producers of aflatoxins [74].

301 Aflatoxin exposure can lead to acute aflatoxicosis, and long-term exposure is a risk  
302 factor for hepatocellular carcinoma [75]. Aflatoxin B<sub>1</sub> (AFB<sub>1</sub>) is considered the most  
303 toxic and has been classified as a Group 1 carcinogen by the International Agency for  
304 Research on Cancer [76]. Contamination with multiple mycotoxins occurs frequently  
305 and can lead to severe health problems for consumers as the cytotoxic effects can  
306 impair the function of several organs, such as the liver and kidney, as well as the  
307 immune and nervous systems [77, 78]. Chronic exposure to mycotoxins has also been  
308 associated with childhood stunting [79, 80].

309 The frequent isolation of fungal species which have the potential to produce  
310 mycotoxins, particularly during the storage of sesame seeds, is a cause for concern.  
311 *Aspergillus flavus* and *Fusarium* spp. were reported as the dominant fungi in retailed  
312 sesame seeds in Nigeria [81]. Ajmal et al. [82] reported an increase in the prevalence of

313 *Aspergillus flavus* and the concentration of aflatoxins during the storage of sesame  
314 seeds.

315 Sesame seeds are susceptible to fungal contamination at different stages of  
316 production and processing. The farm environment can be a source of fungal spores.  
317 Post-harvest storage of sesame seeds is common as sesame cultivation is seasonal,  
318 and storage provides supply between harvests or before seeds can be exported [35,  
319 83]. The storage period can range from a few weeks to several months [84]. Harvested  
320 produce is usually stored in non-hermetic packaging and non-climate-controlled  
321 facilities, which can support microbial growth. Temperature and water activity are the  
322 major extrinsic factors influencing fungal growth and mycotoxin production in food [85,  
323 86]. Storage at high humidity may increase water activity. Many sesame-producing  
324 countries are in tropical regions, and the warmer temperatures may provide suitable  
325 conditions for any fungal spores in the seeds to germinate during storage, thus  
326 producing mycotoxins [82, 87, 88].

327 Exposure to mycotoxins in food and feed is a major issue for human and animal health,  
328 nutrition, and the food trade [89]. International, regional, and national agencies have  
329 set maximum tolerable limits (MTLs) for mycotoxins in food to mitigate dietary exposure  
330 to mycotoxins and safeguard public health. For example, the European Commission  
331 has maximum levels for AFB<sub>1</sub>, total aflatoxins and ochratoxin A at 2, 4 and 5 µg/kg,  
332 respectively [90], while the United States Food and Drug Administration (U.S. FDA)  
333 recommends a maximum limit of 20 µg/kg for aflatoxins in foods intended for human  
334 consumption [91].

335 Several studies have reported a low prevalence of mycotoxins in sesame (Table 3).  
336 Ezekiel et al. [84] demonstrated that no detectable aflatoxins or fumonisins were

337 present in sesame seeds collected from farmers (stored for less than 30 days after  
338 harvest) in Nigeria. These seeds also complied with international standards for  
339 regulated mycotoxins. These data corroborate results by Pongpraket et al. [23], where  
340 only 2 out of 200 (1%) samples of retailed sesame seeds in Thailand were above the  
341 European Commission (EC) regulatory limits for aflatoxins. Tabata et al. [92] observed  
342 aflatoxins in 5 of 47 (10.6%) sesame samples in Japan, noting concentrations of AFB<sub>1</sub>  
343 between 0.6 – 2.4 µg/kg. Similarly, Hosseininia et al. [93] observed that 50% of 269  
344 samples from five shipments of sesame seeds imported into Iran contained less than 1  
345 µg/kg of total aflatoxins. Esan et al. [94] reported a prevalence of 12% and 7% for total  
346 aflatoxins and Fumonisin B<sub>1</sub>, respectively, in sesame samples collected from retail  
347 markets in Nigeria. Ochratoxin A (OTA) was not detected in any of the samples in the  
348 study. It should be noted that in most of these studies, only specific mycotoxins were  
349 investigated. The full spectrum of mycotoxins and fungal metabolites in food products  
350 must be determined to accurately assess dietary mycotoxin exposure from consuming  
351 such foods. Furthermore, consuming foods contaminated with multiple mycotoxins,  
352 even at low concentrations over a prolonged period, may pose a health risk due to the  
353 possible synergistic effects of metabolite combinations [72, 95].

354 An analysis of aflatoxin contamination in sesame seeds in this report has shown that  
355 contaminated samples at the retail or household level regularly exceed regulatory  
356 limits (Table 3). Elaigwu et al. [96] observed concentrations of AFB<sub>1</sub> above 2 µg/kg in all  
357 sesame seed samples (n=96) collected in Nigeria. Heshmati et al. [97] reported that  
358 25% of sesame seeds from the Iranian market were contaminated with AFB<sub>1</sub> above the  
359 EC ML. In the same study, 18% and 15% of *tahini* and *tahini-halva* samples,  
360 respectively, were above the EC ML for AFB<sub>1</sub>. Overall, 38%, 35% and 11% of the sesame

361 seeds, *tahini*, and *tahini-halva* samples contained total aflatoxins above the EC limit. A  
362 study in China investigating the occurrence of aflatoxins in sesame paste collected  
363 from both small-scale and industrial manufacturers noted that 37% of the samples  
364 were contaminated with AFB<sub>1</sub>. The maximum AFB<sub>1</sub> concentration recorded was 20.45  
365 µg/kg, and 12% of samples had concentrations above 2 µg/kg [98]. Echodu et al. [99]  
366 observed that 13% of sesame seed samples collected from households in Northern  
367 Uganda exceeded the EC ML for aflatoxins. In *tahini* samples from Egypt, 21% exceeded  
368 the Egyptian ML of 2 µg/kg [100].

369 Ochratoxin has been demonstrated to be genotoxic and carcinogenic in animals with  
370 the kidney as the primary target organ, and it is classified as a Group 2B possible  
371 carcinogen [101, 102]. There are few reports of OTA contamination of sesame seeds.  
372 Makun et al. [103] investigated the prevalence of OTA in sesame samples from Nigeria.  
373 They reported that all sesame seed samples in their study (n = 19) were contaminated  
374 with OTA, and EC limits were exceeded in 13% of the samples. This contrasts with  
375 Echodu et al. [99], where only 3% of collected samples had OTA concentrations  
376 exceeding EC limits.

377 Only a few major producing countries have set regulatory limits for mycotoxins,  
378 specifically for sesame seeds and products, and where these exist, focus on  
379 international trade [104]. In addition to potential risks to consumer health, mycotoxin  
380 contamination of sesame seeds could have severe economic consequences due to  
381 border rejections and recalls.

## 382 **4.2 Pesticides**

383 Controlling the growth of microorganisms and pests in sesame is critical for improving  
384 food quality and safety. Some previously used biological control methods for reducing

385 microbial hazards in harvested sesame include irradiation, fumigation with carbon  
386 dioxide (CO<sub>2</sub>) or propylene oxide, and the addition of salts [25,105]. Furthermore, plant  
387 protection products, such as pesticides, are used at different stages of cultivation to  
388 reduce post-harvest losses due to pest infestation and pathogens. However, there is  
389 growing concern about the potential adverse effects of pesticide residues on  
390 consumers and the environment [106, 107].

391 Recently, global attention was drawn to the issue of pesticide contamination due to  
392 consumer exposure to ethylene oxide after its detection in sesame seeds imported into  
393 Europe from India in 2020 [108]. The use of ethylene oxide as a plant protection product  
394 is not approved in the EU as it has been classified as a Group 1 carcinogen [109].

395 However, ethylene oxide was detected at over 1000 times the maximum residue level  
396 (MRL) of 0.05 mg/kg [110, 111]. This incident led to an unprecedented recall and  
397 withdrawal of sesame-based foods across the Member States and non-EU Member  
398 States [24]. As a result, new legislation has been implemented to increase import  
399 controls on sesame originating from India [15].

400 Between January 2020 and March 2024, there were 419 notifications regarding  
401 pesticide residues in sesame seeds in the EU RASFF system. Most of the notifications  
402 concerned sesame seeds originating from India (349, 83.3%). The main contaminant  
403 was ethylene oxide (312 out of 349) and its derivatives, 2-chloroethanol, chlorate and  
404 iprobenfos. There have been reduced notifications from India since 2020 (262  
405 notifications in 2020, 78 notifications in 2021, 8 notifications in 2022 and 1 notification  
406 in 2023). This is probably because of the increased frequency of checks and import  
407 control by importing countries. As of April 2024, there are only 5 notifications regarding  
408 pesticide residues in sesame seeds entering the EU for 2024. Four of the notifications

409 were from Nigeria, with Chlorpyrifos (more than two times the MRL) and Chlorate (more  
410 than 8 times the MRL) reported in sesame seeds from Nigeria [112].

411 Some pesticide residues, including lindane, chlorpyrifos, and metalaxyl, have been  
412 observed in sesame seeds and oil [113, 114]. Pesticide residues are not only found in  
413 the sesame seeds but could also be carried over into the processed products. For  
414 example, ethylene oxide was detected in caramelised nuts made with sesame seeds  
415 from Nigeria [115], in baking mixes made with sesame seeds from India [116], in spice  
416 mixes made with sesame seeds from India [117] and in bread baking mixes made with  
417 sesame seeds from India [118]. A residue of ethylene oxide, 2-chloroethane, was also  
418 detected in baking mixes made with sesame seeds from Nigeria [119].

419 The presence and persistence of pesticides in sesame seeds and their products raise  
420 the urgent need for research and development of alternative pest control strategies.

421 This will eliminate the need to use these unsafe chemicals in foods. Furthermore, there  
422 have been repeated notifications of ethylene oxide in sesame seeds imported into the  
423 EU. This suggests a need for continuous monitoring and surveillance of these  
424 chemicals in sesame seeds and their products. This is particularly important in  
425 producing countries for which there is limited data.

#### 426 **4.3 Allergens**

427 Sesame allergy is a growing concern as it triggers hypersensitivities that lead to  
428 symptoms including vomiting, diarrhoea, contact dermatitis and systematic  
429 anaphylaxis [120, 121]. Sesame allergens have been classified into three major groups:  
430 lipid, protein, and unknown allergens [122]. Protein allergens are classified into eight  
431 groups, *Ses i 1* to *Ses i 8* and are associated with IgE-mediated immediate

432 hypersensitivity reactions. Lipid allergens initiate both immediate (seeds) and delayed  
433 (oil) hypersensitivity reactions [123].

434 Reports on the prevalence of sesame allergies globally vary widely from about 0.1% to  
435 0.8%, as this depends on how much sesame is consumed within the local diet [121,  
436 124, 125]. Sesame has been recognised as a source of food allergens in the Middle  
437 East, where it is used extensively in the diet. Sesame ranked third as the most common  
438 food allergy after eggs and milk in Israeli children [122]. A study in Saudi Arabia noted  
439 that sesame was the third most common cause of anaphylaxis, accounting for 15% of  
440 cases prescribed antihistamines over a 2-year period [126]. In Turkey, an estimated  
441 20% of children with food allergies are allergic to sesame [127]. However, sesame  
442 allergies are reported in several other parts of the world. For example, although  
443 sesame-induced anaphylaxis rates were reported to be higher in the Middle East than in  
444 North America [128], sesame allergy is a substantial burden in the United States. An  
445 estimated 0.49% of the population report a current sesame allergy, and 17% of children  
446 with an IgE-mediated food allergy are estimated to have a sesame allergy [129, 130].  
447 Consequently, it is thought that the burden of sesame allergies may be higher than  
448 reported [131].

449 Several countries have established regulatory food labelling on products containing  
450 sesame to protect consumers and reduce the risk of unintentional exposure to sesame  
451 allergens. Since 2023, it has been required by law in the United States to label sesame  
452 as an allergen on food and dietary supplement packaging. This requirement also exists  
453 in the European Union, Canada, Australia, New Zealand, and other parts of the world  
454 [132]. In addition, a joint FAO-WHO Expert Committee recommended that sesame be  
455 considered a priority allergen [133].

456 There is scarce information on the prevalence of sesame allergies and their regulation  
457 in many sesame-producing countries worldwide, particularly those in Africa. This could  
458 be because sesame seeds are produced for export rather than local consumption.  
459 However, it has also been noted that there are significant data gaps on food allergens in  
460 many low-resource countries that bear a significant burden of other food-related  
461 challenges, e.g., malnutrition [134].

462 As observed with microbial hazards, there is limited information on the prevalence and  
463 human health risks of chemical hazards in sesame seeds and sesame-based products.  
464 Inadequate food safety and quality regulatory and monitoring systems and a lack of  
465 public awareness are important limitations in many producing countries [87, 99]. To  
466 address this critical food safety issue, a better understanding of the routes of  
467 contamination of sesame seeds and routine surveillance in producing countries is  
468 required. This will serve as a baseline for developing evidence-based strategies for risk  
469 assessment and identifying intervention strategies to reduce exposure to these  
470 hazards.

## 471 **5. Discussion and Recommendations**

472 Sesame seeds have high economic value and immense potential in enabling producing  
473 countries to achieve Sustainable Development Goals focused on poverty alleviation  
474 and food security. Sesame is mainly grown as an export crop in producing countries,  
475 providing employment and income for producers and processors. While the global  
476 sesame market is anticipated to grow [135], compliance with food safety regulations  
477 remains a significant barrier to the international trade of sesame seeds. Some major  
478 hazards affecting the sesame seed trade identified in this review include *Salmonella*  
479 mycotoxins and pesticide residues.

480 Currently, there is a limited understanding of which stages of sesame production and  
481 processing are most vulnerable to contamination. Many studies investigating the  
482 occurrence of hazards in sesame focus on the storage and retail stages of the value  
483 chain. During production, contaminants can be introduced through pollution from the  
484 farm environment, the use of contaminated soil amendments, irrigation water and  
485 pesticide use [136]. Further contamination could occur due to poor harvesting, drying,  
486 storage and transportation practices and unhygienic conditions during the processing  
487 and retail stages [96, 137].

488 There is a dearth of data from sesame-producing countries describing the link between  
489 local agricultural practices, particularly at the pre-harvest stage, and the occurrence of  
490 microbial and chemical hazards in sesame. Although some good agricultural practices  
491 have been recommended to improve the quality of sesame seeds [138], systematic  
492 investigations are needed to identify the critical points where contamination occurs in  
493 the value chain. This information is important to better target control strategies to  
494 minimise the contamination of sesame. This will contribute to food security for many  
495 smallholder farmers in producing countries and overall food safety for consumers.

496 Research could also focus on infrastructural interventions such as alternative drying  
497 procedures and hermetic technologies for seed storage [138, 139]. In humid climates,  
498 in addition to drying, seeds need to be packed in moisture-proof packaging to prevent  
499 rehydration [140]. Hermetic technologies such as the Purdue Improved Crop Storage  
500 [141] and Super Grain Pro [142] are moisture-proof and prevent oxygen from getting into  
501 the seeds. Microorganisms and pests require oxygen for respiration; therefore, oxygen  
502 concentrations are reduced to concentrations which cannot support their growth [140].

503 This is particularly important as conditions that support fungal growth will lead to

504 mycotoxin contamination. In addition, better pest control reduces the need for the use  
505 and abuse of pesticides. Consequently, hermetic packaging has been promoted in  
506 many low-resource, tropical countries to reduce post-harvest losses of several crops  
507 [143, 144]. There are relatively few studies exploring the use of hermetic packaging for  
508 sesame seed storage that focus on microbial hazards [139]. Sesame seeds stored in  
509 hermetic bags had lower levels of fungal infestation and mycotoxins compared to  
510 standard packaging in polypropylene and jute bags over a six-month storage period  
511 [145]. The effect of environmental factors, storage periods and affordable packaging  
512 technologies on sesame safety and quality is an important research priority in  
513 producing countries.

514 Regular surveillance is required to detect contamination sources and measure the  
515 effectiveness of mitigation strategies for mycotoxin contamination. For pesticides in  
516 sesame seeds, there is a need to conduct a risk assessment of their presence in  
517 sesame seeds and how these are carried over to sesame-based products.

518 Furthermore, it is essential to develop and employ novel rapid detection methods for  
519 determining contaminants across the value chain to mitigate post-harvest and  
520 economic losses where possible. Alternative pest management strategies, which are  
521 sustainable and environmentally- friendly, should be developed and deployed to avoid  
522 using unapproved pesticides in the sesame seed value chain.

523 The safety of sesame seeds for domestic consumption must also be prioritised as a  
524 research need in producing countries. Knowledge transfer between researchers,  
525 producers, and processors of sesame seeds on food safety is essential. This will give  
526 producers and processors the knowledge and tools to produce sesame seeds that  
527 meet the food safety requirements for local consumption and the international market.

528 Researchers should regularly network with stakeholders in the sesame seeds value  
529 chain to identify emerging food safety challenges and make these research priorities for  
530 action (Figure 4).

### 531 **Data Availability**

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

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537 **AA:** Conceptualisation, Writing – Original draft preparation, Writing – Review and  
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