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From fish to fork: An analysis of the fishmeal feed chain & presence of Anisakid material

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ABSTRACT

Anisakid nematodes are zoonotic parasites with a global prevalence in marine fish. Live larvae cause gastrointestinal disease in humans after ingestion of raw or undercooked fish. Alternatively, allergic reactions can occur through exposure to allergens. Emerging evidence shows these allergens may transfer from fishmeal to farmed animals and humans, posing potential public health risks. Fishmeal, a protein-rich feed derived from small pelagic fish and processing by-products, is widely used in aquaculture, poultry, and pig production. Fishmeal can introduce safety risks as it may contain thermoresistant Anisakid allergens which survive processing. This review aims to clarify the fishmeal feed chain from fish to fork, as well as the potential exposure pathways for Anisakid allergens. The traceability of fishmeal is examined, as well as its composition, production processing, trade and use per sector. Anisakid prevalence of fish used for fishmeal is also analyzed. Detailed traceability of fishmeal composition is limited. It is likely that Anisakid allergens are present in fishmeal due to inclusion of infected fish. Due to transmissibility from feed to food, this can have an impact on public health. A continuing decrease of fishmeal in poultry and pig diets will likely decrease risk for these food products. For aquaculture, this will be harder to predict. Marine ingredients will increasingly be derived from by-products potentially carrying a higher Anisakid load. At the same time a reduction in fishmeal inclusion in the feed can be expected. Further research should be undertaken in food products to determine the presence of Anisakid allergens.

1. Introduction

Anisakidae are fishborne parasitic nematodes with a global distribution, and pose a significant threat to public health (Audicana and Kennedy, 2008; Hochberg and Hamer, 2010). Aside from the disease caused by ingestion of live larvae, these nematodes harbour allergenic proteins. Exposure to these allergens can cause allergic reactions such as urticaria, angioedema, asthma, conjunctivitis, and potentially life-threatening anaphylactic shock (Añíbarro et al., 2007; Audicana and Kennedy, 2008; Nieuwenhuizen, 2016). The allergens in question originate from Anisakid nematodes of the genus *Anisakis*, *Pseudoterranova*, *Contracaecum* and *Phocanema* (Caballero and Moneo, 2004; Aibinu, 2018; Kochanowski et al., 2020; Saelens et al., 2022). The public health risk becomes more evident seeing that these nematodes have a global distribution and are present in many marine fish, among them some common and commercially important species (Aibinu et al., 2019). An increasing body of evidence now suggests that biological Anisakid material is

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also present in fishmeal feeds. High-throughput sequencing of commercial fish feed has identified the presence of *Phocanema* and *Hysterothylacium* DNA in 80% of analyzed samples (Abollo et al., 2024). Presence of genomic Anisakid material could mean that proteins and by extension allergens are present. Additionally, some studies have provided either observational or experimental evidence on the transfer of Anisakid allergens from fishmeal to livestock to food (Armentia et al., 2006; Fæste et al., 2015a, 2015b; Polimeno et al., 2021; Saelens et al., 2023).

Globally, fishmeal is an important feed source for multiple sectors, ranging from aquaculture to pork and poultry production. Fishmeal is an easily digestible, protein-rich, flour-type material produced by cooking (95°-100 °C), press drying and shredding of forage fish and offal left from fish processing (Shepherd and Jackson, 2013; Ween et al., 2017; Einarsson, 2019; FAO, 2024c). In 2022, 34% of global fishmeal production was derived from fish by-products. In 2022, more than 17 million tons of wild captured fish was reduced to fishmeal and fish oil, globally. In general, the largest part of fishmeal is used in aquaculture, while a smaller part is shared between pig and poultry production. The remaining share of fishmeal use is mainly destined for pet food (FAO, 2024c).

In the past decades, aquaculture has been a continuously growing industry which now has surpassed capture fisheries in aquatic animal production, comprising 94.4 million tonnes in 2022. Aquaculture feeds are commonly formulated with fishmeal and -oil, which are sourced from small pelagic fish and fish by-products coming from capture fisheries (FAO, 2024c). These ingredients are considered among the most complete and digestible protein sources for farmed fish. On top of having an excellent protein composition, it is a great source of polyunsaturated fat such as the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Zinn et al., 2009; Cho and Kim, 2011; Sevgili et al., 2015).

Despite efforts to reduce fishmeal use because of volatile prices due to weather phenomena such as the El Niño-Southern Oscillation (ENSO) off the coast of Peru and northern Chile, and concerns about sustainability of capture fisheries, this ingredient still remains an important feed source (Arias Schreiber et al., 2011; Bertrand et al., 2020; Coayla et al., 2023).

Disregarding abovementioned concerns of sustainability and food security, the use of fishmeal may introduce other safety issues for the consumer. First, a well-known issue is the presence of contaminants such as metals, organic pollutants, and *per*- and polyfluoroalkyl substances (PFAS), as these can be transferred from feed to food (Van Asselt et al., 2013; Berntssen et al., 2016). To tackle this, surveillance systems are in place to monitor these contaminant levels. However, a possible lesser known issue is that wild forage fish, which this feed is most commonly derived from, are a natural source of an array of zoonotic parasites. While live nematodes are readily killed by the physical and chemical processing steps to reduce fish to fishmeal, there are nonetheless concerns about transmissibility of highly resistant nematode allergens present in this fishmeal to farmed animals (Armentia et al., 2006; Saelens et al., 2023).

This report aims to clarify the fishmeal feed chain from fish to fork. More specifically, the raw material sources for fishmeal, its production processes across different regions, downstream processing, and sectoral applications of fishmeal are investigated, with a particular focus on meal and fishmeal fed products such as aquaculture fish and livestock arriving in the European Union. Additionally, the relation between these factors and the potential presence of Anisakid material are examined. Clarifying this process can help to make an estimation of the amount of Anisakid allergens present in food, or which food products are more likely to contain these allergens.

2. Materials & methods

This narrative review examined the composition, production, and trade of fishmeal, as well as the potential exposure pathways for Anisakid allergens. The literature search included literature published between 2000 and 2025, with a few pre-2000 studies (e.g., 1986, 1998) included for foundational context. The geographical scope was global, but with a particular focus on fishmeal arriving and used in the European Union.

2.1. Search strategy

Literature searches were conducted between July 1, 2024 and July 16, 2025 using PubMed, Web of Science, and Google Scholar. The following search terms were used in various combinations: “fishmeal composition”, “fishmeal analysis”, “proximate analysis of fishmeal”, “fishmeal production”, “global fishmeal producers”, “fishmeal industry”, “*Anisakis* allergens”, “*Pseudoterranova*”, “*Phocanema*”, “*Contracaecum*”, “*Hysterothylacium*” and “allergen thermostability”. Only English-language sources were considered. Titles and abstracts were screened for thematic relevance; full texts were reviewed when necessary.

2.2. Grey literature and supplementary sources

To capture recent industry insights and non-peer-reviewed data, grey literature was included. These sources were identified by the online search engine google, or through the reference list of papers found using the abovementioned search strategy. These sources included web-based publications and reports from relevant organizations such as the European Market Observatory for fisheries and aquaculture products (EUMOFA), the Food and Agriculture Organization of the United Nations (FAO), and the International Fishmeal and Fish Oil Organization (IFFO). FAO FishStatJ (FAO, 2024a) was used for extracting country-level production and species data. Where data was missing or not reported for certain countries, national reports or peer-reviewed articles were searched. To support data on trade flows and producer locations, the EU TRACES New Technology (NT) platform was accessed. This tool provides details on the movement of animal-based feed products, including fishmeal, within and into the EU, and helped identify major producers, exporters, and importers. TRACES NT also supported the identification of company-level actors involved in fishmeal production and trade. Intra-European transports of goods classified as fishmeal were identified for the period of January 1, 2022 to November 10, 2023.

2.3. Data extraction and selection

This review used a narrative, topic-guided approach, rather than a systematic review protocol. Articles and data sources were selected based on thematic relevance to the following areas: Fishmeal supply chains, fishmeal composition (species used, by-products, processing steps), sectoral usage (e.g., aquaculture, livestock, pet food), fishmeal trade patterns, feed formulation and ingredient inclusion levels, Anisakid prevalence in fish species used for fishmeal production. Data were extracted manually and organized thematically.

Data describing fishmeal usage by sector (e.g., aquaculture, livestock, pet food) were obtained from FAO publications. Information on fishmeal processing facilities and their geographical distribution was sourced from individual studies identified via the search queries described above. To evaluate fishmeal composition, country-level data on the annual volume of fish reduced to fishmeal were extracted, including details on target species, and where available, the proportion of by-products used in the process.

To characterize the fishmeal production process, general descriptions of processing steps (e.g., cooking, pressing, drying) were compiled from the included literature. Subsequently, data on ingredient inclusion in feed formulations, with a focus on fishmeal and alternative proteins, were collected from aquaculture nutrition studies and industry feed reports.

With a basic understanding of fishmeal production established, its trade and end-use patterns were further explored. EU import data were extracted for countries importing more than 5000 metric tonnes per year in 2022 and 2023, focusing on trends in destination and source countries.

To estimate the species most likely exposed to Anisakid allergens via feed, fish species and livestock types were assessed based on fishmeal inclusion rates in their standard feed formulations. For those fish species identified as significant inputs in fishmeal production, data on Anisakid parasite prevalence were gathered, with consideration for geographical variation and Anisakid species

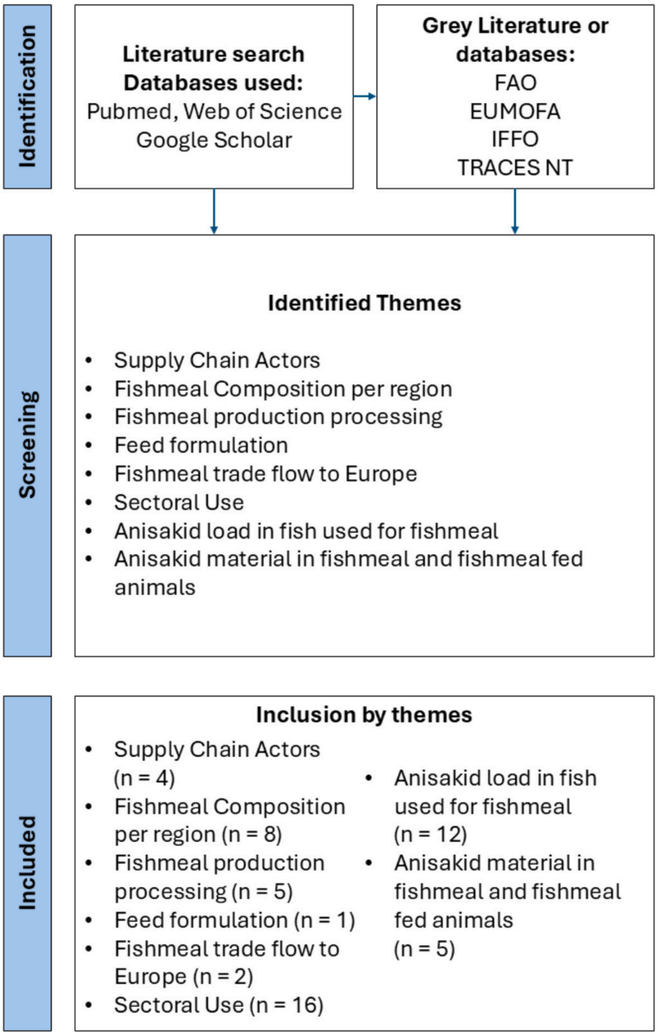

Fig. 1. Flowchart of narrative literature review methodology.

composition.

Data from all abovementioned topics or themes were bundled in an excel file and used to construct this narrative review.

3. Results & discussion

Scientific literature found on PubMed, Web of Science and Google Scholar provided insufficient data on specific fishmeal producers and their operational details to construct a thematic overview. The search identified papers and reports for each theme (Fig. 1).

Traceability of the feed chain and raw materials is limited. Due to the complexity of processing, multiple handling points and distribution channels, tracing the origin of fishmeal from its ultimate destination is rather complicated (Fig. 2). At the initial stage, raw materials can be derived from whole landings or from by-products of the fish processing industry. Whole landings can be caught by vessels owned by the fishmeal processing plant, or from independent fishing vessels. The processing step takes place at dedicated plants, where fishmeal is produced and either sold directly or made into a formulated feed. In some cases, by-products of whitefish are directly processed to fishmeal on-board fishing trawlers (Ween et al., 2017). Using TRACES NT, it was identified that distribution occurs through various channels, including direct, through brokers, wholesale, or a combination thereof, which is supported by other literature (Shepherd and Jackson, 2013). Finally, fishmeal – often included in formulated feed form together with other ingredients– reaches its destination. In 2021, 87% of fishmeal was destined for aquaculture, while 7% went to pig production and 1% to poultry production. The remaining share of fishmeal use was mainly destined for pet food (FAO, 2024c). TRACES NT, the online platform developed by the European Commission, facilitates the health certification process for animals, animal products, food and feed of non-animal origin, and plants imported into the European Union. Additionally, it supports the certification requirements for intra-EU trade and the export of animals and specific animal products from the EU. It was hypothesized that fishmeal composition, its trade routes, and origin could be readily found using TRACES NT. Some major fishmeal trading companies within Europe could be identified, but most receiving parties were intermediate traders, from which the fishmeal could no longer be traced.

3.1. Fishmeal composition per region

To elucidate fishmeal composition scientific literature was consulted, as well as the TRACES NT system, and general google searches. The nutritional value and biochemical composition of fishmeal has been extensively studied and described in scientific literature (Ween et al., 2017; Malcorps et al., 2019). However, when it comes to species composition and type of fish parts used, literature becomes much more sparse. This limits the ability to accurately track the fishmeal food chain, and hinders the determination of this feed's potential parasite and allergen burden, along with its use in aquaculture and livestock. However, some sources gave a

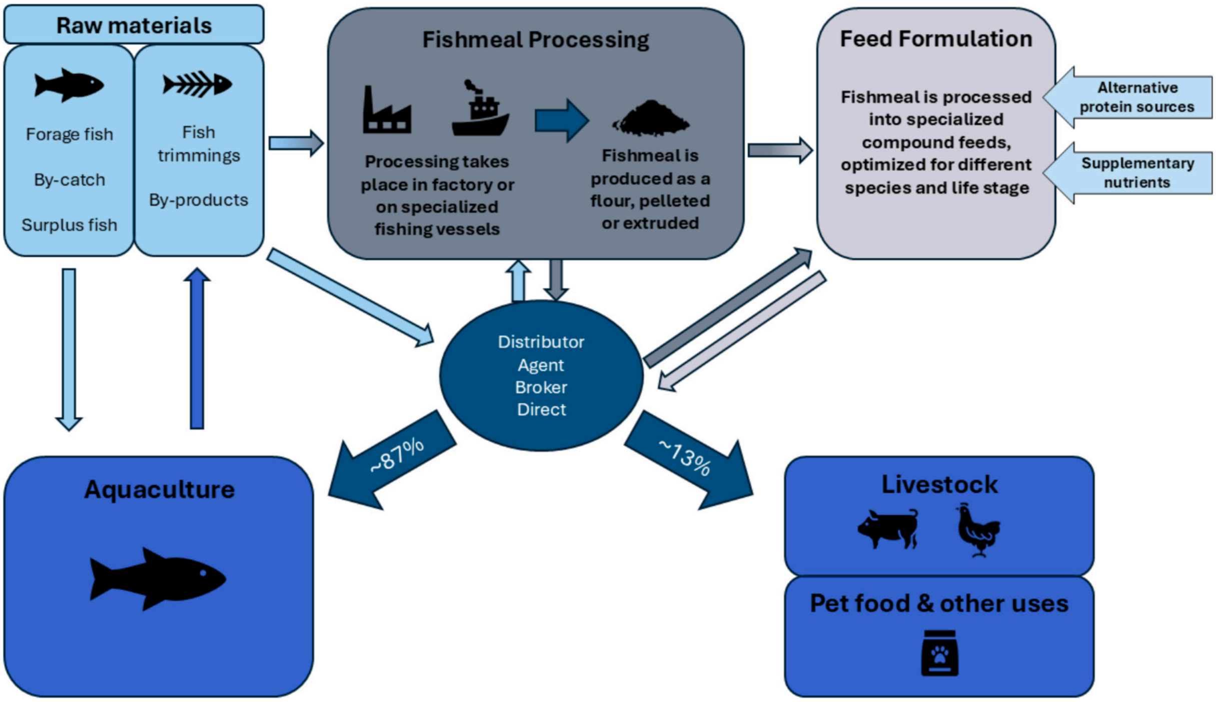

Fig. 2. Simplified feed chain of fishmeal. Raw materials can include whole fish or fish trimmings and by-products. Some trash fish are fed to aquaculture without any processing. By-products from aquaculture can be used as raw materials. Raw material for fishmeal processing is obtained either by traders or directly from dedicated fishing vessels. After processing, fishmeal is produced and can be further formulated in specialized feeds, or distributed to aquaculture, livestock, and other sectors.

general overview of main species used for reduction purposes (Hall, 2010; Shepherd and Jackson, 2013). Additionally, TRACES NT did not result in a better understanding of fishmeal constitution, as the composition of fishmeal was consistently labeled as "Pisces". No further species identification could be found and as a result, online sources were again consulted in combination with scientific publications to elucidate fishmeal composition. Datasets from EUMOFA were consulted, as well as country specific datasets such as Statistics Iceland.

The composition of fishmeal exhibits significant variability depending on its region of origin (Table 1). In Europe, the primary fish species landed for non-food purposes—predominantly fishmeal production—are small pelagic species such as sandeels (*Ammodytes* spp.), European sprat (*Sprattus sprattus*), Atlantic herring (*Clupea harengus*) and increasingly, blue whiting (*Micromesistius poutassou*) (EUMOFA, 2023). In Iceland, the fishmeal industry processes both whole pelagic fish and by-products from fillet production. The most commonly used species include capelin (*Mallotus villosus*) and blue whiting. Cut-offs and trimmings from Atlantic mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*) are also significant sources of raw material (Statistics Iceland, 2024). Norway, another important fishmeal producer, uses mainly blue whiting, Atlantic herring, sand eel and capelin (Einarsson, 2019), but increasingly fish by-products are used (Ween et al., 2017).

In Morocco, fishmeal production is primarily derived from four pelagic fish species, with sardine being the most significant contributor. Mackerel, horse mackerel, and anchovy are also utilized, albeit to a lesser extent. Often, landings are used for fishmeal reduction in the case of surplus, when there is an excess of supply over the canning capacity (Atmani, 2024). Additionally, fishmeal is produced using fish trimmings and whole fish that are unsuitable for human consumption or canning processes.

For Peru, the principal species used in fishmeal production is the Peruvian anchoveta (*Engraulis ringens*), which constitutes the bulk of its raw material. In 2020, up to 4.32 million metric tons of *E. ringens* was landed and destined for reduction to fishmeal (Leadbitter, 2019; Coayla et al., 2023).

3.2. Fishmeal production processing

The process for fishmeal production has largely stayed the same throughout the years and can be reduced to a few principles. Raw fish material gets heated or cooked to release the oil from fat deposits, and to coagulate the protein. Subsequent pressing will separate the press liquor from the solid presscake. This press liquor can be separated into oil and aqueous stickwater. The latter can be evaporated to obtain concentrated soluble, and in turn be added to the presscake. These solids are then dried and grinded to the desired particle size to produce fishmeal. Optionally, fishmeal is pelletized to facilitate bulk storage and transport (FAO, 1986; Hall, 2010; Oosthuizen et al., 2020). A notable development since the turn of the century is the use of extrusion feed. The extrusion manufacturing process involves forcing a mixture of raw ingredients through an extrusion die under high heat and pressure. This enables better

Table 1

Average yearly landings of main fish species used for reduction to fishmeal for the European Union and its main supplying countries. [a](EUMOFA, 2023), [b](Coayla et al., 2023), [c](Statistics Iceland, 2024), [d](Atmani, z.d.), [e](Einarsson, 2019).

Species	Landings For Non-Food Use (volume in 1.000 t)
European Union (Average 2011–2021)[a]	
European sprat (*Sprattus sprattus*)	259
Sandeel (*Ammodytes* spp.)	202
Blue whiting (*Micromesistius poutassou*)	132
Atlantic herring (*Clupea harengus*)	128
Total	782
Peru (2020)[b]	
Peruvian anchoveta (*Engraulis ringens*)	4320
Total	4320
Iceland (Average 2017–2023)[c]	
Blue whiting (*Micromesistius poutassou*)	236
Capelin (*Mallotus villosus*)	211
Atlantic herring (*Clupea harengus*)	44
Atlantic mackerel (*Scomber scombrus*)	31
Total	463
Morocco (2001)[d]	
Total (European pilchard, Mackerel, Horse Mackerel, Anchovy)*	500
Norway (Average 2014–2017)[e]	
Blue whiting (*Micromesistius poutassou*)	399
Atlantic herring (*Clupea harengus*)	357
Sandeel (*Ammodytes* spp.)	86
Capelin (*Mallotus villosus*)	66
Total	950
The Faroe Islands (Average 2014–2017)[e]	
Blue whiting (*Micromesistius poutassou*)	287
Atlantic herring (*Clupea harengus*)	62
Total	365

*Limited data on Moroccan landings, only a total amount of landed fish is provided. Between brackets are the main species used for reduction purposes.

control over nutritional and physical properties of feed, such as texture, size, and floatability. In the present day this has been widely adopted in the developed world (Sørensen, 2012; Glencross et al., 2023). In the Global South however, there continues to be a heavy reliance on pelleted feed, mash and trash fish feeding. In these regions, feed is often manufactured on-farm (Glencross et al., 2023).

Feed formulations are made to accommodate the specific nutritional needs of different livestock animals and aquaculture species, and can be optimized throughout the different live stages. Throughout the 21st century the fishmeal inclusion rate in aquafeed has decreased, being substituted by more cost-effective ingredients, such as the plant protein soybean meal, which contributes the largest share of aquafeed, or more environmentally sustainable ingredients (Glencross et al., 2023).

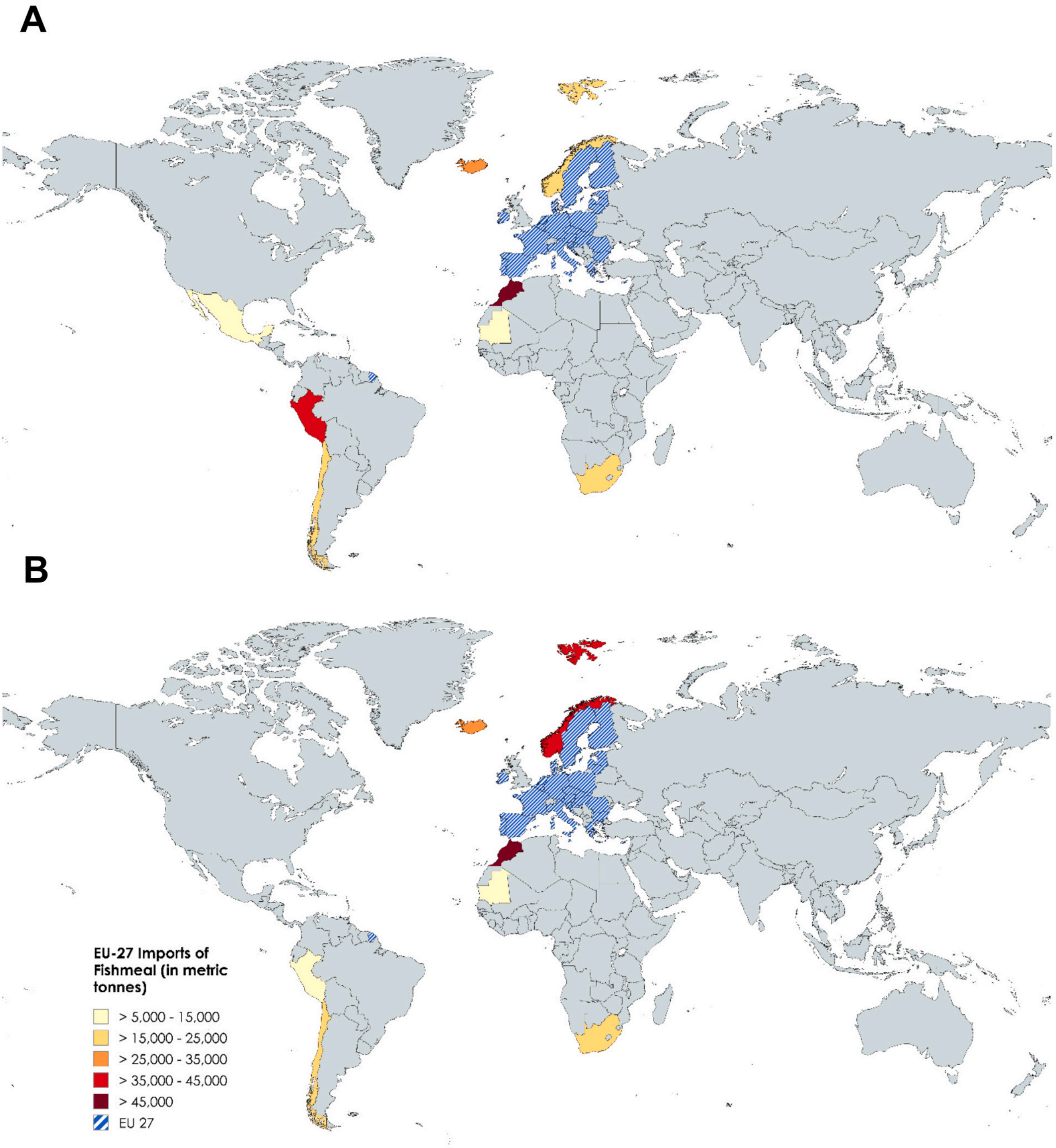

Fig. 3. Geographic distribution of main countries exporting fishmeal to the European Union. Countries supplying more than 5000 t are highlighted. Metric tonnes exported to the EU-27 in 2022 (A) and in 2023 (B). Images created with www.mapchart.net. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

3.3. European trade flow of fishmeal

Every year, the European Union produces around 480,000 t of fishmeal. The main producing countries are Denmark and Spain, accounting for 41% and 23% of the EU total respectively (EUMOFA, 2023). Nonetheless, the EU is still a net importer of fishmeal. In 2022, imports to the EU predominantly originated from Morocco, Peru, and Iceland, with respectively 56,600, 43,200, and 28,900 metric tonnes of meal (EUMOFA, 2023). Fig. 3A illustrates the geographic distribution of these imports. Nevertheless, in 2023 Norway and the Faroe Islands surpassed both Peru and Iceland in supplied volume, becoming the second and third largest suppliers in terms of volume (Fig. 3B). This highlights the fluctuating availability of fishmeal (EUMOFA, 2024).

3.4. Use per sector

The share of fishmeal utilized by the aquaculture sector has increased significantly in the 20th century, with the growth starting around 1980, and continuing into the 21st century, representing just over 40% in 2000, and rising to over 87% of total fishmeal being destined for aquafeed in 2021 (IFFO, 2023). Within aquaculture, the three sectors with the highest fishmeal consumption are crustaceans, salmonids and marine fish with a respective share of 29%, 24% and 23% of all fishmeal destined for aquaculture in 2010 (Shepherd and Jackson, 2013). Although fishmeal inclusion percentage in diets can vary considerably depending on fish species and producer, some data is available. Tacon and Metian (2008) estimated the global use of fishmeal from 1995 to 2020 for a range of aquaculture species (Table 2). However, data for 2007 onward are estimates that were based on expected growth. More recent data shows that fishmeal inclusion does decrease, but not always as projected. For example the total diet of salmonids such as *Salmo salar* and *Oncorhyncus mykiss* included around 19.5% of fishmeal in 2010, while this was reduced to 13.5% in 2013, which is similar to the

Table 2
Estimated global use of fishmeal in compound aquafeeds. Adapted from Tacon and Metian (2008).

Species-group	Year	Estimated mean % fishmeal inclusion
Shrimp (e.g. *Penaeus vannamei*, *P. monodon*)		
	1995	28
	2000	25
	2006	24
	2010[a]	12
	2015[a]	8
	2020[a]	5
Marine fish (e.g. *Sparus aurata*)		
	1995	50
	2000	44
	2006	32
	2010[a]	24
	2015[a]	16
	2020[a]	8
Salmon (e.g. *Salmo salar*)		
	1995	45
	2000	40
	2006	30
	2010 [a]	18
	2015 [a]	12
	2020 [a]	8
Trout (e.g. *Oncorhynchus mykiss)*		
	1995	40
	2000	36
	2006	30
	2010 [a]	18
	2015 [a]	12
	2020 [a]	8
Catfish (e.g. *Pangasius* spp.)		
	1995	5
	2000	8
	2006	10
	2010 [a]	6
	2015 [a]	3
	2020 [a]	2
Tilapia		
	1995	14
	2000	10
	2006	6
	2010 [a]	3
	2015 [a]	2
	2020 [a]	1

[a] Data for 2010, 2015 and 2020 are calculated estimates from expected growth.

estimate (Tacon and Metian, 2008; Ytrestøyl et al., 2015). Currently, feed for shrimp species *Penaeus monodon* and *P. vannamei* include between 20% to 30% of fishmeal in a typical diet, which is a lot higher than the estimated 5–8% inclusion (Malcorps et al., 2019). In 2008, Tacon and Metian estimated that in 2020, inclusion rates would be down to 8% for marine fish species important to aquaculture. However, for example *Sparus aurata* has a reported fishmeal inclusion of up to 27.5% in 2021. Tilapia, another important aquaculture species have a far lower inclusion rate than abovementioned species, ranging from 0 to 20% (Ng and Romano, 2013; Teodósio et al., 2021). Differences in inclusion rate can be explained by regional factors. Key drivers for regional differences in fishmeal use are the type of species farmed. For example, carnivorous shrimps require higher fishmeal inclusion rates than omnivorous or herbivorous species like tilapia and carp (Tacon and Metian, 2008; Malcorps et al., 2019). Economic factors and availability of alternative protein sources also play an important role in the rate of fishmeal substitution. In Europe particularly, a focus on sustainability is driving a protein shift to alternatives such as insect meal, microbial proteins, and fishmeal based on fish by-products (Hua et al., 2019; Jones et al., 2020).

With a share of 7%, pig farming has the second largest share of fishmeal utilization. Although fishmeal was historically a routine ingredient in pig feeds, the dietary inclusion rates have dramatically decreased. Now fishmeal use is mainly restricted to feeding weaning and young piglets, due to its palatability and digestibility (Shepherd and Jackson, 2013; FAO, 2024c). No clear data on regional differences in fishmeal use for pig production could be found. However, as mentioned above, its use could depend on local availability. For example, China – the biggest pig farming country – directs 40% of its annual fishmeal import toward pig feed (FAO, 2024b). Nonetheless, as fishmeal has a much higher cost compared to cereals and soybean meal, this ingredient will be mostly limited to strategic uses.

In the most recent years, the inclusion of fishmeal in poultry diet has drastically reduced despite its beneficial effects such as improved feed conversion efficiency and growth. While once being one of the staple consumers of fishmeal, this sector is presently only at 1% of total fishmeal consumption (FAO, 2024c). This decline in use can be attributed to high cost resulting from a volatile world supply, and successful substitution with other cheaper protein sources such as soybean meal, while having a similar feed conversion ratio (Frempong et al., 2019). Now, fishmeal use is mostly restricted to early chick diets, and higher value poultry such as turkey. Additionally, in these special cases where this feed is used, maximum inclusion rates are typically 5–10%, as poultry meat and eggs can have a fishy taste as result of a high inclusion (IFFO, 2023). When focussing on poultry products in Europe, a majority is imported from Brazil, and to a lesser degree Thailand (EU, 2024). As Thailand is one of the biggest fishmeal producers, its use in Thai poultry feed could be more significant compared to Europe (Shepherd and Jackson, 2013). Brazil, in contrast has domestic soybean production, and feed consists mainly of corn and soybean meal (Aquino, 2023).

3.5. *Anisakid Prevalence in Fish for Fishmeal*

Given the reliance on wild fish for the production of fishmeal, it is worth noting that several fish species used for production are reported to carry significant Anisakid larvae infections. Blue whiting and European sprat, two of the primary fish species landed for fishmeal production in Europe, are frequently infected with Anisakid larvae (Valero et al., 2000; Kleinertz et al., 2012). Blue whiting can have a broad prevalence range depending on its geographic origin, with specimens from the Atlantic Ocean (63–100%) having much higher prevalence than those from the Mediterranean Sea (10%) (Valero et al., 2000). A recent study covering Anisakid prevalence in blue whiting originating from the Portuguese coast confirms the high prevalence in the Atlantic Ocean. Notably, viscera were analyzed and had a prevalence of 100%, with a mean parasitic load of 29.2 (Rigkou et al., 2024). Out of all the inspected fish, 42.9% had multi-species infections with *Anisakis simplex* and *Hysterothylacium aduncum*. This could increase the exposure to a broader allergen spectrum. It should be noted that these samples were acquired from the same market in the same month, which makes generalization to the entire population difficult. For European sprat, one study reported prevalences between 5.7% (Baltic Sea) and 100% (North Sea) for *H. aduncum*, and a prevalence of 25.7% at Bay of Biscay (Kleinertz et al., 2012).

Atlantic herring, another commercially important fish where *Anisakid* infections are well documented, is also widely used for reduction purposes (Guardone et al., 2019; Kumas et al., 2024). Depending on the catch and geographic origin, prevalence of infection can vary widely with some studies reporting prevalence rates as high as 100% (Tolonen, 2003; Levsen and Lunestad, 2010).

In the Barents Sea, capelin is among the most abundant fish species and hence extensively utilized for Norwegian fishmeal production. Multiple Anisakid species infect the viscera and flesh of this host, with *C. osculatum* reaching an overall prevalence of over 67% (Levsen et al., 2016).

Sardines, which make up the bulk of raw material for Moroccan fishmeal, are also known as paratenic hosts of Anisakidae (Molina-Fernández et al., 2015). However, there is a substantial difference in Anisakid prevalence between sardines originating from the Mediterranean Sea and the Atlantic Ocean. Whereas East Mediterranean *Sardina pilchardus* typically have a very low prevalence, sardines from the Atlantic Ocean have an infection prevalence of up to 28.3% (Molina-Fernández et al., 2015; Bušelić et al., 2018). Given the fact that Morocco mainly derives its sardines from Atlantic waters (FAO/CECAF, 2020), a relatively high anisakid prevalence can be expected in its fishmeal.

The parasite fauna of the globally most reduced fish in terms of volume, *Engraulis ringens*, is less well studied. Some *Anisakis* spp. infections have been detected in the anchoveta sampled off the coast of northern Chile, with a prevalence ranging from 2 to 12% (Valdivia et al., 2007).

An increasing trend is the use of fish trimmings and by-products for fishmeal production, including fish viscera (Ween et al., 2017; FAO, 2024c). According to IFFO, in 2023 the share of fishmeal derived from by-products was 39% (IFFO, 2024). Of all by-products used, 66% is derived from wild capture by-products in which Anisakid material is highly likely to be present. Fish such as *Gadus Morhua* and *Pollachius virens* are known to have a dramatically higher occurrence of Anisakids in their viscera compared to muscle tissue. For example, one study shows cod viscera having a prevalence of 96.8%, while this is only 3.2% in the muscle (Strømnes and Andersen, 1998). All this evidence presents potential challenges for fishmeal processing and utilization, as parasitic loads may impact both the quality and safety of the final product.

3.6. Anisakid material in fishmeal and fishmeal fed animals

For *Anisakis simplex*, multiple allergens have been identified and officially recognized by the World Health Organization and International Union of Immunological Societies (WHO/IUIS) (Table 3). In the last decade, multiple studies have provided evidence that Anisakid material present in fishmeal can be transmitted to animals (Armentia et al., 2006; Fæste, Plassen, et al., 2015; Polimeno et al., 2021; Saelens et al., 2023; Abollo et al., 2024). Armentia et al. (2006) found *A. simplex* proteins in chicken sera fed with fishmeal, and provided evidence that the serum of subjects highly sensitized to *A. simplex* contains antibodies to these allergens present in chicken meat. A controlled chicken feeding trial by Saelens et al. (2023) gave proof of concept that Anisakid allergens could be transferred from larvae meal to chicken meat. In an exploratory feeding trial, Fæste et al. (2015b) found Anisakid peptides in zebrafish tissue being fed with feed containing processed larvae. Furthermore, Polimeno et al. (2021) provided data demonstrating the presence of Ani s 4 allergen in aquacultured sea bream extracts. The exact mechanism of how these allergens are transferred from feed to food is still unknown, but could warrant further research. These findings may significantly shift the importance of Anisakidae parasites from originally a purely marine fishborne food risk to potentially a wider allergenic risk from a broad range food sources.

In addition to the officially recognized allergens (Table 3), recent findings suggest that *Anisakis* sp. could be a source of α-Gal-containing glycoproteins (Rodero et al., 2025). These glycoproteins are usually associated with α-Gal syndrome (AGS) following tick bites, also known as red meat allergy. This highlights the relevance of Anisakids in the allergen discussion. Although these nematodes are generally considered to solely be a fish-associated health risk, it could potentially be a broader problem. Exposure to live nematodes could be a parasitic route for α-Gal sensitization, followed by sustained exposure to the glycoproteins by consuming infected fish, or through livestock and aquaculture products fed with contaminated fishmeal. The results warrant further research to elucidate the extent of the problem as well as the risk to the consumer.

3.7. Allergen survival during processing

From Anisakids present in fish, to its processing into fishmeal, and finally feed-to-food transmission, the allergens undergo several processing steps which may affect allergenicity. Indeed, certain food processing techniques result in allergenicity reduction. A recent review highlighted the different technologies for reducing immunoreactivity of the 14 food allergens as listed in Regulation (EU) No 1169/3022 (Wójcik et al., 2025). These include thermal processing, acid treatment, microwave processing, fermentation, non-thermal processing, enzymatic hydrolysis, and cold plasma. Thermal processing is the most widely used, causing confirmation and allergenicity changes, and is also performed on Anisakid allergens during fishmeal production. However, as mentioned above, some of the allergens are thermostable. For example, in one study *A. simplex* larvae were subjected to autoclaving for up to 80 min at 121 °C after which Ani s 1 and Ani s 4 allergens were still detected by immunoblotting with allergic patients' sera. This temperature and heating time significantly exceeds that of the typical fishmeal cooking step.

To get a better view on the risk of these allergens, a quantitative risk assessment would be essential. An exposure assessment could include a similar framework as used by Bao et al. (2017). Instead of determining the number of *Anisakis* spp. ingested per meal, the amount of Anisakid allergens per meal should be calculated. However, this is complicated by the need of extra unknown variables, such as allergen prevalence in fishmeal and allergen transfer rate from fishmeal to food. Although for a lot of fish species there is data available on Anisakid infection prevalence and intensity, data on the amount of allergens in fish, fishmeal, and subsequently livestock and aquaculture products is missing. Hazard characterization is also not possible at this time, as neither the dose of allergens needed for eliciting allergic reactions, nor the proportion of sensitized individuals is known.

Table 3
Overview of WHO/IUIS recognized Anisakis simplex allergens.

Allergen name	Biochemical name/function	Molecular mass (kDa)
Ani s 1.0101 (Q7Z1K3)	Unknown function, similar to Kunitz serine protease inhibitors	24
Ani s 2.0101 (Q9NJA9)	Paramyosin	97
Ani s 3.0101 (Q9NAS5)	Tropomyosin	41
Ani s 4.0101 (Q14QT4)	Cysteine protease inhibitor	9
Ani s 5.0101 (A1IKL2)	SXP/RAL-2 family protein	15
Ani s 6.0101 (A1IKL3)	Serine protease inhibitor	10
Ani s 7.0101 (A9XBJ8)	Unknown function, UA3-recognized allergen	139
Ani s 8.0101 (A7M6Q6)	SXP/RAL-2 family protein	15
Ani s 9.0101 (B2XCP1)	SXP/RAL-2 family protein	14
Ani s 10.0101 (D2K835)	Unknown function	21
Ani s 11.0101 (E9RFF3)	Unknown function	27
Ani s 11.0201 (E9RFF5)	Unknown function	14
Ani s 12.0101 (E9RFF6)	Unknown function	31
Ani s 13.0101 (A0A221C790)	Hemoglobin	37
Ani s 14.0101 (A0A0S3Q267)	3rd stage larval protein unknown function	24

3.8. Missing link

Given the data above, it is still not possible to provide an accurate estimation of the risk these potential allergens pose to the consumer. Although a case study has been provided showing that patients had an allergic reaction to chicken containing Anisakid allergens (Armentia et al., 2006), to this day, the eliciting dose of allergens needed for an allergic reaction is unknown. Double-blind, placebo-controlled oral challenge studies have been performed, without inducing clinical symptoms (Sastre et al., 2000). Further research is needed to determine the dose needed to elicit an allergic reaction in sensitized populations.

3.9. Regulatory discussion

Currently there exists a European regulatory framework on food safety related to parasites in fishery products. In 2010, the European food safety authority (EFSA) published an initial scientific opinion where they concluded that no fishing grounds can be considered free of *A. simplex* larvae and fish must be considered at risk of containing viable parasites of human health hazard if these products are to be eaten raw or almost raw (Hazards (BIOHAZ), 2010). Although allergen risk was acknowledged in this piece, it was concluded that it was not possible to assess the risk for allergy in the absence of live *A. simplex*. Following this, some new European regulations were implemented (EC 1276/2011) updating hygiene requirements. Freezing treatments were required for fishery products intended for raw consumption, or lightly processed products where treatment is insufficient to kill viable parasites. No freezing is required when products are heated to a core temperature of at least 60 °C for at least 1 min. In a recent publication, EFSA explicitly confirmed the persistence of heat-resistant Anisakid allergens. However, it is stated that the relevance of these allergens are still unknown and therefore are not included in their risk assessment (Koutsoumanis et al., 2024).

Taken together, there is a disconnect between the scientific consensus on *Anisakis* allergens as mentioned above, and to other allergen regulatory frameworks (e.g., EU 1169/2011). For other allergens, indication of presence in food products is mandatory. Although at this time there is not enough evidence to determine the eliciting dose of Anisakid allergens, in the future Anisakid material could be added to the list of substances or products causing allergies or intolerances. Another problem to consider is the transfer of allergens from feed to food. This phenomenon has been demonstrated and replicated for Anisakid allergens in multiple studies. In the future, additional labelling requirements could be added to allergen regulatory frameworks, where allergens present in feed should also be indicated.

3.10. Forward trends

In the face of climate change and sustainability concerns, together with a growing aquaculture industry, there are considerable efforts being made to reduce the use of forage fish in fishmeal, and provide alternative protein sources instead (Hua et al., 2019). More fishmeal is expected to be derived from fish by-products of higher trophic fish left over from the fish-processing industry. Along with a different nutritional profile, this could lead to a significant change in Anisakid allergen burden. It is hypothesized that there is a positive relationship between intensity of infection and fish species size. Larger fish are longer-lived and can accumulate larvae over time, as *Anisakis* larvae are known to survive up to two years in Atlantic cod (Hemmingsen et al., 1993). However, infection prevalence is highly variable and linked to a wide range of biotic and abiotic factors (Kuhn et al., 2016). Depending on the type of by-product used, this could lead to a higher or lower prevalence. In the case of usage of fish viscera, which is known to have a higher infection rate than fish muscles, the amount of Anisakid allergens could drastically increase (Cipriani et al., 2024). On the other hand, by-products such as fish skin or bones, the presence of allergens could be lower.

Another major trend in the aquafeed industry is the substitution of marine resource altogether. The use of plant-based sources for aquaculture feed such as vegetables like soybean meal are already common practice (Asche et al., 2013; Jiang et al., 2013). Alternatively, research is being conducted into feed consisting of single-cell protein derived from microorganisms, although there are challenges in scale-up (Jones et al., 2020; Buttle et al., 2024). Insect meals are another source with great potential for supplying protein for aquaculture (Hua et al., 2019).

The use of fishmeal in pig and poultry diets has seen a strong decrease over the years, especially in the west (FAO, 2024c). Due to the growing aquaculture industry, it can be expected that the share of fishmeal used for poultry and pig production will continue to decrease. Its use as a strategic or specialty feed ingredient is already established in the west, while for the global south its use is mainly based on availability (IFFO, 2023). In the future, the use of fishmeal for these livestock animals could continue its decline in the global south due to sustainability concerns, and its value to aquaculture.

4. Conclusion

In conclusion, traceability of fishmeal for research purposes is limited. A general view of fish used for fishmeal production gives us indications that Anisakid allergens can likely be present in feeds. Because of transmissibility from feed to food, this can have a potential impact on public health. Due to a continuing decrease of fishmeal in poultry and pig diets this hazard will likely decrease for these food products. For aquaculture however, this will be harder to predict. Marine ingredients will increasingly be derived from by-products potentially carrying a higher Anisakid prevalence and load. At the same time a reduction in fishmeal inclusion can be expected. Therefore, further research should be undertaken in food products to determine the presence of Anisakid allergens. Fishmeal constitution should be more easily traceable to be able to make direct correlations between allergen or contaminant levels, and used fish species.

CRediT authorship contribution statement

Faust Schotte: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Ganna Saelens:** Writing – review & editing, Conceptualization. **Brecht Devleesschauwer:** Writing – review & editing. **Sarah Gabriël:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Faust Schotte reports financial support was provided by Federal Public Service Health Food Chain Safety and Environment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fawpar.2026.e00328.

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