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Zoonotic helminth fauna in freshwater fish: risk assessment and mitigation strategies

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Abstract

Fish serve as a vital source of nutrition and livelihood worldwide, yet their role as intermediate or paratenic hosts makes them key vehicles in the transmission of various helminth zoonoses. As fish consumption rises, the potential for helminth parasite transfer to humans increases accordingly. Zoonotic helminths are transmitted through fish, including trematodes, cestodes, nematodes, and acanthocephalans. These parasites represent a persistent and evolving public-health challenge at the interface of aquatic ecology, food systems, and human behaviour. Globalized fish trade, expanding aquaculture, shifting dietary habits toward raw or undercooked fish, rising pollution, and climate-driven changes in parasite ecology are collectively elevating the risk of fish-borne helminth emergence. Together, these factors create conditions that favour both the spread and re-emergence of these infections worldwide. This review consolidates current understanding of the epidemiology, transmission ecology, clinical relevance, and detection of fish-borne zoonotic helminths. It emphasizes the need for an integrated, evidence-based framework to strengthen surveillance and reduce associated risks, as shown in the graphical abstract (Figure 1).

Keywords Helminths, trematode, cestode, nematode, zoonotic disease.

Introduction

Fish play a crucial role in aquatic ecosystems, serving as vital links in the transfer of energy, cycling of nutrients, and maintenance of biodiversity. They also provide a critical protein source and livelihood for millions of people around the world (Lynch *et al.*,2016). However, beyond their ecological and nutritional significance, freshwater fish act as crucial hosts and transmission pathways for a wide range of helminth parasites, including trematodes, cestodes, nematodes, and acanthocephalans (2013; Choudhury and Nadler, 2016). Many of these helminths use fish as intermediate, paratenic, or definitive hosts, thereby connecting multiple trophic levels and aiding in the dispersal of parasites across ecosystems. These positions fish not only as vulnerable organisms in parasite life cycles but also as efficient vehicles for zoonotic transmission to higher vertebrates, including humans (Chi *et al.,* 2022). From a public health standpoint, helminths harbored by freshwater fish pose serious zoonotic risks, including fish-borne trematodes such as *Clonorchis sinensis*, *Opisthorchis viverrini*, and *Metagonimus yokogawai*, which are transmitted through the consumption of raw, smoked, or undercooked fish (Wang *et al.,* 2022). Chronic infections with these parasites have been linked to hepatobiliary diseases and cholangiocarcinoma (Sripa *et al.,* 2021).

Similarly, nematodes such as *Gnathostoma spinigerum* and *Contracaecum* spp. may cause severe clinical manifestations, including cutaneous and visceral larva migrans, neurological disorders, and systemic allergic reactions (Herman and Chiodini 2009). These zoonotic diseases remain important public-health problems in Asia, Africa, and parts of Latin America, where traditional culinary practices (eating raw or undercooked fish), limited sanitation or hygiene, and low public awareness help sustain ongoing transmission (WHO, 2021).

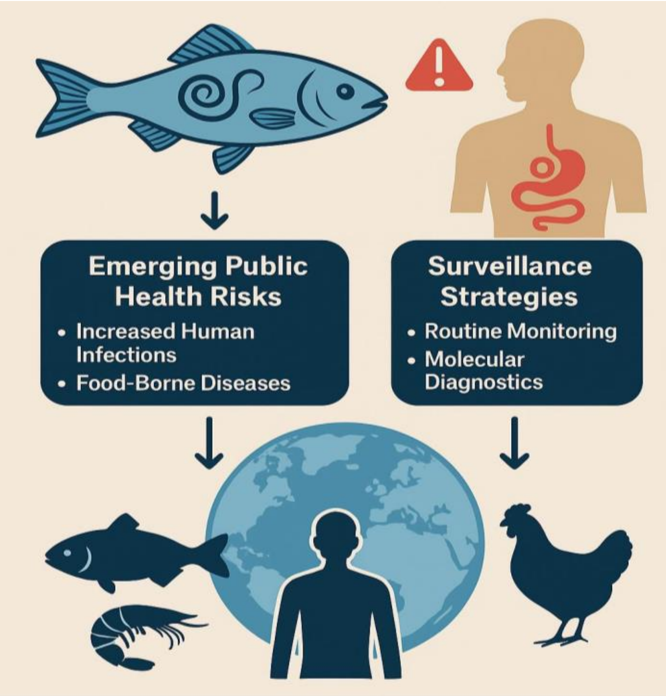

Figure 1: Zoonotic transmission of fish helminths in humans

Helminth infections in freshwater fish are shaped by a combination of host-parasite biology, ecological interactions, and environmental conditions, including water quality, habitat type, and anthropogenic disturbances (Lymbery *et al*., 2020). Parasite burden can negatively impact fish physiology, leading to reduced growth, fecundity, and survival, which in turn affects aquaculture and capture fisheries (Eiras *et al*., 2021). Thus, freshwater fish occupy a unique position at the intersection of ecology and human health. They function simultaneously as biological hosts, transmission vehicles for helminths, and vectors of zoonotic risk. Given the combined ecological, toxicological, and public health implications, there is a pressing need for a comprehensive study that simultaneously addresses various aspects of fish-helminth parasitism. This integrative approach is particularly crucial in regions like Africa and Asia, especially the eastern and southern Asia region, including India. Here, fish resources are intensively utilized. Understanding these dynamics can aid in developing effective monitoring strategies, ensuring food safety, and preserving aquatic biodiversity. Major fish orders parasitized by helminths are presented in Table 1.

Table 1: Helminth parasites reported in different fish orders

Fish Order	**Fish Hosts**	**Reported Helminth Parasites**	**Type of Helminth**	**References**
Cypriniformes (carps, minnows, loaches)	*Cyprinus carpio*, *Labeo rohita*	*Bothriocephalus acheilognathi* (cestode), *Camallanus anabantis* (nematode), *Allocreadium* spp. (trematode),	Cestode, nematode, trematode, acanthocephalan	Moravec, 2007; Choudhury and Nadler, 2016; Sultana *et al*., 2024

		Neoechinorhynchus spp. (acanthocephalan)		
Perciformes (perches, cichlids)	*Oreochromis niloticus*, *Channa punctata*	*Clinostomum complanatum* (trematode), *Contracaecum* spp. (nematode), *Acanthosentis* spp. (acanthocephalan)	Trematode, nematode, acanthocephalan	Gautam *et al*., 2018; Choudhury *et al*., 2006
Siluriformes (catfishes)	*Clarias batrachus*, *Heteropneustes fossilis*	*Procamallanus* spp. (nematode), *Isoparorchis hypselobagri* (trematode), *Corynosoma* spp. (acanthocephalan)	Nematode, trematode, acanthocephalan	Moravec, 2009
Salmoniformes (salmon, trout)	*Oncorhynchus mykiss*, *Salmo salar*	*Diphyllobothrium latum* (cestode), *Diplostomum spathaceum* (trematode), *Anisakis simplex* (nematode)	Cestode, trematode, nematode	Scholz *et al*., 2009; Chai et al., 2005
Clupeiformes (herrings, sardines)	*Sardinella longiceps*, *Clupea harengus*	*Anisakis* spp. (nematode), *Hysterothylacium* spp. (nematode), *Corynosoma strumosum* (acanthocephalan)	Nematode, acanthocephalan	Shamsi, 2019
Mugiliformes (mullets)	*Mugil cephalus*	*Heliconema longissimum* (nematode), *Ascocotyle* spp. (trematode)	Nematode, trematode	Moravec, 2009
Anguilliformes (eels)	*Anguilla anguilla*, *Anguilla japonica*	*Anguillicola crassus* (nematode), *Bothriocephalus* spp. (cestode), *Deropristis inflata* (trematode)	Nematode, cestode, trematode	Moravec, 2009; Køie, 1991
Tetraodontiformes (pufferfishes)	*Takifugu rubripes*	*Heterophyopsis continua* (trematode), *Philometra* spp. (nematode)	Trematode, nematode	Shamsi, 2019; Madhavi & Bray, 2018

Taxonomic diversity of helminth parasites

Fish helminths represent a highly diverse assemblage of parasites with species distributed in both freshwater and marine environments. Within Platyhelminthes, trematodes and cestodes form the dominant groups. Trematodes, primarily digeneans such as *Clinostomum*, *Diplostomum*, and *Echinostoma*, are known to parasitize a wide range of tissues, including gills, muscles, eyes, liver, and intestines of fish, often utilizing mollusks and piscivorous vertebrates as intermediate and definitive hosts (Chai *et al*., 2005). Cestodes, in contrast, are primarily intestinal parasites with several important orders reported in fishes: *Bothriocephalidea* (e.g., *Bothriocephalus acheilognathi*), *Caryophyllidea* (e.g., *Khawia sinensis*), *Diphyllobothriidea* (e.g., *Diphyllobothrium latum*), *Trypanorhyncha* (notably in elasmobranchs), and *Onchoproteocephalidea* (e.g., *Proteocephalus*). Many of these species are pathogenic, causing nutritional loss, intestinal obstruction, or tissue damage, and some, such as *Diphyllobothrium*, are zoonotic with direct public health implications (Durrani *et al.*, 2025; Craig, 2012; Kuchta *et al*., 2008; Scholz *et al*., 2021).

The nematodes form another major group of helminths, characterized by exceptionally high species richness and a broad host distribution. Members of the order *Ascaridida*, such as *Anisakis*, *Contracaecum*, and *Hysterothylacium*, are frequently reported in both marine and freshwater fish and include species of significant zoonotic concern due to their transmission through raw or undercooked fish (McCarthy and Moore, 2000; Moravec, 2013). Other nematodes, such as *Camallanus* and *Philometra* (Spirurida), are important in aquaculture systems, where they cause morbidity and economic losses. In addition, acanthocephalans, such as *Acanthocephalus*, *Neoechinorhynchus*, and *Polymorphus*, are common intestinal parasites that utilize a retractable, spiny proboscis for attachment, often causing severe intestinal damage and impairing fish health (Kennedy, 2006; Amin, 2013). Consequently, fish helminths not only play a crucial role in aquatic biodiversity but also have significant veterinary, ecological, and zoonotic implications.

Role of the larval helminths in the parasitism of vertebrate hosts

In contrast to monoxenous parasites, heteroxenous parasites require one or more hosts to complete their life cycle, facilitating their transmission and distribution. Helminth larvae, the infective stages of parasitic worms, represent critical phases and their interactions with vertebrate hosts. Among helminths, nematodes, cestodes, and trematodes are the major groups, with distinct larval forms and strategies for infecting vertebrate hosts. These larval forms occur in diverse environments, emerging directly from eggs or being released from intermediate hosts, and exhibit remarkable morphological and physiological adaptations that enable them to invade, survive, and mature within vertebrate tissues (Anderson, 2000; Chai *et al.,* 2005). Nematode larvae (e.g., *Ancylostoma duodenale*, *Strongyloides stercoralis*, Anisakis spp.) infect hosts either percutaneously or orally. The infective third-stage (L3) larvae of *A. duodenale* penetrate human skin, migrate via the circulatory system to the lungs, and eventually reach the intestine, leading to chronic anaemia and malnutrition (Bethony *et al*., 2006). Similarly, Anisakis larvae infect marine fish and can cause anisakiasis in humans upon ingestion of raw or undercooked fish food (Audicana and Kennedy, 2008).

Cestode larvae, or metacestodes, include several morphotypes such as cysticerci (*Taenia solium*), coenuri (*Taenia multiceps*), and hydatid cysts (*Echinococcus granulosus*). These larval stages develop within the tissues of intermediate vertebrate hosts, forming cystic structures that can remain viable for extended periods. Consumption of undercooked pork containing *T. solium* cysticerci results in intestinal taeniasis, while accidental ingestion of eggs causes human cysticercosis major cause of neuro-parasitic disease in endemic areas (Garcia *et al.,* 2019). Trematode larvae, particularly cercariae and metacercariae, develop within aquatic environments through snail intermediate hosts. In species such as Schistosoma, free-swimming cercariae emerge from infected snails and actively penetrate human skin upon contact with contaminated water, thereby initiating schistosomiasis (Colley et al., 2014). Other trematodes, such as *Clinostomum* and *Opisthorchis*, form metacercariae encysted in fish muscle; ingestion by humans or piscivorous birds completes the life cycle (Chai *et al*., 2005; Choudhury *et al*., 2006).

Helminth larvae exhibit diverse morphological and biochemical adaptations that facilitate host invasion and persistence. Many species possess penetration or histolytic glands that secrete proteolytic enzymes enabling larval entry through the skin or mucosal surfaces (Cordero and Freedman, 1999). In addition**,** attachment structures such as hooks, suckers, and spines provide firm anchorage to host tissues, supporting successful establishment and resistance to host tissue movements (Roberts and

Janovy, 2013). Moreover, helminth larvae employ sophisticated immune-evasion strategies, including antigenic variation, molecular mimicry, and modulation of host cytokine responses, which enable them to establish chronic infections while limiting host immune recognition and clearance (Maizels *et al*., 2018). Despite the well-documented medical and veterinary importance of helminth larvae, the relative abundance, biodiversity, and ecological impacts of these larval forms on vertebrate populations and human communities remain largely unexplored. Few studies have addressed how larval helminths influence host population dynamics, food-web interactions, or ecosystem health (Poulin, 2011). This gap is especially significant in freshwater and coastal ecosystems, where anthropogenic pressures, aquaculture expansion, and climate change may be reshaping host–parasite equilibria (Marcogliese, 2016). Comprehensive, integrative research employing molecular taxonomy, ecological modelling, and epidemiological surveillance is critically needed to clarify the ecological functions and zoonotic potential of larval helminth infections. These parasites pose significant threats to aquaculture, resulting in economic losses through reduced growth, mortality, and compromised market value of fish products" (Marcogliese, 2016; Maizels *et al.*, 2018; Wang *et al*., 2022)

Dynamics of the helminth transmission in fish populations

The overall diversity of fish helminths is shaped by ecological conditions, host availability, and trophic interactions, as most species involve multiple intermediate or paratenic hosts, such as mollusks, crustaceans, amphibians, and piscivorous birds or mammals (Benesh *et al.,* 2021; Runghen *et al*., 2021). Trematodes (Digenea) typically require three hosts: a mollusk as the first intermediate host, a fish as the second intermediate host, and a piscivorous bird or mammal as the definitive host. Such as, *Clinostomum* and *Diplostomum* species undergo asexual multiplication in snails, develop into metacercariae in fish tissues, and mature into adults in fish-eating birds, thus linking aquatic invertebrates, fish, and avian populations (Chai *et al.,* 2005). Cestodes also show indirect transmission, with copepods or other small crustaceans serving as the first intermediate hosts, while fish serve as intermediate or paratenic hosts, and piscivorous birds as definitive hosts, along with humans as accidental hosts for *Diphyllobothrium*. This dependency on food-web relationships makes their distribution highly sensitive to ecological changes in aquatic systems (Kuchta et al., 2008; Scholz et al., 2021). The transmission dynamics of fish helminths up to their final vertebrate host, either in the form of a vector or as a paratenic host, are presented in Table 2.

Table.2 Transmission dynamics of helminth parasites up to the highest vertebrates

Helminth group	**Representative taxa (examples)**	**Definitive host(s)**	**Intermediate/paratenic host(s)**	**Infective stage to fish**	**Transmission route to fish**	**Zoonotic importance (humans)**	**Key references**
Trematodes (Digenea)	*Clinostomum complanatum*, *Diplostomum spathaceum*, *Metorchis orientalis*, *Opisthorchis viverrini*, *Clonorchis sinensis*, *Metagonimus yokogawai*	Piscivorous birds (*Ardea*, *Phalacrocorax*), mammals (dogs, cats, humans)	1st IH: aquatic snails (*Lymnaea*, *Bithynia*); 2nd IH: freshwater fish (cyprinids, cichlids, catfish, etc.)	**Cercariae → metacercariae** in fish tissues	Cercariae from snails penetrate or are ingested by fish; predators/humans acquire metacercariae by consuming raw/undercooked fish	Major zoonotic agents (opisthorchiasis, clonorchiasis, metagonimiasis, and clinostomiasis) are linked to hepatobiliary and throat infections	Chai *et al.*, 2005; Madhavi and Bray, 2018; Choudhury et al., 2006

Trematodes (Monogeneans): with a Direct life cycle	*Gyrodactylus salaris, G. bullatarudis, Dactylogyrus vastator, Ancyrocephalus* spp.	Fish (ectoparasitic on gills/skin)	None (direct life cycle)	**Oncomiracidium** (free-swimming larva); viviparous neonates in *Gyrodactylus*	Transmission via direct contact or via free-swimming larvae in water	Non-zoonotic; major causes of mass mortality in aquaculture (*G. salaris* in salmonids)	Lefebvre, F., & Poulin, R. (2005); Whittington et al., 2000
Cestodes (Diphyllobothriidea)	*Diphyllobothrium latum* (*Dibothriocephalus*), *D. dendriticum, Ligula intestinalis, Schistocephalus solidus, Bothriocephalus acheilognathi*	Piscivorous birds, mammals (humans for *D. latum*), fish	1st IH: copepods (*Cyclops, Diaptomus*); 2nd IH: fish (plerocercoids in muscle/viscera)	**Procercoid (copepod) → plerocercoid (fish)**	Fish are infected by ingesting infected copepods or prey fish; the definitive host is infected by eating fish with plerocercoids	*Diphyllobothrium latum* causes human diphyllobothriasis ("fish tapeworm"); *Bothriocephalus acheilognathi* is a major invasive pathogen in carp aquaculture	Kuchta et al., 2008; Scholz, T., & Kuchta, R. (2022).
Nematodes (Anisakidae & related)	*Anisakis simplex, A. pegreffii, Pseudoterranova decipiens, Contracaecum rudolphii, C. osculatum, Hysterothylacium aduncum, Camallanus cotti, Capillaria philippinensis*	Marine mammals (*Anisakis*), piscivorous birds (*Contracaecum*), mammals (dogs, cats, humans), fish (for some *Camallanus*)	1st IH: copepods, euphausiids; paratenic/secondary IH: fish, cephalopods, smaller fishes	**L3 larvae** encysted in fish viscera/muscles	Fish acquire infection by consuming infected crustaceans or smaller fish; predators acquire L3 by eating infected fish	*Anisakis* spp. cause anisakiasis (gastrointestinal, allergic reactions); *Capillaria philippinensis* causes intestinal capillariasis in humans	Shamsi ,2019; Chai et al., 2005; Jyrwa et al., 2016; Choudhury et al., 2006
Other nematodes (Capillariidae, Camallanidae)	*Capillaria gracilis, C. philippinensis, Camallanus lacustris, C. cotti*	Piscivorous birds, mammals (including humans for *Capillaria*), fish	Copepods, oligochaetes, aquatic insects; fish intermediate/paratenic hosts	**L2–L3 larvae,** depending on species	Fish are infected by ingesting infected invertebrates or eggs in the water	*Capillaria philippinensis* causes serious zoonosis via raw fish; others mostly pathogenic to fish	Moravec, 2009; Anderson, 2000
Acanthoceph	*Acanthoceph*	Piscivorou	Intermediate	**Cystacanth**	Fish	Not	Kenne

alans	*alus anguillae, Pomphorhynchus laevis, Neoechinorhynchus rutili, Echinorhynchus cinctulus*	s birds (*Ardea*, *Anas*), fish-eating mammals (otters), and some fish	hosts: amphipods (*Gammarus*), isopods, ostracods; fish as paratenic or definitive hosts	in crustaceans or encysted in fish	acquire cystacanths by preying on infected crustaceans or smaller fish	zoonotic but *ecologically significant; bioindicators of metal pollution*	dy, 2006; Amin, 2013

Nematodes and acanthocephalans also follow trophically transmitted cycles. Larvae of nematodes such as *Anisakis*, *Contracaecum*, and *Hysterothylacium* are transmitted through ingestion of infected intermediate or paratenic hosts, with adult development occurring in piscivorous fishes, birds, or marine mammals (Anderson, 2000; Moravec, 2013; Vuić *et al*., 2022). In aquaculture systems, nematodes such as *Camallanus* and *Philometra* can be directly transmitted through ingestion of infected copepods, contributing to high parasite burdens under crowded rearing conditions. Acanthocephalans, such as *Acanthocephalus* and *Neoechinorhynchus*, require crustaceans as intermediate hosts, and fish become infected by consuming them, with adult worms attaching to the intestine via a spiny proboscis (Kennedy, 2006; Amin, 2013). The transmission dynamics of all these helminths are strongly influenced by environmental factors, host density, feeding ecology, and anthropogenic activities, such as aquaculture, water pollution, and the global fish trade. Importantly, several species, including *Anisakis*, *Clinostomum*, and *Diphyllobothrium*, pose zoonotic threats, highlighting the public health relevance of fish helminth transmission cycles (Chai *et al*., 2005). Ecological and epidemiological studies highlight the dynamic nature of helminth-host relationships. Investigations in Lithuania reported 29 helminth species in invasive freshwater fish, including seven previously unrecorded species, underscoring the importance of environmental monitoring for effective disease management (Kaziūnaitė *et al*., 2024; Kudlai *et al*., 2024). Ecologically, limited research exists on host-parasite interactions, including how environmental stressors or invasive parasite species influence parasite prevalence, diversity, and transmission dynamics (Moravec, 2013; Vanhove *et al.*, 2025).

The challenges of identifying helminth parasites and their parasitic impact on fish.

Fish-helminth interaction research faces a convergence of multifaceted challenges ranging from fundamental taxonomic identification to complex ecological and environmental dynamics. A major taxonomic obstacle is the prevalence of cryptic species, where helminths that appear morphologically identical are genetically distinct, which can lead to misidentification (de León, G. P. P., & Poulin, R., 2018). To address this, integrative taxonomy, which combines morphological descriptions with molecular data, e.g., DNA barcoding or metabarcoding and phylogenetic analysis, has become essential. “Climate change introduces multiple environmental stressors, including elevated water temperatures and deteriorating water quality, which can modify helminth developmental rates, transmission dynamics, and the spatial distribution of parasites and their intermediate hosts (Marcogliese, 2016). Alongside this, anthropogenic pollutants from industrial, agricultural, and urban sources can directly and indirectly affect parasite communities and host health. Pollution-induced immunosuppression in fish may increase their susceptibility to opportunistic helminth infections (Sures, 2008). Invasive species can also introduce novel parasites and destabilize existing host–parasite relationships, ultimately increasing the risk of parasite spillover (Poulin, 2011).

Another key challenge lies in understanding the functional and ecological outcomes of fish helminth interactions, which extend beyond simple host-parasite associations to include immunological, pathological, and food-web level implications. Many helminths cause sublethal effects, such as altered behaviour or increased predation risk in fish, which can ripple through aquatic ecosystems and fisheries (Lafferty & Kuris, 2012; Barber, 2024). However, quantifying these impacts is difficult due to variability in infection intensity, host specificity, and co-infections with other pathogens. From a zoonotic perspective, fish-borne helminths pose public health risks, but epidemiological data remain patchy, particularly in regions where raw or undercooked fish is consumed (Chai *et al.*, 2005; Sripa *et al.*, 2021). Thus, the study of fish–helminth interaction requires a multidisciplinary approach combining taxonomy, molecular parasitology, ecology, immunology, and public health perspectives to overcome these existing gaps and accurately assess their ecological and zoonotic significance.

Zoonotic potential of helminth parasites

Zoonotic helminths pose a significant public health concern, particularly in regions with inadequate sanitation and proximity between humans and animals, which facilitates cross-species parasite transmission. These infections can be acquired through various routes, including direct animal contact, ingestion of contaminated food or water, or via intermediate hosts like fish, pigs, or snails (Menconi *et al*., 2020; Vuić *et al*., 2022). Fish-borne zoonotic helminths (FBZHs) pose a significant health risk to humans who consume raw or undercooked fish containing infective larval stages. This process completes the parasite's life cycle, establishing fish as a key link in maintaining helminth circulation across trophic levels. Thus, acting as an ecological bridge, fish enable the trophic transmission of these parasites before being consumed by humans or other definitive hosts.

Table 3 Helminth transmission and Zoonotic diseases in human beings

Parasite Group	Representative Parasite Species	Fish Host(s)	Site of Infection	Zoonotic Potential	Key References
Trematodes (Digenea)	**Clinostomum complanatum**	Tilapia, catfish, perch	Buccal cavity, gills	Yes (pharyngitis in humans)	Chai *et al*., 2005; Pearson and Ow-Yang, 1982
	Diplostomum spathaceum	Salmonids	Eye lens	No	Chappell *et al.*, 1994
	Posthodiplostomum minimum	Sunfish	Liver, mesentery	No	Esch and Huffman, 1976
Cestodes	**Ligula intestinalis**	Cyprinids	Body cavity	Rare	Arme and Owen, 1968
	Schistocephalus solidus	Sticklebacks	Body cavity	No	Smyth, 1990
	Bothriocephalus acheilognathi	Carp, goldfish	Intestine	Yes (rare)	Scholz *et al*., 2011
Nematodes	**Anisakis simplex**	Marine fishes (herring, mackerel)	Body cavity, muscle	Yes (anisakiasis)	Audicana and Kennedy, 2008
	Contracaecum spp.	Catfish, tilapia	Body cavity, liver	Yes (rare)	Shamsi and Suthar, 2016
	Camallanus spp.	Freshwater fishes	Intestine	No	Moravec, 1994
Acanthocephalans	**Neoechinorhynchus rutili**	Cyprinids	Intestine	No	Amin, 1985
	Acanthocephalus lucii	Pike, perch	Intestine	No	Nickol *et al*., 2002
	Pomphorhynchus laevis	Barbel, chub	Intestine	Yes (very rare)	Kennedy, 2006

Transmission of zoonotic helminths is complex, often involving multiple hosts, such as the cycle of *Taenia solium* between humans and pigs, or fish acting as intermediate hosts (Garcia *et al*., 2003). The adult tapeworms then develop in the definitive host's intestine, causing gastrointestinal distress and absorbing large amounts of vitamin B12, which can lead to a deficiency. Consuming raw or fermented freshwater fish can transmit trematodes, such as *Clonorchis sinensis* and *Opisthorchis viverrini,* to humans, causing hepatobiliary disease (Keiser and Utzinger, 2005). Additionally, the "yellow grub" *Clinostomum complanatum* can be transmitted, leading to Halzoun syndrome (Keiser & Utzinger, 2009; Kim et al., 2019). Similarly, nematodes such as *Anisakis simplex* and *Gnathostoma spinigerum* use fish as paratenic hosts, leading to human anisakiasis or gnathostomiasis upon consumption (Audicana and Kennedy, 2008; Vuić *et al.*, 2022). Furthermore, the consumption of small freshwater fish can transmit Capillaria philippinensis**,** leading to intestinal capillariasis (Cross and Basaca-Sevilla, 1991). A wide range of clinical symptoms, from mild gastrointestinal issues to severe systemic complications like neurocysticercosis, a leading cause of acquired epilepsy in endemic regions, or potentially fatal outcomes caused by *Trichinella* sp. infections (Ndimubanzi *et al.,* 2010; Hotez, 2008). Different mechanisms of zoonotic transmission and associated human diseases are summarised in Table 3.

A recent review in Fish Acanthocephalans as Potential Human Pathogens notes that species in the genera Bolbosoma and Corynosoma, which often occur as larval/juvenile stages in fish, are deemed potentially zoonotic because consumption of infected fish without adequate heating or freezing may lead to human infection (Buchmann and Karami, 2024). In freshwater ecosystems, such as those in India, acanthocephalans of the genera *Pallisentis* and *Neoechinorhynchus* are known to parasitize fish, thereby perpetuating aquatic transmission cycles. This demonstrates that fish can function both as vectors and as a reservoir for zoonotic parasites, facilitating the transfer of helminth parasites from freshwater/marine environments to humans and across trophic levels involving multiple vertebrate hosts. Various pathways, as illustrated in Figure 4, facilitate the transmission of helminth parasites from animals to humans, leading to zoonotic diseases.

Figure 2 -Impact of fish–helminth parasitism (Graphical abstract)

ZOONOTIC HELMINTH DISEASES (Helminthiases)

TREMATODES (Flukes)
- *Clonorchis* sinensis
- *Opisthorchis* viverrini
- *Fasciola* hepatica
- Ingestion of raw fish
- Raw/undercooked freshwater fish
- Aquatic (plants meat)

CESTODES (Tapeworms)
- *Taenia* spp.
- *Echinococcus* granulosus
- Undercooked (pork/beef)
- Egg ingestion Hydatid cyst
- Taeniasis (Intestinal / tissue)

NEMATODES (Roundworms)
- *Ascaris lumbricoides*
- *Trichinella spiralis*
- Anisakis spp.
- Soil/food contamination
- Raw fish ingestion
- Nematodiasis (Intestinal / tissue)

ACANTHOCEPHALA (Thorny-headed worms)
- *Macracanthorhynchus* hirudinaceus
- *Corynosoma* spp.
- Beetle larvae ingestion → Fish/Marine food web
- Acanthocephalasis

Human diseases:
- Clonorchiasis / Opisthorchiasis
- Fascioliasis
- Taeniasis / Hydatidosis
- Ascariasis
- Trichinellosis
- Anisakiasis
- Macracanthorhynchiasis
- Corynosomiasis (rare zoonosis)

Emerging Risks and Integrated Surveillance of Fish-Borne Zoonotic Helminths

Effective surveillance and control strategies are crucial to mitigate these risks. Routine monitoring of both wild and cultured fish populations for the prevalence of parasitic pathogens is essential for early detection and management. The use of modern diagnostic tools, particularly molecular techniques such as PCR, significantly improves the accuracy of parasite identification and species-level characterization, thereby enhancing epidemiological surveillance and supporting more effective control interventions (Cunningham, 2002; López-Lastra *et al*., 2022).

From food-safety perspective, the most reliable preventive measures remain the thorough cooking of fish to an internal temperature of 63 ° C (145 ° F) or proper freezing to -20 ° C for at least seven days (or -35 ° C for 15 hours) to kill viable parasites, as recommended by international food-safety guidelines (FDA, 2011; FAO/WHO, 2019). These measures effectively prevent the transmission of fish-borne helminths, such as Anisakis, Diphyllobothrium, and Gnathostoma, to humans. A layered, One Health–oriented surveillance model should be developed to capture cross-species transmission risk. Tactical components include:1-Routine parasitological monitoring of wild and farmed fish using combined morphological and molecular diagnostics such as microscopy, PCR/qPCR, and DNA-metabarcoding is essential for detecting low-abundance or cryptic infections (Trujillo-González et al., 2019; Patchett et al., 2024; Bohara et al., 2022); 2-Environmental surveillance employing eDNA/eRNA and sentinel invertebrate sampling to identify transmission hotspots early (Thomsen and Willerslev, 2015; Deiner *et a*l., 2017); 3-Integration of geospatial risk mapping (GIS) and climate-driven predictive models to prioritize surveillance resources (Gabriël *et al*., 2022; Marcogliese, 2016); 4- Targeted human clinical surveillance in high-risk communities coupled with sero-epidemiology and clinical-laboratory linkages (Keiser and Utzinger, 2010); and 5- Participatory surveillance via fishers, aquaculture operators and community health workers to improve reporting and rapid response (Bondad-Reantaso, *et al.*, 2012). The strategy should also emphasize the value of harmonized laboratory reference standards and open sequence libraries to support species-level identification and source-tracking across regions (Deiner *et al*.**,** 2017; Nakao *et al.*, 2021).

By strengthening biosecurity in aquaculture, implementing Hazard Analysis and Critical Control Point (HACCP) systems in the seafood industry, and fostering international data sharing, public health authorities can proactively manage the emerging threats posed by fish-borne zoonotic helminths (Canton, H., 2021). Other important measures include policy making, prevention, and research priorities, enforcing wastewater and sanitation improvements to reduce environmental contamination (Prüss-Ustün *et al.*, 2019); capacity building for molecular diagnostics in resource-limited settings (Nkengasong *et al.*, 2017); and conducting longitudinal studies to quantify the public-health burden and the socio-ecological determinants of transmission is crucial for identifying high-risk interfaces and predicting future disease trends (Lafferty and Kuris, 2012). Addressing gaps in taxonomy, life-history data, and the effects of environmental change on host–parasite networks remain essential for anticipating future risks (Blasco-Costa and Poulin, 2017). An integrated surveillance posture that combines ecological monitoring with public health action is crucial for reducing the burden of fish-borne helminthiases and safeguarding both food security and human health (Mettenleiter *et al*., 2023).

Recent progress and future directions in helminth parasitological research

Recently, research on helminth parasite identification has advanced techniques in the areas of diagnostics, immunology, therapeutics, and ecological studies. Diagnostic innovations such as DNA metabarcoding and artificial intelligence (AI)-based egg detection have enhanced sensitivity and accuracy in identifying helminth species across diverse hosts and environments. DNA metabarcoding enables comprehensive detection of gastrointestinal helminths, while deep learning models, such as YOLOv4, automate egg identification in microscopic images, improving diagnostic efficiency (He *et al*., 2024; Miller *et al*., 2024; Choi *et al.*, 2024; Chan *et al.*, 2022). Immunological studies have revealed that helminths, including *Strongyloides stercoralis*, can modulate host immune responses, influencing the complement system and reducing inflammation. Additionally, helminth-derived extracellular vesicles containing microRNAs, such as let-7, play a critical role in regulating host immunity, providing insights into host-parasite interactions (Rajamanickam *et al.*, 2024; Chowdhury *et al.*, 2024).

Therapeutic research has progressed with the identification of helminth proteins, such as glutamate dehydrogenase (GDH), which allow parasites to evade host defenses, informing potential vaccine development (Wiley Online Library, 2024). Organizations like the Drugs for Neglected Diseases initiative (DNDi) are also developing safe and effective treatments for parasitic worm diseases, including lymphatic filariasis and schistosomiasis, targeting vulnerable populations such as children and pregnant women (DNDi, 2024). These studies reflect a multidisciplinary approach to understanding helminth parasites, integrating molecular diagnostics, immunology, therapeutics, and ecological perspectives, which is critical for effective disease management, environmental monitoring, and public health interventions. Selected recent case studies focused on important aspects of helminth parasitism are presented in Table 4.

Table 4. Selected recent case studies highlight fish-helminth interaction responses

Study	**Location**	**Parasite(s), Host(s)**	**Approach(s)**	**Key Findings / Relevance**
An Innovative Approach to Control Fish-borne Zoonotic Metacercarial Infections in Aquaculture by Utilizing Nanoparticles (Mahdy *et al*., 2024)	Nile tilapia farms, Egypt	Trematode metacercariae (particularly *Clinostomum*) in *Oreochromis niloticus*	Cross-sectional parasitological sampling; histopathology; nanoparticle exposure trials; measuring parasite burden, host immune markers (e.g., nitric oxide)	Found relatively high prevalence and intensity of *Clinostomum* metacercariae; treatment with nanoparticles reduced parasite burden and tissue damage; implicated possible improvement in tilapia health and reduced zoonotic risk. Important as proof of concept for interventions. (Mahdy *et al.* 2024)
The Immune Responses of *Oreochromis niloticus* Against Parasitic Infection in Freshwater Fish (Upper Egypt) (Younis *et al.*, 2023)	Upper Egypt	Trematodes in Nile tilapia; multiple fish parasites (including metacercariae)	Experimental infection + immunological assays (measuring cytokines, immune cell responses); histopathology; correlating parasite loads with fish health metrics	Showed that heavy infection with trematode metacercariae induces strong immune activation; host pathology (e.g., inflammation, muscle tissue lesions) corresponded to parasite load, suggesting an immune cost that may affect fish growth and aquaculture yield.
Ecological, Molecular, Histopathological, and Public Health Aspects of Clinostomid Metacercariae Infecting Freshwater Fish (Aydogdu *et al*.,	(Not South Asia, but a tropical region)	*Clinostomum* metacercariae in multiple fish species	Detailed sampling; molecular identification; histopathology; assessment of zoonotic risk (through literature review + local eating habits)	Confirmed presence of zoonotic metacercariae in fish consumed by humans; molecular methods helped discriminate species; pathology showed tissue damage; highlighted gaps in public awareness of

2025)				risk.
Fish-borne trematode infections in wild fishes in Bangladesh (Labony *et al*., 2020)	Bangladesh	Fish-borne trematodes' metacercariae in wild freshwater fishes	Field sampling across multiple fish species; morphological identification; prevalence and intensity measures; spatial variation	Found a high diversity of trematode metacercariae in wild fish; prevalence varied between fish species and sites; shows wild capture fisheries as an important reservoir of zoonotic trematodes. Although it is older, it provides contrast with aquaculture studies.
Genetic Diversity and Population Dynamics of *Clinostomum Isolated from Trichopodus pectoralis* (Islam *et al.*, 2024)	Southeast Asia	*Clinostomum* metacercariae from *Trichopodus pectoralis* (a fish species consumed locally)	Molecular identification (sequencing), population genetics, combined with ecological data (host fish size, environmental parameters)	Showed substantial genetic diversity, potential cryptic lineages; environmental variables (water quality, habitat) correlate with parasite prevalence; suggests transmission influenced by both host biology and habitat/ecology.
India-specific Incidence of *Clinostomum spp.* in Banded Gourami *(Trichogaster fasciata*) from Kararia Wetland, India (2025)	India (Kararia Wetland)	*Clinostomum* spp. metacercariae in *Trichogaster fasciata* (a food/niche-fish)	Field sampling; morphological identification; incidence reporting	First documented incidence in this species at Kararia wetland; contributes to baseline data for India; shows fish in smaller wetlands are also affected. (though molecular or zoonotic risk assessment remains limited)
Zoonotic Potential of *Eustrongylides spp*. in Freshwater Fish Meat Ljubojević Pelić (2023)	Likely South Asia /adjacent region (unclear exactly)	*Eustrongylides* spp. (nematode) in fish meat	Survey of fish meat; identification (morphology/genetics); risk discussion	Emphasized that *Eustrongylides* larvae are under-recognized zoonotic hazards; fish meat that is not well-cooked or handled may pose a risk; calls for better inspection or awareness.

Conclusion

In light of the significant zoonotic potential posed by helminth communities in freshwater fish, an urgent and integrated approach is essential to safeguard both human health and ecosystem integrity. Effective mitigation strategies must bridge current knowledge gaps through targeted research, advanced diagnostics, and robust surveillance systems. Ultimately, successful management relies on implementing comprehensive public health education initiatives in conjunction with continuous environmental monitoring. This multifaceted strategy represents the most effective path forward for minimizing food safety risks and protecting public welfare.

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