DOI: https://doi.org/10.70749/ijbr.v3i6.1478

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://induspublishers.com/IJBR
ISSN: 2960-2793/ 2960-2807

Fish Parasites, Host Parasite interaction, Economic Burden, Zoonotic Risks, and Sustainable Control Strategies with Special Refence to Pakistan

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ARTICLE INFO

Keywords: Fish Parasites, Aquaculture, Host-parasite Interactions, Zoonotic Parasites, Climate Change, Pakistan.

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Declaration
Authors' Contribution
All authors equally contributed to the study and approved the final manuscript. *Detail is given at the end.

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 04-03-2025 Revised: 03-05-2025
Accepted: 18-05-2025 Published: 10-06-2025

ABSTRACT

Fish parasites represents, growing threat to global aquaculture, wild fisheries and public health due to their complex life cycles, high pathogenicity, and increasing zoonotic potential. This review highlights the host-parasite interactions, economic impact, and diagnostic challenges of the main groups of fish parasites, such as protozoans, trematodes, cestodes, nematodes, crustacean ectoparasites, and myxozoans. This paper also highlights the role of climate change in altering parasites distribution and accelerating diseases emergence, particularly in aquaculture system under environmental stress. Regional problems, particularly in Pakistan, are highlighted to support the call for enhanced surveillance, diagnostics, and control measures in developing nations. Emergency treatment methods and integrated management practice are reviewed, with a focus on sustainable alternatives to traditional chemotherapeutants. By synthesizing current research and identifying knowledge gaps, this paper aims to assist aquaculture professionals in formulating adaptive measures in parasite management amidst ecological and societal transformations.

INTRODUCTION

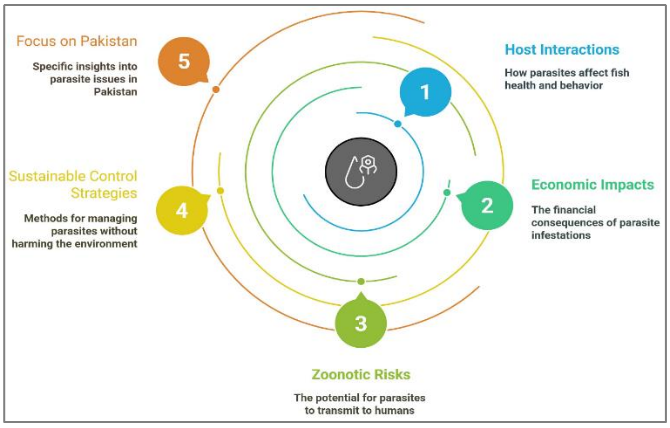
Fish are among the most widespread and ecologically important vertebrates, playing keystone roles in aquatic ecosystems and serving as a vital global food source. However, fish host a wide variety of parasitic organisms that can significantly impact their health, growth, and survival. These parasites are not just a natural part of aquatic food webs but also an increasing issue in both wild fisheries and aquaculture because of their ability to provoke disease outbreaks and economic losses. Parasites affecting fish species range from microscopic protozoan to complex metazoan worms and crustaceans, all having unique life cycles and host relationships. In aquaculture systems, where there are high stocking density and environmental stressors, parasitic diseases tend to result in lower productivity, high mortality, and secondary bacterial or fungal infections. Some species, such as *Ichthyophthirius multifiliis* and *Gyrodactylus salaris*, have become major challenges for fish farmers worldwide due to their rapid transmission and resistance to drugs. In addition to their impact on animal health, certain fish parasites pose risks to human health through zoonotic transmission, particularly in cultures where raw or undercooked fish is consumed. For example, Anisakis simplex can cause gastrointestinal illness in humans after ingestion of infected seafood (1,2).

Similarly, liver flukes like *Clonorchis sinensis* and *Opisthorchis viverrini* have been linked to severe long-term health impacts, such as cholangiocarcinoma (liver cancer) and are Group 1 carcinogens according to the International Agency for Research on Cancer. As climate change affects water temperature and ecosystem processes, the distribution and incidence of parasites in fish are also likely to change, raising new concerns for fish health management and food safety. In addition, globalization and live trade of aquatic animals have made it easier for exotic parasites to travel across borders, spreading disease risk to previously disease-free areas (3,4,5).

This review provides a general introduction to fish parasites, highlighting their taxonomy, host-parasite relationship, economic significance, diagnostic techniques, treatment, and emerging issues. It also emphasizes regional concerns, particularly in developing nations such as Pakistan, where research is lacking and facilities are inadequate for efficient parasite management. Through the integration of existing knowledge, this paper endeavors to enhance understanding and sustainable management of fish parasites against a changing backdrop. Schematic theme of this article is given in figure No 1.

Figure 1

Schematic representation of key aspects of fish parasitology covered in this review article.



METHODOLOGY

This review article is a comprehensive narrative review that aims to summarize current knowledge on fish parasites, their interactions with hosts, economic impacts, zoonotic risks, and sustainable control strategies, with special focus on Pakistan.

Review Approach and Literature Selection

The information presented in this article is gathered from peer reviewed articles, books, reports and literatures found in online databases such as Google Scholar, ScienceDirect, and local publications from Pakistani institutions.

Inclusion and Exclusion Criteria

Articles published between 2000 to 2024 were considered. Priority was given to studies conducted in Asia especially in Pakistan, peer reviewed journals and reports by FAO.

Classification of Fish Parasites

Parasites are organisms that live on or within a host organism and deriving nutrients at the expense of the host and usually harm it. As far as aquatic ecosystems are concerned, fish parasites are a broad spectrum of eukaryotic organisms that infect fish during their life cycle. These organisms include protozoans, helminths like trematodes, cestodes, and nematodes, myxozoans, and parasitic crustaceans. Fish parasites can be ectoparasites, which inhabit outer surfaces like skin and gills, or endoparasites, which inhabit internal organs like the gut, muscles, and viscera. Whereas some infections are symptomless, others induce severe pathology, influencing fish growth, reproduction, behavior, and survival. In aquaculture, parasitic disease is one of the most economically costly diseases, adding to lower productivity and higher mortality. Knowledge of their taxonomy and biology will allow accurate diagnosis, successful treatment, and sustainable management of both farmed and wild fish populations (6,7).

Protozoa (Single cell Organism)

Protozoa are unicellular eukaryotic organisms causing some of the economically most harmful diseases in aquaculture. Ichthyophthirius, Trichodina, Chilodonella, Cryptobia, and Myxobolus are common genera. They usually develop well under stressful conditions like poor water quality, high stocking densities, and temperature fluctuations. *Ichthyophthirius multifiliis* causes white spot disease (ich) with cyst-like lesions on skin and gill, epithelial injury, and secondary bacterial infections. The parasite is highly infectious in freshwater fish farms because of its short life cycle and environmental stress resistance. *Cryptobia salmositica* infects the blood and kidney of salmonids, inducing anemia and kidney failure. *Myxobolus cerebralis* is the causative agent of whirling disease in salmonids, which targets fry and fingerlings. It has an intermediate host (*Tubifex tubifex*) and leads to cartilage degradation and neurological symptoms. These protozoans can lead to extreme economic losses due to high transmission rates and limited treatment options, especially in densely stocked systems (8,9,10).

Trematodes (Flukes)

Trematodes which belong to the phylum Platyhelminthes develop through complex life cycles where first intermediate hosts are snails followed by fish and definitive hosts become birds or mammals. The eye and brain parasites of fish known as *Diplostomum* spp. infect these organs to produce vision loss and impaired swimming abilities that make fish more vulnerable to predators. *Nanophyetus salmincola* stands out for its ability to infect humans through fish which causes salmon poisoning disease in dogs. The parasite *Clinostomum complanatum* which people also call yellow grub establishes itself in the digestive organs of fish before spreading into high numbers throughout reservoirs and farm ponds. The management of trematode infections becomes problematic because these parasites have multiple hosts and maintain their presence in the environment specifically in pond-based aquaculture facilities (11,12).

Cestodes (Tapeworms)

Cestodes are ribbon-like worms that reside in the gastrointestinal tract or body cavity of fish. The most important Cestodes species that exist are *Schistocephalus solidus* and *Bothriocephalus acheilognathi*. The intermediate host stickleback shows modified behavior because of the *Schistocephalus solidus* infection which leads to bird predation their definitive host. *Bothriocephalus acheilognathi* commonly known as Asian fish tapeworm infects cyprinids and other freshwater fish across all regions of the world. The presence of cestodes in farmed fish can affect their growth and reproduction while heavy infestations result in intestinal blockages and weight reduction (13,14).

Nematodes (Roundworms)

Nematodes are roundworms commonly found in the intestines, muscles, and visceral cavities of fish. *Anisakis simplex* along with *Contracaecum osculatum* and *Philometra* spp. stand as significant species. *Anisakis simplex* represents a frequently occurring zoonotic parasite which infects humans through uncooked seafood larvae consumption to develop anisakiasis. The parasitic species *Contracaecum osculatum* targets cod and their relatives by creating both hemorrhagic gastritis and peritonitis. Nematodes known as *Philometra* spp. live under the skin and inside the muscle tissue of fish causing visible nodules that affect their commercial worth. Marine and freshwater environments worldwide have extensive nematode infestations that continue to grow because of ecological changes related to climate variability (15,16).

Crustacean Parasites

The group of crustacean ectoparasites comprises copepods and isopods which live on the gills and skin and fins. The most notable representatives of this category include *Lernaea cyprinacea* (anchor worm) as well as *Gyrodactylus salaris* and *Argulus* spp. (fish lice). The presence of *Gyrodactylus salaris* resulted in catastrophic reductions of Atlantic salmon numbers across Europe which led to the introduction of intense eradication measures. The hematophagous nature of *Argulus* species enables these parasites to obtain nutrients from blood and mucus while simultaneously inducing irritation, anemia and immune system suppression. These parasites display easily detectable symptoms on the host's body. However, they continue to reproduce quickly while showing resistance to standard chemical treatment methods (17,18).

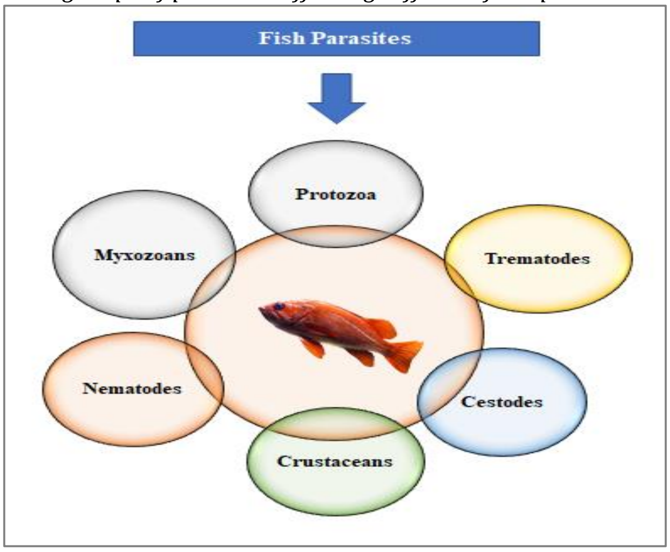
Myxozoans

Myxozoans represent parasite organisms which formed spores and are related to cnidarians. Researchers have focused their attention on *Myxobolus cerebralis* together with *Kudoa thyrsites* and *Henneguya zschokkei*. *Myxobolus cerebralis* triggers whirling disease among salmonid species affecting mostly young fish species. *Kudoa thyrsites* leads to fish muscle softening after death which shortens product lifespan and decreases consumer approval. *Henneguya zschokkei* creates cysts in koi and goldfish muscle tissue that do not cause death but diminish product appearance and market value. Early detection of Myxozoans poses significant challenges which make accurate identification possible only through molecular testing (19,20,21). Parasite groups along with their specific characteristics and fish-related effects shown in table No 1, and figure number 2.

Table 1
Different groups of parasites and their characteristics.

Groups	Example species	Site of infections	Life cycle complexity	Economic impact
Protozoa	*Ichthyophthirius multifiliis*	Skin, Gills	Direct (fish only)	High
Trematodes	*Diplostomum spp.*	Eyes, Brains	Complex (Snails+Birds)	Moderate
Cestodes	*Bothriocephalus acheilognathi*	Intestine	Complex (intermediate host)	High
Nematodes	*Anisakis simplex*	Stomach, Intestine	Complex (marine life cycle)	Zoonotic
Crustaceans	*Gyrodactylus salaris*	Skin, Fins	Direct	High
Myxozoans	*Myxobolus cerebralis*	Cartilage, Nervous tissue	Complex (Oligochaete worm + Fish)	High

Figure 2
Main groups of parasites affecting different fish species.



Host-Parasite Interactions

Host-parasite interactions in fish are complex and dynamic, which shaped by evolutionary pressures, environmental conditions, and immune response. These relationships can range from relatively mild associations to severe pathological effects that influence host behavior, physiology, and survival. Proper management of wild and farmed fish populations depends on our ability to forecast disease effects and create effective control methods (22).

Behavioral Manipulation by Parasites

One of the most interesting aspect of host-parasite dynamics is the ability of some parasites to manipulate host behavior to increase their rate of transmission. For example, *Schistocephalus solidus* a cestode infecting the three-spined stickleback (*Gasterosteus aculeatus*), alters the host's shoaling and predator avoidance behaviors, increasing its likelihood of being consumed by birds—the definitive host. The behavioral changes caused by parasites help these organisms survive while decreasing the survival chances of their host. Similarly, the infection of fish eyes and brain by *Diplostomum* spp. leads to vision and orientation impairment which increases their susceptibility to predation (23,24).

Immunological and Physiological Effects

The immune system of fish hosts uses two different response methods to combat parasitic infections. The gill tissues of fish show inflammatory responses and mucus production and epithelial hyperplasia when they are infected by protozoan and myxozoan parasites. Parasites have developed multiple evasion and immune suppression techniques which include antigenic variation and immunosuppressive secretions. Ectoparasite like *Gyrodactylus salaris* causes severe stress in fish populations which leads to slower growth together with increased vulnerability to bacterial and fungal infections.

The immune suppression from high stocking densities in aquaculture systems commonly leads to extensive death rates when not properly addressed (25,26).

Co-Infections and Immune Trade-offs

Farmed and wild fish species often experience infections from multiple parasite species at the same time. The immune response defines whether these interactions support each other or work against one another. Nematodes trigger changes in the host's immune system which lead to enhanced protozoan infection possibilities thus making diagnosis and treatment complex. The immune system of fish undergoes trade-offs that happen when energy expenditure for fighting one infection weakens defenses against other types of parasites. The interactions between parasites create significant challenges for disease treatment and need comprehensive control measures in parasite control programs (27).

Evolutionary Perspectives

The evolutionary history of host-parasite relationships involves continuous co-evolutionary interactions through arms races. Genetic resistance to particular parasites exists in some fish populations because of their immune system diversity while other populations stay highly vulnerable. The aquaculture industry uses selective breeding to develop host resistance for better disease management in its sustainable production methods. In wild fishes, the presence of parasites can regulate host density and promote genetic diversity through selective pressure. However, anthropogenic changes such as habitat degradation and climate change are altering these natural balances, leading to unexpected outbreaks and shifts in host specificity (28,29).

Economic Impact and Global Burden of Fish Parasites

Parasites on fish impose a huge economic burden on global aquaculture, fisheries, and trade, and losses are incurred through reduced growth rates, increased mortality rates, low feed conversion ratios, and secondary infection. Food and Agriculture Organization estimates that parasitic disease is responsible for about 20% of all reported aquatic animal disease outbreaks every year. In some regions of the globe, though not all, such as Asia and Europe, parasite losses have been hundreds of millions of dollars per year, affecting small-scale fish farmers and giant aquaculture operations (30).

Aquaculture Losses

Aquaculture has extreme levels of susceptibility to parasitic disease. There are high stocking densities and insufficient genetic diversity among farmed species, as well as external environmental stressors that compromise the power of the immune response among host fishes. For instance, outbreaks of *Ichthyophthirius multifiliis* and *Trichodina* spp. infections are the most frequent ones found in freshwater farms of China, Thailand, and Vietnam, and these outbreaks cause mass mortalities in farmed tilapia, catfish, and carp. Parasitic infection costs the aquaculture sector alone more than USD 300 million each year in China. As in Europe, *Gyrodactylus salaris* has caused dreadful catastrophes in the populations of Atlantic salmon (*Salmo salar*). It has particularly affected Norway, where eradication measures have cost tens of millions of dollars since the 1980s. Likewise, sea lice (*Lepeophtheirus salmonis*) still pose a great problem for marine salmonid aquaculture, with a price tag of greater than USD 700 million per annum in Norway alone (31,32,33).

Pakistan has potential inland water bodies like rivers, reservoirs, lakes, and farm ponds holding populations of diverse fish important for food security, livelihood, and rural economy. Parasitic infections, however, are coming up as a major obstacle to sustainable fisheries and aquaculture development in the country. Although the potential exists for growth, there are challenges to the aquaculture sector in Pakistan, from inadequate infrastructure, poor diagnostic capability, and limited parasitic diseases detection.

Trade and Market Restrictions

Aesthetic harm, impaired flesh quality, or zoonotic risk caused by parasite-infected fish may lead to trade limitations or the rejection of exports. Relevant examples include myxozoan infections; *Kudoa thyrsites* infections are often associated with the post-mortem condition referred to as soft flesh. This condition will often make the fish significantly diminishing market value/consumer acceptance. *Anisakis simplex* (a parasitic nematode forming part of the Anisakidae family) is sometimes found in heavy numbers in marine fish, which could result in meat recalls based on associated health risks relevant to eating raw fish in some countries, such as the United States. Countries with poor quality diagnostics and a lack of biosecurity will regularly have the fish product rejections resulting in continued economic pressure from exports embargoes (34,35).

Cost of Control and Treatment

The treatment of parasitic infections in aquaculture is often an expensive and environmentally contentious issue. Chemical treatment methods such as formalin, malachite green, emamectin benzoate, and praziquantel are more or less common but bring into question the issues of drug resistance and long-term environmental contamination. Other control options focused on biological control, including cleaner fish, probiotics, and immunostimulants, are receiving interest but require further development and financial backing for scalability and ultimate commercial efficacy (36).

Human Health and Zoonotic Costs

Some fish parasites also have animal health consequences (zoonotic potential) beyond economic implications. Such as Anisakiasis, clonorchiasis, and opisthorchiasis etc. linked to contaminated fish have resulted in substantial healthcare costs, especially in regions where raw fish consumption is culturally significant. Food safety authorities in Japan, South Korea and select regions in Southeast Asia have initiated expanded inspection scrutiny and awareness campaigns which additionally have imposed regulatory and financial burden on the industry (37).

Fish Parasites in Pakistan Current Status and Challenges

Pakistan hosts a wide variety of freshwater and marine fish species that are essential for food security, rural livelihoods, and economic development. However, they increasingly face parasitic infections, which are now being recognized as a major impediment to sustainable aquaculture and fisheries. Notable parasites reported in the country include protozoans such as *Ichthyophthirius multifiliis* and *Trichodina*, the trematodes *Diplostomum* spp., crustacean ectoparasites *Gyrodactylus salaris* and *Argulus* spp., and the zoonotic nematode *Anisakis simplex* etc. These parasites affect both farmed and wild fish populations, particularly in the economically important water bodies comprising the Indus River system, reservoirs, and farm ponds.

Despite growing research efforts, parasite control in Pakistan is faced with serious challenges. The absence of modern diagnostic laboratories, trained personnel, and effective biosecurity measures is a problem. Routine microscopy is the mainstay of diagnosis in most fish diseases due to the unavailability of molecular technology and well-equipped laboratories. This slows down diagnosis and outbreak response. There is also poor awareness of disease prevention measures among the majority of fish farmers, and chemicals are also not used appropriately, with delayed treatment leading to high mortality and economic loss.

Climate change is also making matters worse by modifying parasite life cycles and amplifying transmission rates. Increased temperatures and reduced winter periods have resulted in sporadic infestations even during off-season periods. Shifting water temperature and quality also compromise fish immune responses, leaving them more vulnerable to infections. Evidence suggests increasing prevalence of ectoparasitic infestations in Punjab and Sindh under evolving climatic conditions (38,39,40).

Diagnosis and Detection Methods

Accurate diagnosis is a foundation feature of fish parasite management, particularly in aquaculture systems where, time critical parasite identification can mitigate a widespread disease outbreak and subsequent economic losses. Fish parasite management typically utilizes traditional diagnostics based on morphology derived from light microscopy and histopathology. Fortunately, traditional methods are still supported by visualizing both external and internal parasites that boast a recognizable morphological feature. Parasites are not always obvious using the traditional light microscopy method; therefore, it remains equally valuable to use a wet mount preparation to visualize external and motile protozoan parasites on gill or skin tissues. Through the fixation and sectioning of infected tissues, histopathology can give us important information about host-parasite interactions and pathological changes associated with the presence of parasites, including *Myxobolus cerebralis* and *Kudoa thyrsites*. Although these methods are relatively inexpensive and practical at the basic field level laboratory and can be universally applied, they may be less sensitive to early-stage infections and require trained individuals for proper species identification.

The advancement of molecular diagnostic tools has significantly improved the accuracy and efficiency of parasite detection. Polymerase Chain Reaction (PCR) allows amplification of parasite-specific DNA sequences, enabling rapid and sensitive identification of species such as *Anisakis simplex*, *Diphyllobothrium latum*, and *Gyrodactylus salaris*. Real time quantitative PCR (qPCR) greatly improves specificity and quantification making it the ideal method to monitor parasite loads in both live and processed fish. The use of next-generation sequencing (NGS) provides the ability to detect multiple species of parasites in one sample, thus representing a powerful technology for surveillance and biodiversity studies. It is particularly useful in detecting zoonotic parasites and monitoring outbreaks in aquaculture facilities. However, the use of these advanced technologies continues to be limited in developing countries due to cost and complexity (42,43,44).

Treatment and Prevention Strategies

The main strategy used to achieve effective control of fish parasites should be an integrated approach that takes in the use of chemotherapeutic treatments, biological control agents, best husbandry practices, and prevention based on the situation (species of parasites and type of farming system). The use of treatment relies upon the type of parasite, host type, stage of infection and environmental conditions. However, growing concern about drug resistance, pollution and food safety has caused a shift towards sustainable and alternative methods of parasite management. Chemical therapeutants are one of the more mainstream intervention techniques in aquaculture for their rapid effectiveness under field conditions. Historically, formalin and malachite green have been common treatments for protozoan infections such as *Ichthyophthirius multifiliis* and *Trichodina* spp., Praziquantel is common when treating trematodes and cestodes, especially in freshwater systems where flukes are common. For ectoparasites like crustaceans (e.g. sea lice (*Lepeophtheirus salmonis*), systemic drugs like emamectin benzoate and ivermectin have been successful, although there are reports of resistance development and concerns over long-term effectiveness (45,46).

In addition to chemical approaches biological control methods are being promoted as ways to decrease the dependency on synthetic compounds. This includes cleaner fish (lumpfish *Cyclopterus lumpus* and wrasse species *Labrus bergylta*) that naturally feed on parasitic copepods in salmonid farms. Probiotics and immunostimulants that may be able to increase host immunity and suppress the growth of parasites, either through competitive displacement or immune modulation, are also being researched. The antiparasitic activity of herbal extracts from plants (e.g., *Azadirachta indica* (neem), *Allium sativum* (garlic) has been demonstrated in laboratory and field situations, with consideration of supplying an eco-friendly option to small scale farmers. Prevention is the best form of parasite control, there's a focus on parasite prevention, in particular, management via biosecurity measures through quarantine measures, and using good mortality and stock density records alongside water quality measures like dissolved oxygen, ammonium, and nitrite levels along with regular health checks. Efforts in selective breeding of stock for disease resistance, and preventive measures via vaccines have seen development for economically significant parasites like *Ichthyophthirius multifiliis*, but commercial vaccines are generally limited. An integrated pest management (IPM) framework of prevention, control, and mitigation represent the best way forward for the aquaculture industry trying to engage in sustainable parasite control (47,48,49).

Climate Change and Emerging Threats

Climate change is being more widely recognized as a potential cause of the emergence of parasitic diseases in aquatic ecosystems, affecting distribution, life cycles, and virulence of fish parasites globally. Environmental factors including temperature elevation, salinity changes, and alteration of indigenous hydrology are changing the host-parasite relationships and are largely detrimental to the health of fishes and aquaculture sustainability. Through changes to parasite development and transmission, and by modifying immune response and host susceptibility. These alterations in environmental factors are causing further difficulties by bringing challenges to disease control and management of both wild and cultured fishes, and exposing fish to many further stresses. One of the most notable impacts of climate change is the acceleration of parasite life cycles. Warmer water temperatures increase metabolic rates and reproductive efficiency of many ectoparasites leading to shorter generation times and higher infection intensities. For example, studies have shown that temperature increases of just 2–3°C can significantly enhance the proliferation of monogeneans on gill tissues, resulting in more frequent and severe outbreaks in aquaculture systems. Likewise, increases in sea surface temperatures are expanding the distribution of marine parasites (e.g., *Amyloodinium ocellatum* and *Lepeophtheirus salmonis*) from their prior tropical or temperate boundaries to higher latitudes. On top of direct impacts to parasite biology, climate change impacts disease dynamics indirectly as a result of their effects on host distribution and immune status. For example, changes in fish species migration patterns and habitat where previously healthy naïve fish populations are now encountering new parasites in their geographic range may result in increased disease emergence in locations where disease emergence has not occurred. Similarly, thermal stress can diminish host immune responses, resulting in increased infections, which as previously mentioned, has often been seen in species such as Atlantic salmon and tilapia where parasites and infections with protozoans and myxozoans occurred more often as their thermal temperature increased (50,51,52).

Future Perspectives and Policy Implications

Aquaculture industry faces ongoing challenges in controlling parasitic diseases, which significantly impact fish health and production efficiency. Recent advancements in fish vaccination offer promising avenues for disease control. Innovations such as recombinant subunit, DNA, and RNA vaccines are being explored to enhance immunity against various pathogens, including parasites. However, the development of effective antiparasitic vaccines remains complex due to the intricate life cycles and immune evasion strategies of many parasites. Continued research into fish immunology and vaccine delivery methods is essential to overcome these hurdles and improve disease resistance in aquaculture species (53).

Strengthening biosecurity measures and regulatory frameworks cooperation will help mitigate the impacts of parasitic infections or infestations. Fewer disease transmission risks can be achieved by standardized diagnosis protocols, strict biosecurity measures, and improved surveillance systems. The National Strategy on Aquatic Animal Health in Pakistan gives much importance to further development of comprehensive biosecurity programs meant for sustaining aquaculture as well as protecting aquatic biodiversity. Furthermore, the efforts mean international collaboration and accords with international standards such as those advocated by the Food and Agriculture Organization (FAO) to bring about harmonized actions in the control of fish parasites while ensuring food safety to the aquaculture sector as a whole. (54,55).

CONCLUSION

Fish parasites pose a serious challenge to aquaculture, wild fisheries and human health, especially in developing countries. Their impact ranging from economic losses to ecological disruption is intensified by factors like intensive farming, climate change, and global movement of species. Despite advances in knowledge and control methods, many gaps remain, particularly where resources are limited. To tackle these issues effectively, an integrated one health approach is crucial connecting animal, human, and environmental health through improved diagnostics, responsible treatment, research investment, and climate adaptive management strategies.

Acknowledgments

The authors would like to thank the Department of Chemical and Life Sciences, Qurtuba University Peshawar, Pakistan, and Department of Botany and Zoology, Bacha Khan University Charsadda, Pakistan, for providing institutional support.

Author Contributions

Inayat Ullah and Chan Bibi contributed equally to the conceptualization and literature review. Abdul Baset supervised the project and provided critical input on structure and scientific accuracy. Muhammad Fawad and Farhat Sunny assisted in data compilation and formatting. All the authors reviewed and approved the final version of the manuscript.

REFERENCES

1. Giari, L., Castaldelli, G., & Timi, J. T. (2022). Ecology and effects of metazoan parasites of fish in transitional waters. *Parasitology*, *149*(14), 1829-1841. https://doi.org/10.1017/s0031182022001068
2. Audicana, M. T., & Kennedy, M. W. (2008). *Anisakis simplex*: From obscure infectious worm to inducer of immune hypersensitivity. *Clinical Microbiology Reviews*, *21*(2), 360-379. https://doi.org/10.1128/cmr.00012-07
3. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. (2012). *A review of human carcinogens: Part B: Biological agents*. World Health Organization.
4. Marcogliese, D. J. (2001). Implications of climate change for parasitism of animals in the aquatic environment. *Canadian Journal of Zoology*, *79*(8), 1331-1352. https://doi.org/10.1139/cjz-79-8-1331

5. Bondad-Reantaso, M. G., Lem, A., & Subasinghe, R. P. (2009). International trade in aquatic animals and aquatic animal health: What lessons have we learned so far in managing the risks? *Fish Pathology*, *44*(3), 107-114. https://doi.org/10.3147/jsfp.44.107
6. Poulin, R. (2011). *Evolutionary ecology of parasites*. Princeton university press. https://www.degruyterbrill.com/document/doi/10.1515/9781400840809/html
7. SHINN, A. P., PRATOOMYOT, J., BRON, J. E., PALADINI, G., BROOKER, E. E., & BROOKER, A. J. (2014). Economic costs of protistan and metazoan parasites to global mariculture. *Parasitology*, *142*(1), 196-270. https://doi.org/10.1017/s0031182014001437
8. Matthews, R. (2005). Ichthyophthirius multifiliis Fouquet and Ichthyophthiriosis in freshwater teleosts. *Advances in Parasitology*, 159-241. https://doi.org/10.1016/s0065-308x(05)59003-1
9. Woo, P. T. (2003). Cryptobia (Trypanoplasma) salmositica and salmonid cryptobiosis. *Journal of Fish Diseases*, *26*(11-12), 627-646. https://doi.org/10.1046/j.1365-2761.2003.00500.x
10. Chandra, S. (2024). Emerging Coldwater Fish Disease: Diagnosis and Treatment. In *Aquaculture and Conservation of Inland Coldwater Fishes* (pp. 205-234). Singapore: Springer Nature Singapore.
11. Khan, R., & Thulin, J. (1991). Influence of pollution on parasites of aquatic animals. *Advances in Parasitology*, 201-238. https://doi.org/10.1016/s0065-308x(08)60309-7
12. Greiman, S. E., Kent, M. L., Betts, J., Cochell, D., Sigler, T., & Tkach, V. V. (2016). Nanophyetus salmincola, vector of the salmon poisoning disease agent Neorickettsia helminthoeca, harbors a second pathogenic Neorickettsia species. *Veterinary Parasitology*, *229*, 107-109. https://doi.org/10.1016/j.vetpar.2016.10.003
13. Jakobsen, P., Scharsack, J., Hammerschmidt, K., Deines, P., Kalbe, M., & Milinski, M. (2012). In vitro transition of Schistocephalus solidus (Cestoda) from coracidium to procercoid and from procercoid to plerocercoid. *Experimental Parasitology*, *130*(3), 267-273. https://doi.org/10.1016/j.exppara.2011.09.009
14. Dezfuli, B. S., Franchella, E., Bernacchia, G., Bastiani, M. D., Lorenzoni, F., Carosi, A., Lorenzoni, M., & Bosi, G. (2023). Infection of endemic chub *Squalius tenellus* with the intestinal tapeworm *Caryophyllaeus brachycollis* (Cestoda): Histopathology and ultrastructural surveys. *Parasitology*, *151*(2), 1–38. https://doi.org/10.1017/s0031182023001233
15. Audicana, M. T., & Kennedy, M. W. (2008). *Anisakis simplex*: From obscure infectious worm to inducer of immune hypersensitivity. *Clinical Microbiology Reviews*, *21*(2), 360-379. https://doi.org/10.1128/cmr.00012-07
16. Moravec, F., & Barton, D. P. (2018). New records of philometrids (Nematoda: Philometridae) from marine fishes off Australia, including description of four new species and erection of Digitiphilometroides gen. n. *Folia Parasitologica*, *65*. https://doi.org/10.14411/fp.2018.005
17. Bakke, T., Cable, J., & Harris, P. (2007). The biology of Gyrodactylid Monogeneans: The “Russian-doll killers”. *Advances in Parasitology*, 161-460. https://doi.org/10.1016/s0065-308x(06)64003-7
18. Boxshall, G. A., & Defaye, D. (n.d.). Global diversity of copepods (Crustacea: Copepoda) in freshwater. *Developments in Hydrobiology*, 195-207. https://doi.org/10.1007/978-1-4020-8259-7_21
19. Abdel-Latif, H. M., Dawood, M. A., Menanteau-Ledouble, S., & El-Matbouli, M. (2020). The nature and consequences of Co-infections in tilapia: A review. *Journal of Fish Diseases*, *43*(6), 651-664. https://doi.org/10.1111/jfd.13164
20. Giulietti, L., Levsen, A., Bao, M., Karlsbakk, E., Storesund, J. E., Tung, H., & Cipriani, P. (2024). First Report of ‘Soft Flesh’Induced by the Parasite Kudoa thyrsites (Myxosporea) in Commercial Codfish from Norway. *Journal of Fish Diseases*, *48*(4). https://doi.org/10.1111/jfd.14067
21. Banu, H., & Rathinam, R. B. (2023). Myxozoan fish diseases: Possible treatment and zoonoses. *Journal of Parasitic Diseases*, *47*(2), 215-223. https://doi.org/10.1007/s12639-023-01568-9
22. Poulin, R. (2011). *Evolutionary ecology of parasites* (2nd ed.). Princeton university press.
23. Morley, N. J., Costa, H. H., & Lewis, J. W. (2009). Effects of a chemically polluted discharge on the relationship between fecundity and parasitic infections in the chub (Leuciscus Cephalus) from a river in southern England. *Archives of Environmental Contamination and Toxicology*, *58*(3), 783-792. https://doi.org/10.1007/s00244-009-9386-8
24. Demandt, N., Praetz, M., Kurvers, R. H., Krause, J., Kurtz, J., & Scharsack, J. P. (2020). Parasite infection disrupts escape behaviours in fish shoals. *Proceedings of the Royal Society B: Biological Sciences*, *287*(1938), 20201158. https://doi.org/10.1098/rspb.2020.1158
25. Dezfuli, B. S., Giari, L., & Bosi, G. (2021). Survival of metazoan parasites in fish: Putting into context the protective immune responses of teleost fish. *Advances in Parasitology*, 77-132. https://doi.org/10.1016/bs.apar.2021.03.001
26. Harris, P. D., Bachmann, L., & Bakke, T. A. (2010). The parasites and pathogens of the Atlantic salmon: Lessons from*Gyrodactylus salaris*. *Atlantic Salmon Ecology*, 221-252. https://doi.org/10.1002/9781444327755.ch9
27. Secombes, C., & Chappell, L. (1996). Fish immune responses to experimental and natural infection with helminth parasites. *Annual Review of Fish Diseases*, *6*, 167-177. https://doi.org/10.1016/s0959-8030(96)90012-5
28. Fiala, I., Bartošová-Sojková, P., & Whipps, C. M. (2015). Classification and phylogenetics of Myxozoa. *Myxozoan Evolution, Ecology and Development*, 85-110. https://doi.org/10.1007/978-3-319-14753-6_5
29. Nguyen, N. H. (2024). Genetics and genomics of infectious diseases in key aquaculture species. *Biology*, *13*(1), 29. https://doi.org/10.3390/biology13010029
30. Agriculture Organization of the United Nations. Fisheries Department. (2018). *The state of world fisheries and aquaculture*. Food and Agriculture Organization of the United Nations.
31. Bondad-Reantaso, M. G., Lem, A., & Subasinghe, R. P. (2009). International trade in aquatic animals and aquatic animal health: What lessons have we learned so far in managing the risks? *Fish Pathology*, *44*(3), 107-114. https://doi.org/10.3147/jsfp.44.107
32. Yang, H., Tu, X., Xiao, J., Hu, J., & Gu, Z. (2023). Investigations on white spot disease reveal high genetic diversity of the fish parasite, Ichthyophthirius multifiliis (Fouquet, 1876) in China. *Aquaculture*, *562*, 738804. https://doi.org/10.1016/j.aquaculture.2022.738804
33. Bravo, S., Erranz, F., & Lagos, C. (2009). A comparison of sea lice, *Caligus rogercresseyi*, fecundity in four areas in southern Chile. *Journal of Fish Diseases*, *32*(1), 107-113. https://doi.org/10.1111/j.1365-2761.2008.01012.x

34. Yokoyama, H. (2003). A review: Gaps in our knowledge on Myxozoan parasites of fishes. *Fish Pathology*, *38*(4), 125-136. https://doi.org/10.3147/jsfp.38.125
35. Audicana, M. T., & Kennedy, M. W. (2008). *Anisakis simplex*: From obscure infectious worm to inducer of immune hypersensitivity. *Clinical Microbiology Reviews*, *21*(2), 360-379. https://doi.org/10.1128/cmr.00012-07
36. Buchmann, K. (2022). Control of parasitic diseases in aquaculture. *Parasitology*, *149*(14), 1985-1997. https://doi.org/10.1017/s0031182022001093
37. Keiser, J., & Utzinger, J. (2005). Emerging foodborne Trematodiasis. *Emerging Infectious Diseases*, *11*(10), 1507-1514. https://doi.org/10.3201/eid1110.050614
38. Mehak, A., Mu, Y., Mohsin, M., & Zhang, X. (2023). MCDM-based ranking and prioritization of fisheries' risks: A case study of Sindh, Pakistan. *Sustainability*, *15*(11), 8519. https://doi.org/10.3390/su15118519
39. Khalid, S., Khan, W., Das, S. N., Ahmad, A., Mehmood, S. A., Pahanwar, W. A., Ahmed, S., Kamal, M., Waqas, M., Waqas, R. M., Hassan, H. U., Zahoor, S., & Maqbool, A. (2021). Evaluation of ecto and Endo parasitic fauna of Schizothorax plagiostomus inhabitants of river swat, Khyber Pakhtunkhwa, Pakistan. *Brazilian Journal of Biology*, *81*(1), 98-104. https://doi.org/10.1590/1519-6984.222215
40. Shah, S. Q. A., Mehmood, K., Rashid, M. I., Naz, H., Luqman, M., Sohail, O. N., ... & Ahmad, A. S. Prevalence, Morphological and Molecular Characterization of *Lernaea cyprinacea* Isolated from Major Carps of Southern Punjab, Pakistan. *Pakistan veterinary journal*, 45(1): 422-427. https://doi.org/10.29261/pakvetj/2024.308
41. Fiala, I. (2006). The phylogeny of Myxosporea (Myxozoa) based on small subunit ribosomal RNA gene analysis. *International Journal for Parasitology*, *36*(14), 1521-1534. https://doi.org/10.1016/j.ijpara.2006.06.016
42. Akram, N., El-Matbouli, M., & Saleh, M. (2023). The immune response to the Myxozoan parasite Myxobolus cerebralis in salmonids: A review on whirling disease. *International Journal of Molecular Sciences*, *24*(24), 17392. https://doi.org/10.3390/ijms242417392
43. Saleh, M., Friedl, A., Srivastava, M., Secombes, C. J., & El-Matbouli, M. (2020). Modulation of local and systemic immune responses in Brown trout (Salmo trutta) following exposure to Myxobolus cerebralis. *Fish & Shellfish Immunology*, *106*, 844-851. https://doi.org/10.1016/j.fsi.2020.09.003
44. St-Hilaire, S., Cheng, T. H., Chan, S. C., Leung, C. F., Chan, K. M., Lim, K. Z., Furtado, W., & Bastos Gomes, G. (2021). Emamectin benzoate treatment of hybrid grouper infected with sea lice in Hong Kong. *Frontiers in Veterinary Science*, *8*. https://doi.org/10.3389/fvets.2021.646652
45. Collins, C., Kerr, R., McIntosh, R., & Snow, M. (2010). Development of a real-time PCR assay for the identification of Gyrodactylus parasites infecting salmonids in Northern Europe. *Diseases of Aquatic Organisms*, *90*(2), 135-142. https://doi.org/10.3354/dao02201
46. HARRELL, L. W., & SCOTT, T. M. (1985). Kudoa thyrsitis (Gilchrist) (Myxosporea: Multivalvulida) in Atlantic salmon, Salmo salar L. *Journal of Fish Diseases*, *8*(3), 329-332. https://doi.org/10.1111/j.1365-2761.1985.tb00950.x
47. Lam, C. T., Rosanowski, S. M., Walker, M., & St-Hilaire, S. (2020). Sea lice exposure to non-lethal levels of emamectin benzoate after treatments: A potential risk factor for drug resistance. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-57594-7
48. Bricknell, I., & Bron, J. (Eds.). (2022). *Sea lice biology and control*. 5m Books Ltd.
49. Jørgensen, L. V. (2017). The Fish parasite Ichthyophthirius multifiliis – Host immunology, vaccines and novel treatments. *Fish & Shellfish Immunology*, *67*, 586-595. https://doi.org/10.1016/j.fsi.2017.06.044
50. Marcogliese, D. J. (2001). Implications of climate change for parasitism of animals in the aquatic environment. *Canadian Journal of Zoology*, *79*(8), 1331-1352. https://doi.org/10.1139/z01-067
51. Woo, W., Kang, G., Kim, K., Son, H., Sohn, M., Jung, J., Choi, K., Mun, S. H., & Park, C. (2024). Effects of water temperature and light/dark cycles on in vitro egg laying and hatching of the monogenean Microcotyle sebastis on Korean rockfish (Sebastes schlegelii). *Aquaculture*, *579*, 740193. https://doi.org/10.1016/j.aquaculture.2023.740193
52. Takahashi, Y., Okamura, Y., Morimoto, N., Mihara, K., Maekawa, S., Wang, H., Aoki, T., Kono, T., Sakai, M., & Hikima, J. (2020). Interleukin-17A/F1 from Japanese pufferfish (Takifugu rubripes) stimulates the immune response in head kidney and intestinal cells. *Fish & Shellfish Immunology*, *103*, 143-149. https://doi.org/10.1016/j.fsi.2020.05.016
53. Rathor, G. S., & Swain, B. (2024). Advancements in fish vaccination: Current innovations and future horizons in aquaculture health management. *Applied Sciences*, *14*(13), 5672. https://doi.org/10.3390/app14135672
54. Madsen, H., & Stauffer, J. R. (2024). Aquaculture of animal species: Their eukaryotic parasites and the control of parasitic infections. *Biology*, *13*(1), 41. https://doi.org/10.3390/biology13010041
55. Buchmann, K. (2022). Control of parasitic diseases in aquaculture. *Parasitology*, *149*(14), 1–13. https://doi.org/10.1017/s0031182022001093