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Review Paper

Parasitology of one of the world's foremost fisheries target species lacks a One Health approach

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Abstract The global demand for affordable animal protein, particularly Nile tilapia, has driven increased adoption of (semi-)intensive farming practices. This intensification poses challenges like fish disease outbreaks, higher parasite loads, increased mortality rates, and environmental degradation. Addressing these issues requires a comprehensive understanding of the biology and ecology of these disrupted equilibria, emphasizing the need to characterize parasites, their pathogenic effects, and the conditions facilitating their emergence. Despite 276 known parasite species infecting Nile tilapia, existing reports are fragmented, often conducted locally or focused on a few species in experimental settings. A timely challenge is summarizing the state of knowledge and presenting links between human, animal, and environmental health. Unfortunately, limited studies focus on these parasites' actual effects and environmental correlates, indicating little research effort. Comparing the number of parasite species described with few studies documenting their impacts reveals large knowledge gaps. The current information on these parasites lacks practical applicability for stakeholders in production and management. Bridging this knowledge gap requires both descriptive and experimental studies. Adopting the One Health approach in parasitological assessments and conducting further research will ensure aquaculture stakeholders can access valuable information for informed decision-making, prioritizing environmental integrity, fish health and welfare, and consumer well-being.

Keywords Nile tilapia · *Oreochromis niloticus* · Fish health · Environmental health · Human health · Parasites

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Introduction

Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) has a wide-ranging native habitat that extends from the Nile River basin, southward through the Western and Eastern Rift Valley lakes in East Africa and westward through the basins of Lake Chad, Niger, Benue, Gambia, and Senegal (Trewavas, 1983). Its adaptability to thrive in diverse environmental conditions ranging from tropical to subtropical and temperate enables successful farming and establishment in new areas when introduced (Pullin, 1996; Agnèse et al., 1997; Canonico et al., 2005; El-Sayed, 2020). Nile tilapia production started during the second half of the twentieth century (El-Sayed & Fitzsimmons, 2023). In 2020, Nile tilapia ranked as the third most abundant farmed finfish species globally, with a production of 4,590,292 tonnes (valued at USD 2000 per tonne). The only species surpassing it in production were the grass carp (*Ctenopharyngodon idella* Valenciennes, 1844) with 5,791,541 tonnes (valued at USD 2291 per tonne) and the silver carp (*Hypophthalmichthys molitrix* Valenciennes, 1844) with 4,896,611 tonnes (valued at USD 2147 per tonne) (FAO, 2020). The demand for Nile tilapia as an affordable source of animal protein has driven its extensive cultivation in more than 140 countries across Asia, Africa, America, and the Pacific (Fitzsimmons, 2000, 2016; FAO, 2012).

Notably, most of the production occurs in low- and middle-income countries. Due to the high demand for domestic and international markets, tilapia farming rapidly expands worldwide (Béné et al., 2015, 2016). According to the Food and Agricultural Organization of the United Nations (2009), studying the parasites of freshwater fish, including Nile tilapia, is essential for ensuring optimal production levels (Mitiku et al., 2018). The adoption of semi-intensive and intensive farming systems has led to an increase in disease incidence, morbidity and mortalities (Pillay & Kutty, 2005). On the other hand, its global introduction has been reported to affect ecosystems worldwide negatively. These include competition with and subsequent rapid decline of native fish species (Goudswaard et al., 2002; Wise et al., 2007), hybridization with other tilapia (Tibihika et al., 2018; Shechonge et al., 2019), predation on eggs of aquatic organisms (Canonico et al., 2005; Alcaraz et al., 2015), stimulation of phytoplankton growth and eutrophication (Starling et al., 2002), and co-introduction of parasites (Šimková et al., 2019; Jorissen et al., 2020, 2022; Geraerts et al., 2023). While there have been detailed assessments of the ecological and socio-economic impacts of these tilapia introductions, Deines et al. (2016) report gaps in our understanding of the detrimental effects of diseases and parasites.

The perception of tilapia as a resilient and disease-resistant fish has shifted due to various factors, such as the intensification of farming practices, climate change, and the global trade of live aquatic species (Dong et al., 2023). Nile tilapia (both wild and cultured) is infected by 276 known species of parasites, including protists and metazoans (Shinn et al., 2023). Among these parasites, there have been 23 trematodes, 20 monogeneans, 2 cestodes, 2 acanthocephalans, and 7 nematodes formally reported in Nile tilapia, making it one of the parasitologically most extensively studied fish species in Africa (Scholz et al., 2018). Despite the considerable number of parasites associated with Nile tilapia, the available information on these parasites remains highly fragmented, with most studies focusing on local scales or specific experimental settings. A search using the Web of Science database with the search string "tilapia AND parasite" and a timeline from 1989 to 2022 yielded almost 350 peer-reviewed articles. However, it is worth noting that there has been a considerable gap of approximately 35 years between the most recent review (Shinn et al., 2023) and the previous review published in 1989 (Michel, 1989).

To achieve sustainability in the aquaculture sector, it is essential to recognize the intimate connection between the health of the fish, consumers, and environmental integrity (Stentiford et al., 2020; Jamwal & Phulia, 2021). Similarly, evaluating the burden linked to diseases is critical to improving our relationship with animal production and building a more sustainable world. For this reason, the One Health approach has been acknowledged in aquaculture sustainability as it facilitates an increase in production with efficient and sustainable environmental footprints while at the same time supporting local socio-economic needs (Stentiford et al., 2020). One Health is a comprehensive and collaborative strategy integrating diverse fields operating at the local, national, and international levels to maintain a sustainable balance and improve the well-being of people, animals, plants, and ecosystems. This review examines the research effort regarding the role of Nile tilapia parasites, specifically in fish health, bio-indication, and zoonotic potential, as proxies for the animal, environmental, and human components, respectively, of a One Health approach. Physical well-being in fish is commonly associated with good health, which encompasses being disease-free and managing physical and environmental stress factors to maintain optimal healthy conditions (Pillay & Kutty, 2005). Aquatic parasite research remains under-represented in the One Health literature, accounting for less than 4% of the total (Selbach et al., 2022). On the other hand, traditional siloed approaches to fish health may not provide a comprehensive understanding of the risks posed by parasites, which call for a One Health take on fish production.

Environmental parasitology has witnessed a rise in research papers emphasizing the role of parasites as indicators of environmental conditions (Sures, 2001). Due to the functional importance of parasites within animal communities and their sensitivity to various forms of pollution, including heavy metals, pesticides, industrial waste, and agricultural runoff, they have proven to be valuable tools in the biomonitoring of anthropogenic pollution (Sures, 2001; Sures et al., 2017). Fluctuations can influence parasites' presence and community composition in aquatic environments in abiotic water parameters, including water temperature, electrical conductivity, dissolved oxygen, turbidity, and pH. These variations can occur naturally with seasonal changes or due to human activities. Consequently, alterations in water parameters and the presence of pollutants can lead to changes in the population size of parasites, either increasing or decreasing their abundance (Cavalcanti et al., 2020; Jerônimo et al., 2022). Due to an urgent need for sentinels and a better understanding of the intricate aquaculture–environment interactions, Nile tilapia parasites can be useful and their potential for environmental quality bio-indication should be checked.

In addition to fish health and environmental integrity, aquaculturists should prioritize the welfare of the species they cultivate and recognize the importance of their operations on human health and welfare. Therefore, they must evaluate the potential effects of their practices on human health to maintain the credibility of their business and foster public trust (Pillay & Kutty, 2005). The World Health Organization and the United Nations Food and Agriculture Organization have recently included fish-borne zoonotic trematodes in their updated list of emerging infectious diseases (Chai et al., 2005). When considering the risk of fish-borne zoonoses in the developing world and the ever-increasing consumption of Nile tilapia, the importance of fish-derived zoonoses still stands out. The growing global trend of consuming raw or undercooked fish dishes, influenced by long-standing cultural traditions in several Asian countries, has resulted in an increased risk of parasitic hazards for individuals who choose these food practices over cooked fish products (Chai et al., 2005; Shamsi & Sheorey, 2018; Golden et al., 2023). Even though developed countries are aware of meat-borne zoonoses, they often neglect the importance and impact of parasitic zoonoses transmitted through fish. While Nile tilapia has not been definitively shown to be a host for all these diseases, it can potentially harbor parasites that cause conditions, such as anisakiasis, diphyllobothriasis, intestinal trematodiasis, and opisthorchiasis, which can cause a considerable number of human infections (Chai et al., 2005). While zoonotic diseases are an important aspect of One Health, the concept encompasses broader impacts on human well-being (Adisasmito et al., 2022). In the context of Nile tilapia parasites, this could include effects on global nutrition, economic impacts on farmers and communities, and sustainability challenges in aquaculture. This review focuses primarily on zoonotic potential as a key concept in the human health-related aspect of One Health. Despite the lack of comprehensive epidemiological data, the fact that fish-borne zoonotic parasites are highly prevalent and diverse in species suggests that they are an important public health concern (Chai et al., 2005). Therefore, a One Health approach must be included to address the issue of parasitic zoonosis (Robertson et al., 2014), especially in such an often-consumed species as Nile tilapia.

Human, animal, and environmental domains can benefit from a One Health approach and a compelling rationale exists for its application in fisheries issues. Due to the high parasite diversity in Nile tilapia, incorporating such an approach becomes essential for understanding the connections between these parasites, disease, their effects on fish and human health, and their potential implications for bio-indication. By considering these interrelationships, a holistic perspective can be achieved, leading to more effective strategies for sustainable production.

Data sources and searches

A systematic literature search via Web of Science (https://www.webofknowledge.com/), accessed on

November 30, 2022) and PubMed (https://pubmed.ncbi.nlm.nih.gov/), accessed on November 30, 2022) was carried out using a predetermined protocol following the PRISMA Extension for Scoping Reviews (PRISMA-ScR). This systematic approach allows for a rigorous assessment of the available literature, helps identify knowledge gaps, and provides a reproducible methodology for comparisons. The selection process followed the PRISMA-ScR recommendations (Tricco et al., 2018), identifying all potential papers from databases and screening to remove duplicate publications. Papers meeting the criteria for any one of the three categories in Table 1 were included in the review. By following PRISMA-ScR guidelines, we aimed to enhance the transparency and reliability of our review process. Following Smith & Smith (2015) and Schmid-Hempel (2021) and given their ecological and evolutionary analogy (e.g., Araujo et al., 2015), we define parasites broadly to include both microparasites (bacteria, protists, and viruses) and macroparasites (metazoans and fungi). This definition is applied consistently throughout the animal, human, and environmental health sections, approximated by focusing on effects on fish health, bio-indication, and zoonotic potential, respectively. The full approach and keywords combined with Boolean operators are shown in Table 1.

The flow diagram of search results is displayed in Fig. 1. The search yielded 4,166 articles. First, a total of 616 duplicates were removed before screening. In the second screening stage, we excluded 3,439 records based on title and abstract, mainly due to being out of the scope of the current study. The remaining 111 records were sought for full text, of which six could not be retrieved. After a full-text reading of 105 articles, we excluded eleven and retained 94 papers for this review.

Nile tilapia parasites and geographical focus

Research on parasites that affect either the health of Nile tilapia, human health, or ecosystem health have only been conducted in a limited number of countries. Out of the 140+countries that produce Nile tilapia, research has been conducted in only 24 countries on the implications of these parasites on *O. niloticus*. This research distribution can be categorized as follows: lower-middle-income countries accounted for the largest proportion at 41.7%, upper-middle-income countries at 33.3%, high-income countries at 16.7%, and low-income countries at 8.3% (World Bank, 2011). Most of these studies were in areas where *O. niloticus* has been introduced (20) versus native (four). An illustration of the number of studies included in this review by country is shown in Fig. 2.

When comparing the number of studies (94) included in this review, 75 of these were in aquaculture/farm settings, 14 were in the wild, and five were in experimental settings (Fig. 3). This gives a clear indication of the disproportionate focus of studies on fish parasites of Nile tilapia in aquaculture settings (80%) compared to those conducted in the wild (15%) and experimental settings (5%) even though this species has a wide distribution range. This distribution could be attributed to the practicability and convenience of studying the effects of parasites in controlled environments (Sindermann, 1987) compared to natural ecosystems, which are highly complex with numerous interacting factors. Additionally, given aquaculture's economic importance, more resources may be allocated to understanding and mitigating parasite impacts in aquaculture settings, especially in major aquaculture-producing countries.

Among the countries analyzed in this review, Egypt has the highest number of reports on pathogen taxa infecting Nile tilapia. Following Egypt in

Table 1 Search strings to identify studies on the implications of Nile tilapia parasites to fish, environmental, and human health

Fish health	((Nile tilapia OR *Oreochromis niloticus*) AND (parasit[a] OR bacteria OR fung[a] OR virus OR prion OR pathogen[a] OR helminth)) AND (loss[a] OR econ[a] OR impact OR mortality OR risk OR disease)
Environmental health	(((Nile tilapia OR *Oreochromis niloticus*) AND (parasit[a] OR bacteria OR fung[a] OR virus OR prion OR pathogen[a] OR helminth)) AND (ecosystem[a] OR environment[a] OR biodiversity OR water)) AND (indicator OR sentinel OR marker OR tag)
Human health	((Nile tilapia OR *Oreochromis niloticus*) AND (parasit[a] OR bacteria OR fung[a] OR virus OR prion OR pathogen[a] OR helminth)) AND (zoono[a] OR human health OR public health)

[a]Indicates a truncation Boolean operator

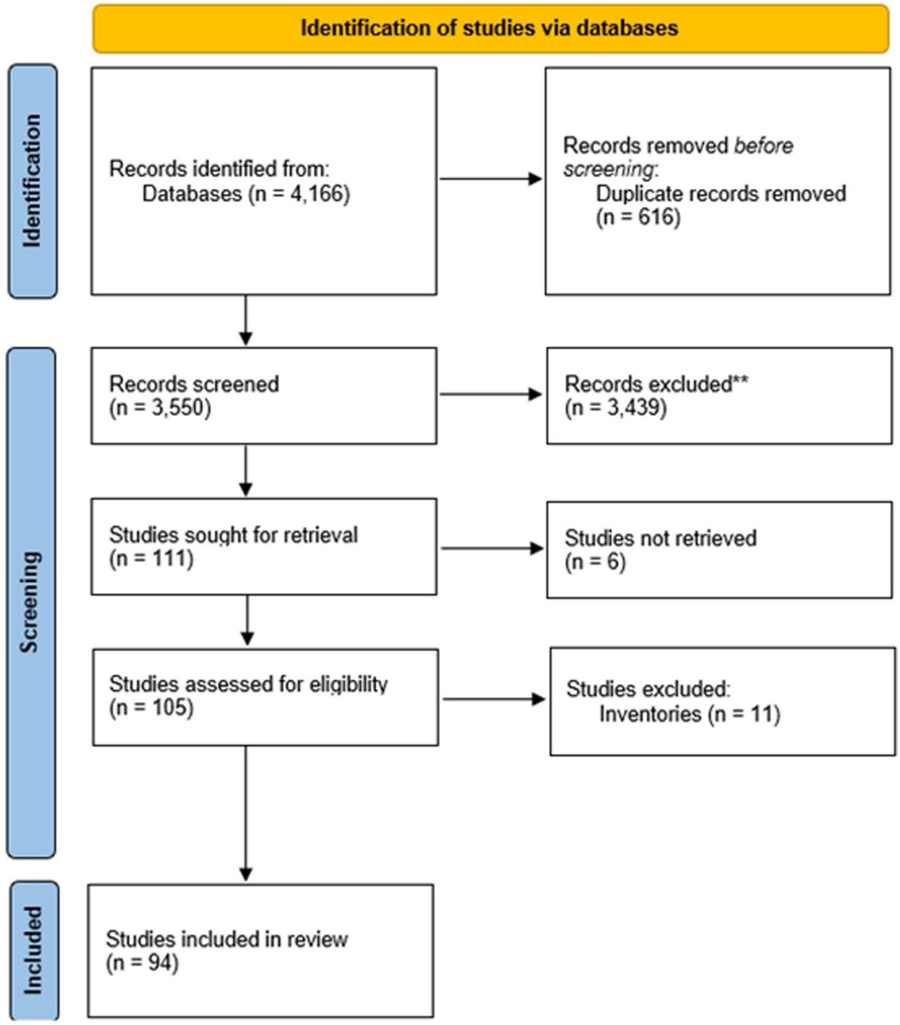

Fig. 1 Flow diagram describing the paper selection process according to PRISMA-ScR guidelines

descending order of occurrence are Brazil, India, the USA, and Mexico (Fig. 4). An explanation for the high number of reports in Egypt and Brazil is that they are the foremost producers of Nile tilapia in Africa and the Americas, respectively (El-Sayed & Fitzsimmons, 2023).

Nile tilapia parasites and fish health

From the combination of search terms and Boolean operators (Table 1), 3,006 papers (a subset of 4,166 in Fig. 1) contained information regarding the impacts of parasites on Nile tilapia health and aquaculture production. Of these, we analyzed 76 papers (66 of these studies were in an aquaculture setting, three were exclusively experimental, while seven were conducted in the wild), representing only 2.5% of the total papers identified. To be included in the analysis, we checked for papers that looked at the actual effect of the parasite either in an observational study, host tissue sample collections, or challenge experiments. Although numerous parasite species are documented in Nile tilapia, only a few have been known to cause high mortalities or substantial economic losses in fish production, as seen from our analysis. Presumptive diagnoses of these infections were made by assessing clinical symptoms, examining wet mounts and tissue smears stained with Giemsa or Gram stain, necropsy, histopathological analysis, bacterial culture, and biochemical screening (Dong et al., 2023). According to the analysis, bacterial infections had the

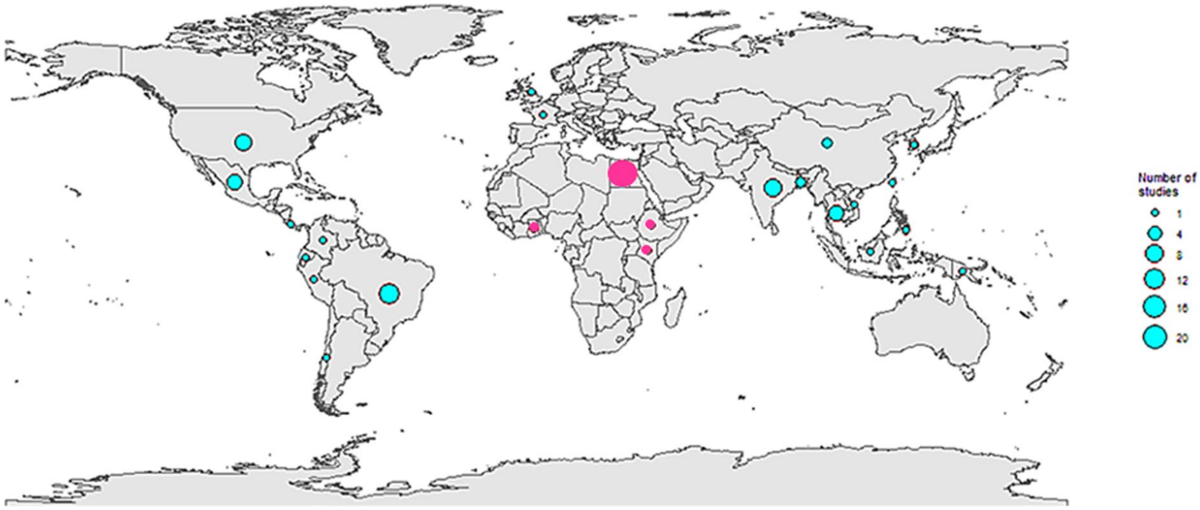

Fig. 2 Countries and number of studies on the links between Nile tilapia parasites and fish, human, and environmental health. Pink circles represent where Nile tilapia is native, while blue circles show where it has been introduced

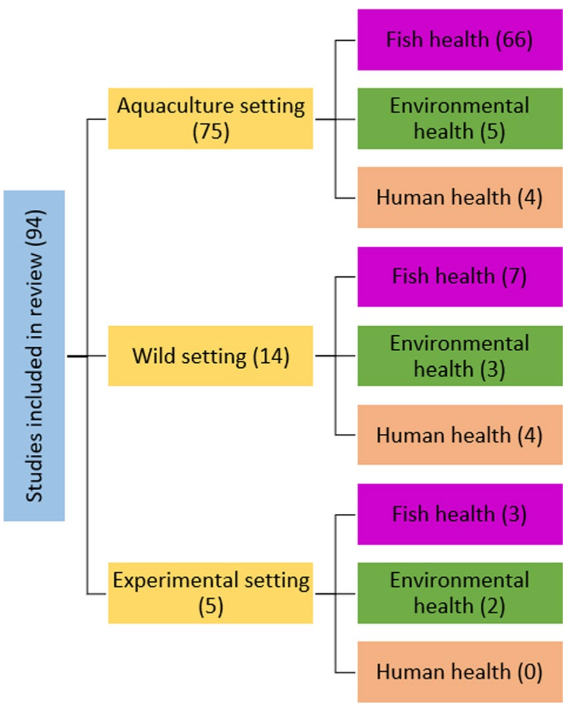

Fig. 3 Flow diagram showing the number of studies included in this review, those in aquaculture/wild/experimental settings, and the number of studies based on the topic, i.e., fish/environmental/human health

highest recorded impact on Nile tilapia, accounting for 63% of the disease outbreaks and mortality events, followed by viral infections, which accounted for 18% of such cases (Fig. 5).

The data in Figs. 4 and 5 show that while bacterial and viral infections dominate pathogen impacts on Nile tilapia, infections from myxozoans, monogeneans, protozoans, fungi, and digeneans collectively account for 19% of the effects reported. This observation is consistent with the findings of Shinn et al. (2023), which also noted a knowledge gap in the pathogenicity of these parasite taxa in aquatic environments and calls for the need for more research on these less-studied pathogen groups to understand their effects on Nile tilapia health and production fully.

When Nile tilapia experience conditions that cause stress, such as being crowded together in high numbers, experiencing sudden changes in water temperature, not being fed adequately, or being exposed to high levels of organic matter in the water, it is more probable for the pathogens to spread among them (Pillay & Kutty, 2005; Akoll & Mwanja, 2012; Walakira et al., 2014). Aquaculture systems offer an advantage in studying host–parasite interactions over the wild as they provide an opportunity to closely monitor and document disease outbreaks in fish populations, which can provide valuable insights into pathogen evolution and virulence (Leung & Bates, 2013).

Bacterial pathogens are considered the primary cause of fish death in tilapia farming, responsible for

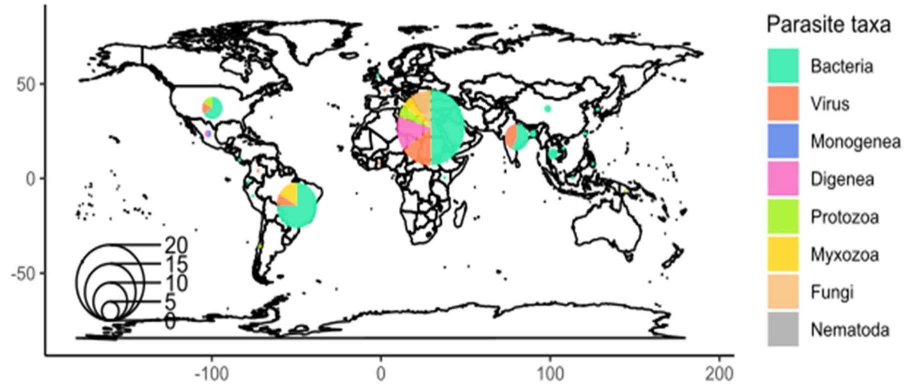

Fig. 4 Reports of pathogen taxa distribution of Nile tilapia per country

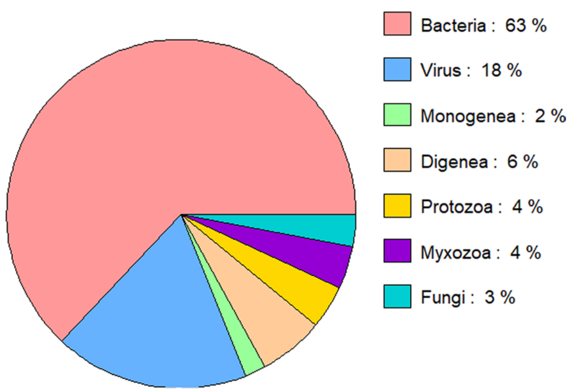

Fig. 5 Percentage distribution of pathogen taxa impacting Nile tilapia health

about 80% of mortality cases (Ibrahim, 2019). Bacterial pathogens belonging to families such as Enterobacteriaceae, Aeromonadaceae, Vibrionaceae, and Pseudomonadaceae (Mesalhy, 2013) cause most of the diseases. The bacterial pathogens reported by Mauel et al. (2007), Eissa et al. (2008), Soto et al. (2009), Leal et al. (2014), Elgendy et al. (2015), Rodrigues et al. (2018), and Sumithra et al. (2019) in Nile tilapia caused disease outbreaks, morbidity, massive mortalities, and ~ 50% reduction in tilapia biomass.

Tilapia Lake Virus (TiLV) infection is an emerging and transboundary disease (Aich et al., 2022). Currently, infection with TiLV has been reported from samples of Nile tilapia collected in India (Behera et al., 2018; Saranya & Sudhakaran, 2020; Rao et al., 2021), Egypt (Fathi et al., 2017; Nicholson et al., 2017), Thailand (Nicholson et al., 2020), Colombia (Contreras et al., 2021), and Bangladesh (Debnath et al., 2020). In the outbreaks reported by Dong et al. (2017) and Ferguson et al. (2014), fingerlings (juvenile fish in early developmental stages) were mainly affected. However, other studies showed that TiLV can infect Nile tilapia at any stage of their life cycle, and it has been reported to cause mortality rates of up to 90% worldwide (Jansen & Mohan, 2017; Aich et al., 2022).

Reports and studies on co-infections in Nile tilapia demonstrate considerable variations in terms of pathogenic mechanisms, progression of disease, and the severity of infections compared to cases of single-pathogenic infections. These co-infections involve two or multiple pathogens infecting the same host, either simultaneously or as secondary concurrent infections (Abdel-Latif et al., 2020). The clinical and pathological characteristics also differ from those observed in cases where the pathogens act in isolation. In Nile tilapia, co-infecting pathogens such as *Aeromonas jandaei* Carnahan et al. 1992 and *Aeromonas veronii* Hickman-Brenner et al., 1987, both gram-negative bacteria; *Francisella noatunensis* subsp. *orientalis* Ottem et al. 2009 and *Streptococcus iniae* Pier and Madin 1976, gram-negative and gram-positive bacteria, respectively; *Streptococcus agalactiae* Lehmann and Neumann 1896, gram-positive bacteria; *Gyrodactylus cichlidarum* Paperna, 1968 and *Cichlidogyrus sclerosus* Paperna & Thurston, 1969, monogeneans; *Gyrodactylus niloticus* Cone, Arthur et Bondad-Reantaso, 1995, monogenean and *S. iniae*, bacterium; *Ichthyophthirius multifiliis* Fouquet, 1876, ciliate protozoan and *S. iniae,* bacterium;, and *Flavobacterium columnare* (Bernardet and Grimont 1989 *ex* Davis 1922) Bernardet et al. 1996; gram-negative bacteria; *Myxobolus tilapiae* Abolarin, 1974, myxozoan; *S. iniae* and *Candida albicans* Berkhout, 1923, fungus; and *Pseudomonas fluorescens* Migula 1895, gram-negative bacteria, and *C. albicans,* fungus; have resulted in increased mortality rates, reduced growth, decreased immune reaction, and overall compromised health, which makes it easier for other pathogens to invade and establish infections (Xu et al., 2009, 2007; Eissa et al., 2013, 2021; Dong et al., 2015; Oda et al., 2016; Nicholson et al., 2017, 2020; Surachetpong et al., 2017; Ramírez-Paredes et al., 2021; Assane et al., 2022). To mitigate the harmful effects of co-infection in Nile tilapia, it is essential to increase research to investigate the potential mechanisms of interaction between these concurrent pathogens, which are still poorly understood (Abdel-Latif & Khafaga, 2020).

While certain diseases like the digenean-associated black spot disease (BSD), caused by *Neascus* spp., *Diplostomum* spp., and *Uvulifer* spp., may not result in considerable pathological harm in Nile tilapia, they do affect the physical appearance of the fish, leading to their rejection in the market (Violante-González et al., 2009; Wanja et al., 2020; Charo-Karisa et al., 2021).

To evaluate the economic consequences of Nile tilapia parasites, researchers examine the impact of these parasites on infected fish and determine the number of mortalities that have occurred. Although mortality is a commonly employed metric, precise measurement can be difficult, mainly when dealing with many fish deaths, as is often the case with juvenile fish (Peeler & Taylor, 2011; Shinn et al., 2023). Even though necropsies and histopathology are used to determine the cause of death, accurate monitoring of fish mortality rates can assist in identifying threats and risks of zoonosis and address management concerns. However, many Nile tilapia farmers do not maintain reliable and consistent records of such data. This lack of consistency in keeping mortality records makes it challenging to determine the extent of production loss and ultimately hinders the ability to calculate economic losses (Jia et al., 2018; Delphino et al., 2019).

Nile tilapia parasites and environmental health

We identified 306 papers (a subset of 4,166 in Fig. 1) that discuss parasites of Nile tilapia as indicators of environmental quality. We included ten (five studies in an aquaculture setting; two were experimental, while three were in the wild) out of 306 papers representing a proportion of 3.3%; the inclusion criteria were studies conducted to investigate the potential of these parasites as environmental quality bioindicators. This low proportion of studies shows how the bio-indication potential for Nile tilapia parasites is almost entirely overlooked. At the same time, many opportunities exist in environmental parasitology and ecosystem health assessment. Several investigations conducted on Nile tilapia aquaculture have examined different types of parasites, such as cestodes, crustaceans, protozoans, and monogeneans, and their abundance has been evaluated with respect to the water quality parameters within the farm (Ojwala et al., 2018; Aly et al., 2020; Cavalcanti et al., 2020). The aforementioned parasites were observed to have either positive or negative associations with the physiological and chemical variables, as shown in Table 2.

Analyzing the correlations between the parasite numbers and physiological and chemical variables reveals intricate relationships, suggesting environmental stressors and potential indicators for parasite outbreaks. This also emphasizes the multifaceted nature of parasite dynamics in aquatic ecosystems. In response to using parasites as early warning indicators for degraded aquatic ecosystems, Sanchez-Ramirez et al. (2007) developed a model to assess the state of tropical aquatic environments based on the relationship between Nile tilapia and *C. sclerosus* (gill monogenean). Their research revealed that exposure to sediments polluted with polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls, and heavy metals significantly increased *C. sclerosus* abundance. The abundance of *C. sclerosus* increased in treatments with low to reasonably high-pollutant concentrations but declined at high sediment pollutant concentrations. Similarly, exposure to polluted sediments induced immunosuppression in Nile tilapia, consequently increasing histological damage (including hypertrophy and hyperplasia in secondary gill lamellae and spleen melanomacrophage centers, respectively) and allowing persistent *C. sclerosus* infection.

On the other hand, acanthocephalans can accumulate heavy metals, surpassing that of free-living organisms used as indicators of environmental pollution. They exhibit a high capacity for metal uptake and demonstrate a rapid response to changes in environmental metal exposure (Sures, 2003). Compared to their hosts' tissues, these parasites can accumulate

Table 2 Correlation of water quality parameters with Nile tilapia parasite numbers

Parasite species	Parasite taxa	Temperature	DO	Turbidity	pH	Conductivity	SRP	TN	Organic matter	Nitrates	References
Amirthalingamia macracantha (Joyeux & Baer, 1935)	Cestode			+			+				Ojwala et al. (2018)
Acanthogyrus tilapiae (Baylis, 1948)	Acanthocephalan			+			+				Ojwala et al. (2018)
Cryptobia spp.	Kinetoplastean	+	+		+						Ojwala et al. (2018)
Chilodonella spp.	Protozoan	+	+		+			+	+		Ojwala et al. (2018)
Microsporidia spp.	Microsporidian	+	+		+			+	+		Ojwala et al. (2018)
Ichthyobodo spp.	Protozoan	+	+		+			+	+		Ojwala et al. (2018)
Trichodina spp.	Protozoan	+	+		+			+	+		Ojwala et al. (2018)
Trichodina fultoni Hoffman, 1967	Protozoan	+									Aly et al. (2020)
Trichodina salmincola Wellborn, 1967	Protozoan	+									Aly et al. (2020)
Cichlidogyrus halli (Price & Kirk, 1967)	Monogenean					+		+	+		Ojwala et al. (2018)
Cichlidogyrus sclerosus	Monogenean	-	-	-	+	+			+		Cavalcanti et al. (2020)
Cichlidogyrus thurstonae Ergens, 1981	Monogenean	+	-	-		+			+		Cavalcanti et al. (2020)
Cichlidogyrus tilapiae Paperna, 1960	Monogenean		+	+		-			-		Cavalcanti et al. (2020)
Scutogyrus longicornis Paperna and Thurston, 1969	Monogenean		-	-		+			+		Cavalcanti et al. (2020)
Argulus spp.	Crustacean							+	+		Ojwala et al. (2018)
Lernaea cyprinacea Hermann, 1783	Crustacean	+						+	+		Ojwala et al. (2018)

DO Dissolved oxygen, *SRP* Soluble Reactive Phosphorous, *TN* Total Nitrogen, + positive correlation, – negative correlation metal concentrations several thousand times higher (Nachev et al., 2013; Mehana et al., 2020). In the case of Nile tilapia, *Acanthogyrus* sp. has been observed to display elevated levels of lead in its tissue compared to the tissues of the host fish. A study conducted in a Philippine freshwater lake revealed that the acanthocephalan accumulated higher levels of lead than the fish host's tissues (*O. niloticus*). This study found that the parasites accumulated lead by 102, 119, and 147 times more than the host's intestine, liver, and muscle, respectively. The finding indicates the potential of *Acanthogyrus* sp. as a bioindicator for monitoring metal concentrations as it can efficiently accumulate and store lead, effectively acting as an active biosink for this metal (Paller et al., 2016).

Nile tilapia parasites and zoonosis

We identified 854 papers (a subset of 4,166 in Fig. 1) with information on Nile tilapia parasites that may pose a potential zoonotic threat. From our review, only eight (four in the wild setting and four in the aquaculture setting) out of the 854 papers representing a proportion of 0.9% met the inclusion criteria, i.e., focused on studying the parasite explicitly as zoonotic (hence not merely mentioning its zoonotic potential). Fish-borne zoonotic parasites can be passed to humans by eating inadequately cooked fish, coming into contact with contaminated water, and handling fish carrying these parasites (Chai et al., 2005). The list of potential zoonotic parasite species included in this review and their prevalence and locality in Nile tilapia is shown in Table 3.

In Nile tilapia, only one case report of a representative of the aquatic intestinal fluke, *Heterophyes*, has been reported to be zoonotic to residents in northern Egypt. The zoonotic transmission was more prevalent among females, individuals engaged in fishing activities, housewives, and those aged between 5 and 14 years (Lobna et al., 2010). There is still limited information on the zoonotic parasites of Nile tilapia. However, the lack of published information on food-borne parasites in Nile tilapia in any given country does not necessarily mean these parasites are absent. Instead, this lack tends to mirror the lack of involvement and awareness of the relevant scientific communities, mirroring the poor availability of funds dedicated to the issue, making this a case of "undone science" (Frickel et al., 2009). Due to the non-specific symptoms, such as diarrhea, vomiting, and abdominal pain, which can be easily mistaken for food poisoning or other gastrointestinal problems (Shamsi & Sheorey, 2018), the actual number of human cases of zoonotic parasites transmitted by Nile tilapia could be considerably higher than reported. Furthermore, while many bacterial pathogens primarily affect fish health, some, such as *Aeromonas*, *Vibrio*, and *Streptococcus* strains, can cause human infections by handling or consuming raw or undercooked fish (Haenen et al., 2023). These bacterial zoonotic cases originating from tilapia farming are globally underreported, ranging from mild infections, e.g., mycobacteriosis and swimmer's granuloma, to severe conditions, e.g., necrotic fasciitis. Similarly, only a few fish-borne zoonoses are detected, with the number of cases per year being small compared to other zoonotic diseases in animals or humans, such as salmonellosis.

Table 3 Potential zoonotic parasite species in Nile tilapia

Parasite species	Prevalence	Locality	References
Haplorchis pumilio (Looss, 1896) Looss, 1899	12.5%	Vietnam	Chi et al. (2008)
Cryptosporidium parvum Tyzzer, 1912	2.4%	Papua New Guinea	Koinari et al. (2013)
Contracaecum sp.	54.4%	Ethiopia	Abiyu et al. (2020)
Heterophyes sp.	30%	Egypt*	Lobna et al. (2010)
Prohemistomum vivax (Sonsino, 1892), *H. pumilio* & *Pygidiopsis genata* Looss, 1907	–	Egypt	Mahdy et al. (2021)
H. pumilio	12.5%	Vietnam	Phan et al. (2010)
Haplorchis spp. & *Procerovum varium* Onji & Nishio, 1916	–	Vietnam	Hung et al. (2015)
H. pumilio	–	Taiwan	Chai et al. (2005)

Egypt*—the only case report of zoonosis in Nile tilapia

Consequently, these fish-borne zoonotic parasites are often regarded as less important than other disease-causing agents. They are mostly excluded from the curricula of medical or veterinary schools, leading to a lack of awareness among medical practitioners and diagnosticians at the national level (Shamsi & Sheorey, 2018).

Conclusion

The emphasis in Nile tilapia disease research is primarily placed on identifying and isolating pathogens, with comparatively less attention given to establishing potential correlations between risk factors and outbreaks of the pathogens (Shinn et al., 2023). Similarly, research on fish health is often prompted by crisis events, such as high farm mortality rates. This is partly due to the limited understanding of health management issues among some fish farmers, making recognizing signs of disease in their fish challenging. As a result, disease outbreaks may go undetected until they become severe, leading to urgent investigations (Akoll & Mwanja, 2012).

Following the implications of parasitological studies analyzed in this review, the effect of parasitic infections on wild populations is poorly understood even though the parasites reported in aquaculture facilities could have an impact on local fauna, mainly through the co-introduction of parasites alongside non-native Nile tilapia either as escapees or intentional release into the wild. This lack of knowledge makes it difficult to predict and mitigate the effects of non-native fish species and their parasites on native species and ecosystems, highlighting the need for more research on the ecological consequences of Nile tilapia introductions, particularly spillover to native species.

Due to the limited number of fish health specialists and remote locations of most tilapia farms, laboratory testing facilities are not easily accessible. This means the causative agents responsible for diseases are not characterized, and inappropriate treatment processes may increase fish mortality. This poses a challenge because sending animal samples to specialized laboratories can result in significant delays of days to weeks before receiving results (Dong et al., 2023). This delay is especially problematic for diseases that rapidly lead to high morbidity and mortality, as waiting one or two weeks for test results is not an ideal situation. Point-of-care-testing (POCT) tools that can deliver prompt and accurate test results at the tilapia farm level are crucial in reducing the turnaround time for testing. These tools are essential in facilitating timely decision-making by providing rapid access to diagnostic information (Stentiford et al., 2017; Shinn et al., 2023).

The lower market value of Nile tilapia compared to cyprinids and salmonids can create a problematic situation in terms of health management. This is because the low profits earned from Nile tilapia production may not be enough to justify thorough investigations and a wide range of treatment options (Shinn et al., 2023). As a result, producers may be less inclined to take proactive measures to manage the health of Nile tilapia, as the costs of intervention may outweigh the potential profits gained from increased survival rates up to the harvest stage.

Understanding the dynamics of fish parasites and their impacts on human, fish, and environmental health is essential for developing and implementing effective One Health strategies. The available evidence suggests that this kind of information is lacking. Therefore, it is vital to recognize and include fish parasites within the One Health framework to ensure that they receive adequate attention. Despite not necessarily causing acute infections, they still are a huge burden on the health of fish, humans, and the environment. To address the existing knowledge gaps concerning the biology and impacts of these parasites, interdisciplinary efforts are needed. Indeed, the difficulty in creating such needed collaboration involving biologists, veterinarians, medical doctors, economists, sociologists, and aquaculture actors appears as one more potential explanation for the current knowledge gap this paper is highlighting.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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