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Fish Parasites as Biological Indicators: A Systematic Review

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ABSTRACT

The quality of the aquatic ecosystem has been severely degraded by anthropogenic activities over the last decade. The industrial wastes, effluents from paper mills, thermal effluents and run-off from agricultural lands act synergistically with the global climatic changes and alterations in seasonal cycles to affect the physico-chemical parameters of the water bodies and the life they sustain. Out of various impacts of the health of aquatic ecosystem on the environment, one tangible effect is definitely on the fishing industry. This emphasizes the importance of the study of bioindicators to estimate the extent of contamination of water bodies. Recently, various studies have highlighted the prospects of fish parasites as ecological indicators. Most of these studies include digenean trematodes, cestodes, nematodes and acanthocephalans parasitizing the fish gut. Ciliates and other protozoan parasites have also been studied, though not extensively.Endoparasites are more common in these studies because ectoparasites have been found to be more sensitive to changes in water quality parameters restricting their availability from polluted water bodies. Many endoparasites, especially the acanthocephalans, can acquire and store heavy metals in their bodies at concentration higher than those in host tissues. The parasites have been found to differ in their bioaccumulation and bioconcentration abilities and thus their bioindicator properties. They have also been found to act as indicators for eutrophication, acidification, hydrocarbons and other organic pollutants. As in every study in its nascent stage this too has certain limitations. Some of these include the complexities of the host-parasite relationships in a polluted environment, the taxonomic inter-relationships between them and the complicated physiology of metabolism of pollutants. The current review goes through the research studies undertaken in this field and tries to explore the potentialities of fish parasites to be used as bioindicators, analyse the constraints therein and highlight the thrust areas for future studies.

KEY WORDS: AQUATIC ECOSYSTEM, BIOINDICATOR, FISH PARASITE, POLLUTION.

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INTRODUCTION

The concept of parasite has changed in the recent years. Marcogliese (2005) rightly pointed out that parasites shouldn't just be treated as organisms that need to be eliminated. They are important and integral part of the ecosystem conveying information not only on environmental stress, trophic structure and function but also on biodiversity (Marcogliese, 2004). However, there is a dearth of knowledge about the important roles of parasites in ecosystems (Marcogliese, 2004). Reportedly, the parasites serve as useful indicators of persistent ecological interactions since their life cycles clearly depict seasonal patterns and reflect the history of co-evolution between host-parasite relationships (George-Nascimento, 1987).

Parasites are useful indicators of ecosystem stability (Marcogliese and Cone, 1997). As Steedman (1994) had remarked that ecosystem health cannot be measured directly, study of the parasites and host-parasite system would serve a more important and effective way of monitoring ecosystem health. Fish parasites form an important part of the aquatic biodiversity and thereby show close co-relations with the changes of both the external and internal environment of the hosts (Palm, 2011). The changes invoked in the hosts may cause changes in the parasites both directly and/or indirectly (Palm, 2011). Pollution and stress have resulted in reduction of species richness of parasites (Marcogliese, 2004).

Some recent investigations (Yen Le et al., 2014; Bayoumy et al., 2015; Biswas and Pramanik, 2016; Gilbert and Avenant-Oldewage, 2017; Leite et al., 2017; Sures et al., 2017; Ashmawy et al., 2018; Naggar et al., 2018; Al-Hasawi, 2019; Mehana et al., 2020) point towards the manifold importance of the study of fish parasites as biological indicators. Indirectly they serve as parameters to assess the extent of damage caused by human activities as a result of overexploitation of the marine and/or freshwater bodies used as "dumping grounds" which combined together with the effects of climate change on the aquatic ecosystems sends a warning signal (Palm, 2011).

The relationship between the parasitic species and its environment is reportedly affected by almost 30 biotic and abiotic factors (Williams and Jones, 1994). This exemplifies the use of parasites in these studies. Lafferty (1997) described eight parameters to assess the environmental health based on parasite systems. This included heavy metals, acidification, sewage-sludge, industrial effluents, crude oil, pulp-mill effluent, thermal effluent, eutrophication and unspecified human disturbance. They studied mainly the Digenea, Acanthocephala, Cestoda, Monogenea, Nematoda and Ciliophora. Lafferty (1997) had mentioned that eutrophication caused an increase in parasitism whereas heavy metals and "unspecified human disturbance" caused a reduction in parasitism.

Attrill and Power (2002) reported the complexities of the combined effects of climate change and temperature on the ecology of host-parasite system. Marcogliese (2001) highlighted the consequences of climate change on the biotic and abiotic aspects of the aquatic ecosystem. Landsberg et al. (1998) aimed at developing a cost-effective index for monitoring and assessment of estuarine health depending on the fish-parasite ecology in combination with the changes caused by pollution. Studies have shown that marine ecosystems are much more stable as compared with that of fresh water ecosystems. As a result, the fish parasite diversity per host is higher in marine ecosystem (Palm, 2011). Marine parasites are thus equally important and have fewer drawbacks than the free-living animals as pollution-indicators (Marcogliese and Cone, 1997).

The current paper aims at the review of the recent trends in development of the use of this recent interdisciplinary approach involving the field parasitologists and ecotoxicologists as an important tool for monitoring and assessment of the health of aquatic ecosystem, its importance and prospects. In developing countries where the fishery industry is an important commercial aspect with millions being dependent on it, such studies are very important. Apart from this, the field also provides opportunities galore to devise cost-effective ways of monitoring the aquatic ecosystem.

Foundations of the use of fish parasites for monitoring and assessment of the aquatic environment: Pollutants and other environment manipulating factors may affect parasitism environment in both ways. Parasitism may be on the rise if the impact serves to reduce the host resistance or causes an increase in the density of the intermediate and/or definitive hosts (Lafferty, 1997). Other way round, parasitism may decrease if the impact results in the reduction of density of the intermediate and/or definitive hosts or it directly causes high mortality rates in the parasites because of the toxic effects or by indirectly causing the sufferance of the infected hosts and thereby the parasites (Lafferty, 1997).

The use of fish parasites as indicators is based on the fact that they are known to have life cycles that vary greatly in different species with one or more developmental stages infecting animals commonly used as markers or associated with the sea-sediments (especially the eggs and /or larvae) (Williams and MacKenzie, 2003). In case the free living stage(s) of the parasites are closely related to the sea bottom or sea sediments they alone can serve as indicators (White, 1984). These free-living infective stages of various parasites are delicate and highly sensitive to the surrounding environmental conditions enabling them to act as good indicators of pollution (Overstreet, 1993; MacKenzie, 1999). Free-living stages of parasites are also used in standard toxicity tests (Morley et al., 2003; Pietrock and Marcogliese, 2003).

MacKenzie et al. (1995) and MacKenzie (1999) suggested that the transmission stages of parasites, specially the helminths could serve as early warning sign of marine pollution and was supported by the results of works carried out by Cross et al. (2001). Thus, sufficient knowledge on the biology of the parasites and their host as well as the host-parasite relationship is an important tool to detect environmental changes.

In case of heteroxenous parasites, the environmental conditions must be favourable at all stages of the intermediate hosts and the free living stage(s) of the parasite (if present) (Sures, 2008). However, in case of the monoxenous parasites only the environmental conditions of the host and the parasite should be taken into account (Sures, 2008). The density of these parasites in their respective host(s) may change if their life cycle is affected due to non-availability or poor availability of the intermediate hosts as a result of pollution (Palm, 2011). Thus, a study of the intermediate hosts and their availability at certain sites serve as important indicators for the occurrence of heteroxenous parasites in a polluted area (Overstreet et al., 1996).

The intermediate host(s) exposed to the environment directly may be more sensitive to changes while the endoparasites living within the hosts are prevented from such drastic changes and have a more or less stable existence (Paperna and Overstreet, 1981). Parasite species that are short lived and have direct life cycles like those of the ectoparasite protozoans or monogenean trematodes react to the direct environment of the hosts (Lester, 1990). Sures (2008) had opined that since the ectoparasites are in continuous contact with the water they may develop resistance to changes in water quality by alterations in their immune system (MacKenzie et al., 1995; MacKenzie, 1999). The outcome of such interactions is that the changing environmental conditions have less effect on monoxenous parasites as compared to that of heteroxenous parasites (MacKenzie, 1999).

Reports show that there is a trend in the increase of ectoparasitic infections and a decrease in endoparasitic infections with rising levels of pollution (Sures, 2005; MacKenzie, 1999). Reports of Khan and Kiceniuk (1983) and Khan (1987) show that decrease in the endoparasite infections with rising levels of pollution may be attributed to its negative effects on the intermediate hosts which in turn reduces infection in the definitive hosts. They had substantiated their reports using *Steringophorus furciger* (Trematoda) and *Echinorhynchus gadi* (Acanthocephala) as examples.

The parasite content of the fish may also serve as an important parameter for studying their feeding ecology and behavioural aspects (Klimpel et al., 2010; Palm, 2011). Parasites often represent an integration of several food chains, thereby forming an important part of the food web and many of them are in fact transmitted form one trophic level to another via intermediate host(s) (Marcogliese, 2004). Taking cue from this, one can successfully use the long lived life-cycle stages of the parasites and integrate the information with the detailed analysis of the stomach content of the fishes to derive information regarding the prey organisms which in turn helps in better understanding of the food web and other ecological aspects of the fish which would otherwise be difficult to study in some cases because they live under extreme conditions and are not easily accessible (Palm, 2011). Many workers have used the information to study the life cycles of many parasites like *Contracaecum* sp. and *Pseudoterranova* sp. (Klöser et al., 1992; Palm, 1999).

The impact of anthropogenic activity can also be deciphered form the biodiversity study of aquatic environments. For example, overfishing may cause a marked reduction (or even depletion under extreme conditions) of one or more species thereby reducing the biodiversity. This affects the parasite population adversely by affecting the availability of the intermediate host(s). Thus these studies are very important tools for assessment of environmental stress and the study of food web structures and biodiversity as shown by Marcogliese (2005).

The parasite populations may also serve as good indicators of climatic change since it is co-related with changes in ocean temperatures, salinity and circulation (Palm, 2011). Harvell et al. (2002) had demonstrated that climate change may affect the host-parasite interaction by augmenting the pathogen development rates, transmission or generation times annually or increasing the overwinter survival rate of the parasite or by raising the host susceptibility to thermal stress factors. This view has been supported by many time-based studies carried out by several workers like those of MacKenzie (1987) on the cestodes, *Grillotia angeli* (in mackerel) and *Lacistorhynchus* sp. (in herring).

Parasite species of certain digenean trematodes, cestodes or nematodes or any of their life cycle stage(s) that are long lived help in predicting the seasonal migration of the host species as well as the migratory behaviour of different life-history stages of the host (Williams et al.,1992; Palm, 2011). The original locality of the infection may be determined if there is sufficient knowledge regarding their abundance in different regions and the stages of hosts attacked by the parasites. Studies of Lühe (1910), Shulman (1957), Palm (2004), Klimpel et al. (2010) and Buchmann (2019) show the transfer of parasites or their dispersal by the migration of fishes from one region/part to another.

These reports also show that the parasites originating in the sea waters/ oceans may be transferred to the fresh water by extensive fish migrations.

Gibson (1972) could separate flounders (*Platichtys flesus*) form two estuaries and the sea based on dissimilar parasite faunas harboured by them. Thereby, the foreign flounder population migrating into these water bodies could also be identified by their set of parasite fauna. In another work, Margolis (1982) differentiated between three different spawning stocks of salmon, *Onorhynchus nerka* using the presence/absence of two species of myxozoans, *Myxobolus articus* in their brain and *Henneguya salmonicola* in the musculature. Such stock differentiations were helpful for in-season management of fishery (Moser, 1991). Recently this knowledge has been used by Lester et al. (2001) and Charters et al. (2010) to differentiate between the Spanish mackerel from Australia and Indonesia based on differences in the metazoan parasite content of these fishes. This is valuable information for the fishery industry for better utilization and sustainable harvest of the commercially important fishes (Palm, 2011; Buchmann, 2019). The details of these studies may be successfully applied to the native fish species of India or in any other country where the fishery industry contributes to national income.

Information regarding the parasite content of the fish species is equally important for identification of the parasites that may be transferred to the human beings via the fish musculature and may become a serious health issue (Palm and Overstreet, 2000). Study of such parasites of public health importance is another important aspect of the fisheries industry that should be taken care of. The reason for the abundance of such parasites at particular locations or ecological conditions (if observed) should be studied in details to develop control measures for them by simple manipulation of the environment of the fishes. Studies have demonstrated the prevalence and abundance of zoonotic parasites among different fish stocks from different geographical regions of the world (Palm, 2011). This forms the base for public health issue as well as for the thriving of tourism industry in a region (Palm et al., 2008; Klimpel and Palm, 2011).

The interplay between the effect of the pollutants on the immune system of the host and its reduced resistance to the parasites forms another important aspect of these investigations. Studies have demonstrated that exposure to immunosuppressive chemicals like heavy metals and PCB has negative effect on the immune system of the animals (Arkoosh et al., 1998; Bols et al., 2001). Immunosuppression caused by environmental pollutants might be one of the key-players in the successful establishment of the parasites (Sures, 2008). Some pollutants, mainly PAH, with immune-suppressive activities in the fish host affect the phagocytic activity either positively or negatively thereby affecting the intensity of gill-parasite infections (Williams and MacKenzie, 2003).

Such immune system based biomarkers may find important applications in assessment of water quality (Williams and MacKenzie, 2003). Hoole (1997) reviewed the effect of pollutants on the immune system of the host related to innate immunity, levels of antibody and leucocyte activity. He concluded that some of these factors of immune system may be augmented by certain pollutants which may in turn increase host-resistance to parasites. The opposite may also happen (Hoole, 1997). Studies should focus on immune evasion by parasites, evasion/tolerance of reactive oxygen intermediates, evasion of antibodies, proteinase inhibitor production and masking host proteins (Williams and MacKenzie, 2003).

The parasites not only affect the accumulation of the pollutants in the host but also their effects (Sures, 2008). Studies conducted by Baudrimont and De Montaudouin (2007) serve an important example. Their study demonstrated that the presence of digenean parasites in cockles exposed to cadmium (Cd) causes a decrease in the metallothionein concentration compared to uninfected individuals. There is a dearth of studies on the combined effects of the parasites and pollution with reference to the endocrine system of the hosts (Sures et al., 2006). Their analyses demonstrated an antagonistic relationship between the parasite and pollution. Eels infected with the swim bladder nematode, *Anguilicola crassus* exhibited increased concentrations of cortisol while the simultaneous presence of metal or PCB pollution or both caused a reduction in the levels of plasma cortisol. Same studies based on mammals however gave different and contradictory results. Generalised predictions on the effect of pollution and parasites on hormonal homeostasis of the host were found to be difficult and erroneous in some cases (Sures, 2008). This field requires a more exhaustive study before arriving at definite conclusions.

Another interesting aspect of the study of the parasites as biological indicators is its use in the identification of hosts, phylogenetic studies and also to decipher the systematic position (Rokici, 1983). Palm (2007) and Palm et al. (2009) devised a model system to study the ecology and co-evolution of the life-cycle of parasities in oceans using trypanorhynch cestodes. These works helped in the better understanding of the host switching of parasites (Palm et al., 2009) and the relaxed host specificity within certain groups of parasites (Palm and Caira, 2008). Analyses on the phylogeny of the deep-sea trematodes in fish by Bray et al. (1999) and nematode, *Anisakis simplex* in the whale hosts by Klimpel and Palm (2011) provide good examples of such studies.

Fish parasites as aquatic ecosystem indicators: The presence of certain parasites have been found to be closely co-related with some pollutants present in the water body. (i) Metals: Digeneans and acanthocephalans serve as good indicators of heavy metals and human disturbance (Lafferty, 1997). Experiments on acanthocephalans as accumulation indicators (Palm, 2011) include those on *Pomphorhynchus laevis* and *Paratenuisentis ambiguous* which demonstrated higher concentrations of cadmium (Cd) and lead (Pb) than their corresponding hosts (Sures, 2003; Sures and Siddall, 2003); *Aspersentis megarhynchus* with a higher heavy metal concentration (Ag, Co and Ni) than its host (Sures and Reimann, 2003) and many others (Mehana et al., 2020).

Cestodes have also been found to act as good indicators for heavy metals. Sures et al. (1997) reported a higher concentration of lead (Pb) and cadmium (Cd) from the tissue (posterior part of the proglottids) of the marine cestodes, *Bothriocephalus scorpii* than the tissue of the host, *Scophthalmus maximus*. Higher amounts of cadmium (Cd), lead (Pb) and zinc (Zn) was recovered from the tissue of *Carryophyllaeus laticeps* as compared to their cyprinid host, *Chondrostoma nasus* by Jirsa et al. (2008).

Barus et al. (2007) reported some nematodes like *Anguillicola crassus* and *Philometra ovata* also demonstrate higher heavy metal accumulations as compared to their fish hosts. Leite et al. (2017) studied the concentrations of thirteen different elements like lead (Pb), barium (Ba), aluminium (Al), magnesium (Mg), iron (Fe), copper (Cu), titanium (Ti), manganese (Mn), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd) and nickel (Ni) from the larval tissue of the nematode parasite, *Contracaecum* sp. and from the tissue of the fish host, *Acestrorhynchus lacustris*. The result showed that all of them, except one, had higher concentrations in the parasite larvae than in the host tissues (Leite et al., 2017). Eventually, it was concluded that the larvae of *Contracaecum* sp. could be successfully used for biomonitoring metal pollution because they could accumulate various essential, non-essential and toxic elements even during their larval stages (Leite et al., 2017).

Some intestinal parasites like the acanthocephalans have remarkable properties to bioaccumulate heavy metals in their tissues at concentrations as high as thousand times more than those of the host tissues (Mehana et al., 2020). However, these endoparasites vary in their abilities to bioaccumulate. Experiments performed with three groups of parasites, namely, trematoda (*Gyliauchen volubilis*), nematoda (*Procamalanus elatensis*) and acanthocephala (*Sclerocollum rubrimaris*) collected from the fish, *Siganus rivulatus* in the Red sea showed *S. rubrimaris* was a better bioindicator than the other two (Al-Hasawi, 2019). This was because *S. rubrimaris* had greater ability to bioaccumulate trace metals like cadmium (Cd) and lead (Pb) at concentrations higher than those of the host tissues (Al-Hasawi, 2019). Therefore, the bioconcentration factors of the parasite species determine their ability to act as good bioindicators of metal pollution (Al-Hasawi, 2019).

(ii) Hydrocarbons: MacKenzie et al. (1995) carried out extensive studies on the effects of marine pollution on two monogeneans *Diclidophora merlangi* (parasite on *Merlangus merlangus*) and *Dictyocotyle coeliaca* (parasite in *Raja radiata* and *Raja naevus*). Williams and MacKenzie (2003) highlighted their use as potential biomonitors of hydrocarbon pollution. Marcogliese et al. (1998) reported an increase in *Gyrodactylus* sp. infections in fishes as a result of increasing concentrations of PAHs (polycyclic aromatic hydrocarbons) and PCBs (polychlorinated biphenyls) in the aquatic environment. Study of the ratio of ciliates to digeneans in fish hosts serves an important index of the effect of crude oil in aquatic ecosystems (Lafferty, 1997).

Reports of Ruus et al. (2001) show that metacercariae of the trematode, *Bucephaloides gracilescens* from their host *Myoxocephalus scorpius* serves as an indicator for accumulation of lindane, a prominent environmental contaminant. The protozoan ciliophore, *Trichodina cottidarum* and *T. saintjohnsi* infecting *Myxocephalus octodecempinosus* have been reported to serve as important bioindicators for petroleum hydrocarbons present in the water (Khan and Thulin, 1991). Increased prevalence of the myxosporidia, *Ceratomyxa acadiensis* indicates rise in the levels of polycyclic aromatic hydrocarbons (PAHs) in the surrounding water (Khan, 1986). Increased PAH also results in the increased prevalence of monogenean trematodes (Khan and Kiceniuk, 1988).

Brázová et al. (2012) suggested that the acanthocephalan parasite, *Acanthocepahlis lucii* from perch intestines could acquire and accumulate PCBs (polychlorinated biphenyls) at concentrations higher than those of host tissues. The finding proposes the use of *A. lucii* as bioindicators of hydrocarbon pollution (Brázová et al. (2012). From studies conducted on larval stages of the parasitic cestodes, *Oncomegas wageneri* collected from the intestine of their fish hosts, *Cyclopsetta chittendeni* it was concluded that the concentrations of PAHm (polycyclic aromatic hydrocarbon metabolites) was higher in the larval cestodes than in the host bile (Soler-Jiménez et al., 2020). Therefore, they can be used to biomonitor PAH levels in the surrounding water (Soler-Jiménez et al., 2020).

Investigations on concentrations of PAHs like chrysene, dibenzo(a,l)pyrene, dibenzo(a,i)pyrene, benzo(g,h,i) perylene and indo(1.2,3-cd)pyrene among others from the parasitic trematode, *Aspidogastrea africanus* and their fish hosts, *Chrysichthys nigrodigitatus* showed the parasites absorb considerable amount of PAHs lowering their concentrations in their host (Akinsanya et al., 2020). Thus, they may be used as bioindicators to monitor PAHs in the water body. Additionally, it was also reported that the parasites preferred to infect female hosts and caused oxidative stress in their intestines (Akinsanya et al., 2020).

(iii) Eutrophication/Paper mill effluents/Thermal effluents: Ciliates and nematodes serve as sensitive indicators of eutrophication and thermal effluents(Lafferty, 1997). Barker et al. (1994) reported increased levels of the digenean parasite *Cryptocotyle lingua* in sites contaminated by pulp and paper mill effluents. Density of *Diplostomum* sp. has been reported to be an indicator of increasing eutrophication (Hartmann and Nümann, 1977). Other reported parasite bioindicators for eutrophication includes the acanthocephalan, *Echinorhynchus* sp.; the nematode, *Ascarophis nototheniae*; the trematode, *Dinosoma* sp. and the cestode, *Phyllobothrium* sp. (Moser and Cowen, 1991). Though there is a dearth of information regarding suitable fish parasite indicators for eutrophication and other effluents, studies by Johnson and Chase (2004) and Johnson et al. (2007) show that higher levels of eutrophication promotes higher prevalence of trematode infections in frogs because of the increased abundance of the intermediate snail hosts. Thus, this field has scope for further studies.

(iv) Acidification: Acidification has the most notable effects on population of digeneans (Marcogliese, 2005). Presence or absence of digeneans in fishes serve as indicators for assessment of the impact of acidification in the water sheds because acidification causes a reduction in the population of the intermediate host snails (Kurris and Lafferty, 1994). MacLeod and Poulin (2012) concluded from their experiments that parasites could be used as bioindicators of ocean acidification (OA) disturbance. In their further studies they had expressed their anxiety over the rising ocean acidification and its effect on productivity, biodiversity and ecosystem health (MacLeod and Poulin, 2016).

Their investigations showed that the presence of parasites affects the sensitivity of their hosts to ocean acidification. The death of the infected gastropods was significantly lowered under laboratory conditions imitating the circumstances of OA (MacLeod and Poulin, 2016). They had recommended further research on the area. Harland (2015) had mentioned the use of intertidal parasites as good bioindicators for assessing the impacts of ocean acidification. Harland (2015) had also suggested that ocean acidification may affect the transmission of parasites.

(v) Organic pollution/Bacterial biomass: According to the reports of Ogut and Palm (2005) *Trichodina* spp. act as indicators of organic pollution depicting the concentrations of nitrate, nitrite and phosphate in aquatic environment. Chubb (1997), Yeomans et al. (1997) and Yoemans et al. (1999) carried out investigations and discovered a link between the bacterial load of water bodies and increased trichodinid infestations in fishes. Palm and Dobberstein (1999) reported that *Trichodina* spp. also acts as an important bioindicator of bacterial biomass in the environment as they are known to be filter feeders with bacteria and algae forming important parts of their diet. Investigations by Yen Le et al. (2014) show that the parasites can not only bioaccumulate metals and heavy metals but also POPs (persistent organic pollutants) by virtue of the lipophilic nature of these molecules. The accumulation factor of these organic compounds is affected by certain biotic and abiotic factors as well (Yen Le et al., 2014).

Limitations of the use of fish parasites as indicators: The studies based on host-parasite system are not free from restrictions. Some of these include:

(i) Host-parasite relationships in a polluted environment: The host-parasite relationships in a polluted environment is highly complicated. For example, from the studies on roles of parasite in accumulating heavy metal(s)/other pollutant(s) it may appear that the reduced concentration of the pollutants in the host may be beneficial for the infected animals. It may thus be predicted that an infected animal when exposed to environmental pollution, the presence of parasite may be advantageous for them as the pollutants tend to accumulate more in the parasites harboured by them rather than the host themselves (Sures, 2008). This may seem to have a shielding effect from the toxic reactions of the pollutants when compared with the uninfected animals. However, this is not such a simple process and before such assumptions can be made, this field needs more studies to check whether the deleterious effects of the parasite on the host can be overlooked by the advantage it enjoys from the shielding effect (Sures, 2008).

(ii) Relationship between environmental factors and parasites: Lafferty (1997) had suggested that there was a weak association between parasites and environmental degradation because environmental factors had different effects and parasites responded differently complicating the whole scenario. Kennedy (1997) opined that fish parasites could be used as bioindicators only after the relationship between pollution and fish parasite have been studied in detail otherwise it would not be advantageous to use them over free living organisms. Marcogliese (2005) suggested that parasite communities do not serve as good pollution indicators in case of moderate levels of contaminants.

(iii) Lack of knowledge on ideal conditions for a fish parasite to qualify as a bioindicator: Vidal-Martínez et al. (2010) opined that the definite conditions under which a parasite may be considered to act as indicators of environmental change or impact becomes very difficult in large scale considerations because too many factors are involved and the study of such factors individually offers various complications. Catttadori et al. (2005) suggested that climate change events may lead to outbreak of parasitic infections which may cause dramatic, synchronized abundance of their hosts citing the nematode parasite, *Trichostrongylus tenuis* affecting red grouse as example. Studies of Kennedy et al. (2001) based on the larval cestode, *Ligula intestinalis* and roach hosts (*Rutilus rutilus*) suggested that parasite-host systems can also regulate the population structure of the ecosystem rather than climate change alone. Whatever may be, this field is rather naïve and needs more elaborate studies before making generalised comments.

(iv) Variability in response of the parasites to external changes: Parasites respond to environmental changes in various ways making generalized predictions extremely difficult. For example, Gheorghiu et al. (2006) reported an increase in the parasite population of *Gyrodactylus turnbulli* with the increase in concentration of zinc upto 120g/l in the surrounding water while an increase of zinc concentration beyond this may cause a reduction in the population of *Gyrodactylus turnbulli* (Gheorghiu et al., 2007) as it adversely affects the growth and reproduction of the parasites. A study by Gilbert and Avenant-Oldewage (2017) showed the sensitivity of oncomiracidia of *Paradiplozoon ichthyoxanthon* to dissolved aluminium (Al) under laboratory conditions. They had suggested that the parasites from both the marine and freshwater ecosystems in Africa could serve as bioindicators but the effects of the pollutants on those organisms needed to be studied in details. Such reports make it very clear that simple prediction between prevalence of parasite population and increase in concentration of a particular pollutant may be erroneous and needs an elaborate study.

(v) Difficulties in community-based monitoring of parasites: Studies based on single measures of parasite communities, like species richness, as indicators of specific environmental changes are not scientific and often erroneous because different taxonomic groups tend to respond in opposite directions (Lafferty, 1997). Community-level monitoring serves a more important tool for exhaustive assessment of environmental change and requires deeper insights in the association between the wide range of parasites and impacts (Lafferty, 1997). This requires both laboratory-based studies and field-based studies. There is however, a dearth of studies that combine field and laboratory evidences together (Lafferty, 1997). The effect of pollutants on the developmental stages of the parasites like the cercariae and miracidia of digeneans may also affect the parasitic communities and needs to be further investigated as suggested by Lafferty (1997). Most parasites are species specific being restricted to certain host species but there are some which infect a wide range of hosts. This sharing of parasites by the hosts affect the structure of parasitic communities in aquatic bodies (Buchmann, 2019) and any factor (including a pollutant) affecting this behaviour may interfere with parasitic communities. Such altered interactions may also affect the metabolism pathways of various pollutants as well as their toxic effects. This calls for further research in this field.

DISCUSSION

Sures (2008) had rightly remarked that the combined effects of the parasites and pollution on the host is very complicated and may be additive, synergistic or antagonistic making predictions extremely difficult. The gravity of this line lies in the fact that a parasite alone cannot be simply used as a bioindicator until and unless it is clear which stage of the parasite qualifies for the purpose and the myriad of factors affecting it. This is because there may be one to several free-living stages of a fish parasite that are exposed to the surrounding medium directly and the sensitivity of these stages (Poulin, 1992; Valtonen et al., 1997) to different concentrations of the pollutants need to be documented over a long period of time (Williams and Mackenzie, 2003) to understand how the dynamics of the parasitic population in the water bodies is affected by contamination. Since the behaviour of the parasite population varies with the pollutants, entire parasitic community in a water body may be affected.

This area has contradictory reports. While some studies claim that the population of the fish ectoparasites increases due to pollution (Khan and Thulin, 1991; Sures, 2005; Biswas and Pramanik, 2016) there are some studies which insist that the ectoparasite population decreases considerably because of their high sensitivity to the contaminating agents (Gilbert and Avenant-Oldewage, 2017). There maybe two explanations for this variation in results – first that the parasite species being considered in both the studies are different and the second one is probably the length of the free-living stages of the parasites in question. It cannot be negated that the duration for which the ectoparasites are exposed to the pollutants is sufficiently higher than those of the free-living stages of the endoparasites.

The shorter the length of the free-living stage the lesser is the effect of pollutants on it eventually resulting in increased parasitic burden of the final host. Another thing that needs consideration is the immunological reactions of both the ecto and endoparasites that allows them to survive the harmful effects of the pollutants. Sures (2008), however, suggested that ectoparasites probably develop immunological resistance to fluctuating environment due to their long periods of exposure. Immunity studies becomes particularly important in endoparasites because their free-living stages should be having some special mechanisms to evade the responses to enable them to survive over the ectoparasites under similar circumstances. Studies should be encouraged in these fields to enable the workers to understand how the system works and rethink the prospects of parasites being used as bioindicators.

Another aspect that seems to be neglected is the study of the effect of pollutants on intermediate hosts (Khan and Kiceniuk, 1983; Khan, 1987) because the continuity of the life cycle of the parasites demands the availability of the intermediate hosts. The pollutants may therefore affect the parasitic communities of an aquatic ecosystem mainly by three ways – a) exerting their direct effects on the developmental stages of the parasite, b) exerting their effects on the intermediate hosts affecting their availability and c) affecting the susceptibility of the definitive hosts to be affected by the parasites. Then, there is a fourth way by which the pollutants may impact the sharing of parasites between the available definitive hosts in the water body. All of these need further examination before drawing conclusions. Studies like those of Johnson and Chase (2004) and Johnson et al. (2007) should be encouraged.

From all the available literature it seems that the endoparasitic helminths have emerged as the candidates of choice for biomonitoring aquatic bodies for metal pollution. The results with acanthocephalans have been found to be particularly promising. Various hypotheses have been proposed with respect to the presence of metals in higher concentration and detectible amounts in these helminths than the host tissues like intestine, muscles and liver (Leite et al., 2017). According to some studies the sites of location of the parasites within the hosts affects the concentration of metals (Moravec, 1998).

The preferred locations include the stomach or intestine before they move on to the muscles or other organs (Moravec, 1998). The bile acids have been proposed to react with the metal ions within the digestive tract of the fish hosts resulting in the production of organo-metallic complexes (Mehana et al., 2020). These organo-metallic complexes are lipophilic substances that can be easily taken up by the helminths resulting in their high concentrations within their body (Mehana et al., 2020). Another hypothesis states that the bioaccumulation properties of helminths depend upon their developmental stages.

Comparative studies on accumulation properties of metals using adults and larvae of *Anisakis simplex* showed that the larvae had higher accumulation rates of cadmium (Cd), zinc (Zn), lead (Pb) and copper (Cu) than those of the adults (Pascual and Abollo, 2003). As an explanation for this observation it had been stated that the less complex nature of the larval cuticle enabled the adsorption of metals across the body surface (Leite et al., 2017). Studies in these fields must be encouraged because there is a dearth of sufficient data to understand the bioindicator properties of the helminths. Moreover, information on effects of other pollutants like hydrocarbons, thermal effluents, effluents from paper mills, pesticides and sewage on ecto and endoparasites are insufficient and need to be worked out.

Despite the detrimental effects of PAHs (polycyclic aromatic hydrocarbons) and PCBs (Polychlorinated Biphenyls) on the aquatic ecosystem the area has rarely been studied resulting in scanty information over the subject. The far-reaching effects of hydrocarbon pollution include alterations in benthic communities to biodiversity erosion to even modified feeding activities of the aquatic organisms (Ellis et al., 2012). It has been found that marine fish species take up PAHs when exposed to oil spills (Soler-Jiménez et al., 2020). Earlier studies show that the fishes and other aquatic vertebrates after absorbing the aromatic hydrocarbons from their environment metabolize the PAHs by various pathways and give rise to PAHm (polycyclic aromatic hydrocarbon metabolites) which are excreted through bile (Soler-Jiménez et al., 2020). The bile of these animals can thus be analysed for the presence of PAHm and their concentrations can be compared with PAHm concentrations of the endoparasites harboured by them (Soler-Jiménez et al., 2020). It needs to be mentioned here that the parasites have their own pathways to metabolize PAH and produce PAHm (Soler-Jiménez et al., 2020).

The studies are indeed intriguing but the most interesting part is that parasites, especially intestinal endoparasites, have lipid concentrations lower than their corresponding hosts (Yen Le et al., 2014). Despite this, the lipophilic substances including PAHm have been found in higher concentrations in the parasites than their host (Soler-Jiménez et al., 2020). A few hypotheses have been proposed for such peculiar observation. One such hypothesis proposes that the parasites are not very efficient in eliminating the PAHm like their hosts resulting in these high molecular weight compounds being stored within the parasite body (Soler-Jiménez et al., 2020).

Another hypothesis suggests that the parasites probably produce higher amounts of PAHm compared to their hosts (Soler-Jiménez et al., 2020). A third hypothesis suggests that population density of the parasites lodged within their host's intestine affect their uptake of lipophilic substances from the surroundings impacting the concentrations of PAHm in both the parasites and the host (Soler-Jiménez et al., 2020). Needless to mention that sufficient data to support any of these hypotheses are not yet available though there is a probability that all of these might be true. This area needs special attention.

CONCLUSION

This field is naïve and a revolutionary one that has broadened the scope of parasites beyond simply "disease causing organisms." The concept of parasites as "superorganisms" (Marcogliese, 2005) is evolving gradually. Studies of parasites from this aspect give many important insights regarding their ecological demands and/or behaviour. For example, recovery of parasite communities after decrease in chemical and nutrient loads in the aquatic ecosystems has been documented by Cone et al. (1993) and Valtonen et al. (2003). The choice of the parasite(s) and/or host-parasite system is crucial to these studies and the set of guidelines summarized by Williams et al. (1992) is indeed a landmark for workers in this field.

Literature from all aspects show that the maximum volume of studies in this field has been restricted to metal pollution. Despite the deleterious effects of other pollutants on the aquatic ecosystems and environmental health effective techniques to biomonitor these compounds using parasites have been poorly studied. A few recent studies, however, have exhibited encouraging results and needs further research. Considering the deplorable condition of the current ecosystem health this may go a long way in understanding the shocking and far-reaching impacts of anthropogenic activities.

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