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REVIEW

A One Health Approach Relative to Trematode-Caused Diseases of People and Animals Associated with Aquaculture

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ABSTRACT
A marked increase in food production is necessary if the World Health Assembly goal of ending world hunger and malnutrition in all its forms by 2030 is to be achieved. To this end, aquaculture plays a major role, but it could play an even more prominent role at least in some areas, especially Africa. There is a need to further develop aquaculture because harvesting from natural populations of potential food-species is not sustainable. At the same time aquaculture may also have some negative environmental and public health effects. Environmental effects are primarily due to eutrophication of natural habitats. Negative health effects are related to the potential presence of chemical residuals (medicine residuals or heavy metals from feed), pathogens or parasites in the final product. In Africa, there is a special concern that aquaculture facilities could contribute to increased transmission of schistosomes. Aquaculture development and the possible problems and their mitigation are discussed. The possible integration of mini-livestock with aquaculture is considered.

KEYWORDS
One-health; zoonotic trematodes; snail control; mini-livestock; food security; global malnutrition

Introduction

The World faces huge challenges if the World Health Assembly goal to end world hunger and malnutrition in all its forms by 2030 is to be achieved (FAO, IFAD, UNICEF, WFP, WHO, 2021; FAO 2021a). According to FAO, IFAD, UNICEF, WFP, WHO (2021), at the global level, the gender gap in the prevalence of moderate or severe food insecurity has grown even larger in the year of the COVID-19 pandemic, with the prevalence of moderate or severe food insecurity being 10% higher among women than among men in 2020, compared to 6% in 2019. New projections confirm that hunger will not be eradicated by 2030 unless bold actions are taken to accelerate progress, especially actions to address inequality in access to food (FAO, IFAD, UNICEF, WFP, WHO 2021). Most children with malnutrition live in Africa and Asia. These regions account for more than 90% of all children with stunting, greater than 90% with wasting, and more than 70% who are affected by obesity (FAO, IFAD, UNICEF, WFP, WHO (2021). More than 30% of women in Africa and Asia were affected by anemia, compared with only 14.6% of women in North America and Europe.

FAO, ECA, AUC (2020) estimates that 256 million Africans, or 20% of the population, are undernourished. Of these, 239 million are in sub-Saharan Africa and 17 million in Northern Africa. Aquacultural developments have the potential to significantly contribute to reaching the Sustainable Development Goals as presented in FAO, IFAD, UNICEF, WFP, WHO (2021). Priority should be to further develop aquaculture in Africa and in other regions where population growth will challenge food systems most (FAO 2020). Fish-farming dominates in Asia, which has produced 89% of the global total in volume in the last 20 years. Over the same period, the contributions of Africa and the Americas have increased, while those of Europe and Oceania have decreased slightly (FAO 2020). Africa accounts for 25% of the global inland captures (wild-caught fishes), where they

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represent an important source of food security, particularly in the case of landlocked and low-income countries (FAO 2020). The fisheries and aquacultural sector has much to contribute to securing all the sustainable development goals (SDGs) of the United Nations (United Nations 2015; https://www.un.org/en/sustainable-development-goals), not only SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being) and SDG 14 (Life Below Water), as fish and fish-products have an essential, growing, and yet largely unrecognized role in fighting hunger, malnutrition, and poverty (FAO 2021b).

A balanced, diverse, and appropriate selection of foods eaten over a period of time include (FAO, IFAD, UNICEF, WFP, WHO 2021, p. 191):

> A healthy diet protects against malnutrition in all its forms as well as noncommunicable diseases (NCDs), and ensures that the needs for macronutrients (proteins, fats, and carbohydrates including dietary fibers) and essential micronutrients (vitamins, minerals, and trace elements) are met specific to a persons gender, age, physical activity level, and physiological state. A healthy diet requires that: (1) daily needs of energy and micronutrients are met, but energy intake should not exceed needs; (2) consumption of fruits and vegetables should be at least 400 g per day; (3) intake of fats should be no more than 30% of total energy intake, with a shift in fat consumption away from saturated fats to unsaturated fats and the elimination of industrial trans fats; (4) intake of free sugars should be less than 10% of total energy intake or, preferably, no more than 5%; (5) intake of salt should be less than 5 g per day. A healthy diet for infants and young children is similar to that for adults, but the following elements are also important: (1) infants should be breastfed exclusively during the first 6 months of life; (2) infants should be breastfed continuously until 2 years of age and beyond; (3) from 6 months of age, breast milk should be complemented with a variety of adequate, safe and nutrient-dense foods. Salt and sugars should not be added to complementary foods.

Increasing production and augmenting access to aquatic foods and the nutrients they provide are fundamental to the transformation of the global food supply (Fiorella et al. 2021). Aquaculture is increasing and diversifying the global supply of foods and complements traditional agriculture and husbandry, and therefore holds tremendous potential to address malnutrition and diet-related diseases (Fiorella et al. 2021, Koehn et al. 2022). Particularly, vulnerable groups such as children, adolescents and pregnant women would benefit from a varied and high-quality diet (de Roos et al. 2020; Kwasek et al. 2020; Sapkota et al. 2020). The species selected and feeds used affects the nutrients available from aquaculture (Hixson 2014; Kwasek et al. 2020; Fiorella et al. 2021; Kaminski et al. 2022).This paper summarizes and analyses ideas on aquacultural development in Africa based on the One Health concept and experiences from Asian fish-culture.

One Health approach

One Health is an integrated approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems (Prata et al. 2022). One Health recognizes that the health of people is closely connected to the health of animals and the environment (Cleaveland et al. 2017; Stauffer and Madsen 2018; Mackenzie and Jeggo 2019). One Health issues include zoonotic diseases, antimicrobial resistance, metal bioaccumulation, food safety and food security, vector-borne diseases, NCDs, environmental contamination, and other health-threats shared by people, animals, and the environment (Gormaz et al. 2014; Santos and Ramos 2018; Stentiford et al. 2020; Urdes and Alcivar-Warren 2021). Consumption of a varied diet is essential for human health and aquaculture could be the way to secure this. Aquatic animals contain essential nutrients, such as iodine and omega-3 long-chain polyunsaturated fatty acids and micro nutrients that are generally limited in other animal foods (Thompson and Amoroso 2011; Gormaz et al. 2014). Recognition of this has spurred a push for nutrition-sensitive aquaculture, which aims to benefit public health through the production of diverse, nutrient-rich seafood and enabling equitable access (Gephart et al. 2021).

Availability of sufficient and high-quality food is an important element of human health and to secure this, further developments in agriculture, e.g., horticulture and aquaculture, are essential as many natural habitats otherwise might be overexploited and their biodiversity reduced (Köhler et al. 2012; Stauffer et al. 2022). Harvesting of natural populations can affect transmission intensity of trematodes. For example, overfishing of natural waterbodies can result in reduced predation pressure on intermediate host populations of schistosomes and this can lead to establishment or intensify existing transmission (Stauffer et al. 1997; Madsen and Stauffer 2011).

It is a major challenge to provide a sufficient per capita amount of food to the increasing human population as this must be done within a lesser cultivable area due to induced land degradation and other anthropogenic influences causing soil erosion or deterioration (Handelsman and Cohen 2021).

Although aquaculture has well documented positive effects, i.e., improved nutrition, better food security, better job opportunities, and financial benefits, there are also justified concerns that such activities may lead to increased transmission of various water-related diseases because installations (e.g., canals and ponds) often function as excellent habitats for intermediate hosts of trematodes, notably schistosomes, liver flukes, and other food-borne zoonotic trematodes or vectors, particularly larvae of mosquitoes transmitting *Plasmodium* spp. (Madsen and Stauffer 2022). Thus, creation of aquaculture facilities may affect transmission of schistosomiasis to a point where aquaculture activities should be discouraged in schistosomiasis-endemic areas unless ponds are fenced from the villagers, especially children (Slootweg et al. 1993). An alternative would be polyculture where a molluscivore fish species is included among the cultured species (Chiotha et al. 1991; Hung et al. 2013b).

Also, aquaculture practices may cause concentrations of pathogenic microorganisms (bacteria or viruses), parasites (including trematodes), metals or chemical residues (from medicine or pesticides) in the products if manure from domestic animals or people is used for pond fertilization (Bueno 1998; McCoy et al. 2011; Pelic et al. 2021; Urdes and Alcivar-Warren 2021; Hossain et al. 2022; Lin et al. 2022). Especially, there are concerns about antibiotic resistant bacteria as they could seriously affect the biosecurity of the products produced in aquaculture (Hine et al. 2012; Phu et al. 2016). Due to these problems, various treatment options for manure or wastewater, e.g., biogas digesters or composting should be considered before use in aquaculture (Dumontet et al. 1999; Huong et al. 2014a, 2014b; Naidoo et al. 2020; Tram et al. 2022). The bacterial composition may be related to culture type (Zheng et al. 2017). Surplus nutrients added to ponds may be discharged to waterways with aquacultural wastewater that results in decreased dissolved oxygen, decreased biodiversity, and other deleterious effects. Surplus nutrients could also be trapped in pond sediment (Azim and Little 2006; Bert 2007). The major environmental impact of aquaculture is the addition of nutrients to surrounding waterbodies with aquacultural wastewater (Kumar and Cripps 2011). Hence, focus on aquacultural development should be on ways to extract as many nutrients from water as possible before discharge from ponds and/or ways to reduce the need for water-renewal in aquacultural ponds with a number of options to consider (see below). In the following, practices and techniques and their role for transmission of trematodes is reviewed.

Aquacultural practices, ecology of fishponds, and techniques, and their role for transmission of trematodes

Trematode-caused diseases are serious problems of both public health and veterinary importance and some of them may be associated with aquaculture in some areas (Madsen and Stauffer 2022). Trematodes and other parasites can reduce somatic growth and survival of cultured species (Noga 2010; Ngodhe et al. 2021). In particular, trematodes may become serious problems in aquacultural projects in Africa, which has a less developed aquacultural tradition than in Asia (Slootweg et al. 1993). In Africa, the major concern would be schistosome transmission as aquacultural facilities may serve as habitat for the intermediate hosts. Although aquaculture could reduce the need for water contact in natural waterbodies and thereby reduce transmission, it should not be seen as a means to control schistosomiasis but it should be implemented in a way that does not contribute to the disease burden; disease control should still be the responsibility of the health system. Although infections by some of these trematodes in the final hosts (humans and possibly reservoir hosts) can be effectively reduced through medical treatment often administered as mass drug administration, reinfection appears very quickly (Madsen et al. 2011; Lier et al. 2014; Clausen et al. 2015). This highlights the necessity to take a holistic approach to control (One Health) such that the parasite is attacked at all stages of its life cycle (Stauffer and Madsen 2018; Madsen and Stauffer 2022). Interventions should include (1) attempts to reduce the contamination of water bodies with trematode eggs; (2) attempts to reduce the chance of eggs or miracidia infecting the first intermediate host; and (3) attempts to reduce the likelihood that cercariae or metacercariae infect the final host (Madsen and Stauffer 2022). Measures such as increasing safe water supply and sanitation are important in reducing schistosome-transmission (Grimes et al. 2015; Mogeni et al. 2020) and possibly other trematodes as well. These measures, however, may have little impact on transmission due to occupational activities, such as fishing, agricultural, and aquacultural activities where water contact cannot be avoided.

Aquaculture production systems

Aquacultural systems worldwide vary from earthen ponds of various size, lined ponds, ponds, tanks with recirculation of water, cage culture in rivers or lakes to completely indoor systems. Freshwaters were the source for 60% of the world aquacultural production in 2008 (Bostock et al. 2010). Most freshwater aquaculture is pond-based using semi-intensive methods that rely on controlled eutrophication for their productivity, using a wide variety of organic and inorganic fertilizers as well as supplementary feedstuffs (Bostock et al. 2010). In throughput systems, tank culture requires higher volumes of water to maintain a good water quality, but closed systems are suitable for employing biofloc technology and this may greatly reduce the need to replace culture-water (El-Sayed 2021; Nisar et al. 2021). Nanotechnology is another tool that might have a potential for prevention of disease in fishes, water purification, and delivery of nutrients (Shah and Mraz 2020).

Cage-based aquaculture (Figure 1) in both freshwater lakes and rivers is common in many countries, although some are now regulated due to concerns of environmental impacts (Bostock et al. 2010). In unregulated conditions, eutrophication from cage-farms can influence farms downstream, other water uses, and ecosystems in general. Rapid expansion of cage-based catfish farming in the Mekong is of similar concern but has not led to such a drastic regulatory response, although the expansion of pond farms is now apparent (Bostock et al. 2010).

Potentially there can be trematode-associated issues also in brackish or marine water aquaculture (Keiser and Utzinger 2009; Hung et al. 2013a; Madsen and Stauffer 2022). Especially, species of Heterophyidae (Sohn 2009) and some species of avian schistosomes causing swimmers itch (Brant et al. 2010) can be found in brackish water. Coastal ponds and lagoons have been exploited in simple ways for fish, mollusks, crustaceans, and seaweed production for centuries and has expanded (Bostock et al. 2010).

Integrated fishponds (Figure 2) are a very common system for especially small-scale family-based aquaculture. In its traditional form, a garden, a fishpond, and an animal shed constitute a functional unit, where manure from the husbandry is used to fertilize ponds, to stimulate algal growth, and

Figure 1. Cage culture. (a, b) Cage culture *Pangasianodon hypophthalmus* in the Mekong River, Vietnam; (c) cage culture of *Oreochromis niloticus* (d) in river in Thailand.

Figure 2. The integrated aquaculture pond. (a) Pond with pipe for outflow from pig sty; (b) pig sty close to pond; (c) duck pen in fish pond; (d) pond with floating vegetation.

subsequently fish growth; remnants from garden products and fish remains may be fed to for example pigs (Edwards 1998; Nhan et al. 2007, 2008b; Dung et al. 2010). Mud from the pond can be used to fertilize gardens or fields. The system can be expanded such that gardening includes all kinds of terrestrial farming and may include raising cattle, pigs, and poultry. These systems are widely practiced in Asia.

To have effective aquaculture at the family-level, it is essential that a reliable source of juvenile fishes for seeding in ponds is available (Brummett 1999). Usually, in areas with intense aquaculture such as Vietnam (Clausen et al. 2015), some commercial farms specialize in production of fish fry (Figure 3), so-called hatcheries, while others produce juvenile fishes in intensive care ponds, so-called nursery ponds. These juvenile fishes are then sold to individual farmers who introduce them in grow-out ponds. The specific technique used in hatcheries and nursing systems depends on the fish species cultured and local traditions (Clausen et al. 2015). FAO provides fact sheets on technologies for common cultured species "Cultured Aquatic Species Information Programme," e.g., for *Oreochromis niloticus* (FAO 2022).

Aquacultural production in both freshwater and marine systems is mainly fish, crustaceans, mollusks and aquatic plants (Lucas 2012; Tacon 2020). Brackish or marine aquaculture of bivalves has been practiced historically (Lucas 2012) and also marine gastropods are cultured, for their shells and/or their meat (Castell 2012). Culture of mollusks generally requires no feed inputs (Bostock et al. 2010). Freshwater snails are rarely specifically cultured but production in aquacultural ponds can be a substantial byproduct. Species can be raised in monoculture or in polyculture where more species with complementary feeding niches are kept together (Appleford et al. 2012). An example of polyculture is shrimp and fish (Martínez-Córdova et al. 2015; Zeng et al. 2021). Another special aquacultural method practiced in many countries in Asia is the rice-fish (or crab or prawn) farming system, which is an integrated agro-ecosystem practice (Lin and Wu 2020).

Figure 3. Production of fish fry. (a) Hatchery for common carp; (b) eggs of common carp attached to *Eichhornia crassipes* roots; 3) hatchery for other carp species (eggs are suspended in water and kept circulating; (c) breeding happas for *Oreochromis niloticus* (fry can be scooped from the edge of the pond.

Ecology of fishpond

There is a strong linear relationship between primary productivity and fish yields in earthen ponds and primary productivity depends mainly on the availability of elementary nutrients (N, P, and C) and sunlight (Azim and Little 2006). Fertilization and liming are common practices in aquacultural ponds to maintain natural productivity and water quality (Azim and Little 2006; Bosma and Verdegem 2011). In the integrated pond-system, animal manure (pigs, ducks, chicken and possibly humans) is often added to ponds as fertilizer to stimulate growth of algae, both planktonic and attached, which are utilized as food by some species of fish (Nhan et al. 2008a). Studies have shown that on average, only 5–6% of total N, organic carbon (OC), or P inputs introduced into ponds were recovered in the harvested fish (Nhan et al. 2008a). About 29% N, 81% OC, and 51% P accumulated in the sediments (Nhan et al. 2008a). This, however, may be affected by pond operation, e.g., high water-exchange ponds received two to three times more of on-farm nutrients (N, OC, and P) while requiring nine times more water and discharging 10–14 times more nutrients than the low water-exchange ponds (Nhan et al. 2008b). Obviously, overloading of fishponds with organic matter could cause depletion of oxygen. Algae and organic material also serve as food for freshwater snails including species that serve as intermediate hosts for trematodes (Clausen et al. 2015; Madsen and Stauffer 2022). To enhance pond productivity in the form of periphyton, vertical hard substrates can be introduced in ponds (Azim and Little 2006).

Some species of snails such as those capable of filterfeeding might utilize the suspended material more efficiently than species that only browse. Feeding of viviparids (e.g., *Angulyagra polyzonata* in Vietnamese ponds) is by filter-feeding and the species can exist at very high densities and can as a result of their filter feeding clear the water, which improves conditions for fish, although a high standing biomass of snails could result in oxygen-stress, and it could also be seen as snails compete with the fishes for food. A high density of viviparids might also exclude other species of snails due to competition for space or due to interference competition (Wang et al. 2020). Therefore in the African context, attempts should be made to establish dense populations of species of *Bellamya* (native to the local catchment area) and assess how these would affect intermediate host species of schistosomes. Some bivalve species (e.g., zebra mussel, *Dreissena* spp., *Corbicula* spp.) are also efficient filter feeders (Beaver et al. 1991; Fanslow et al. 1995). The biomass produced by these filter feeders could be used for human consumption (see later) or as fodder for husbandry (Bombeo-Tuburan et al. 1995). Planktonic algae will exclude light preventing growth of submerged aquatic macrophytes.

Excess suspended organic material will accumulate at the pond bottom and this will necessitate that ponds sometimes are drained and this organically rich sediment removed. The sediment, if it is not contaminated with heavy metals or other compounds from the feed can be used as fertilizer for gardens or fields. Removing silt from the pond will also remove snails, but if the standing crop of viviparids is high, these should first be harvested and the largest specimens sold for human consumption. The smaller specimens could be returned to the pond after refilling. Snails harvested could also be used as feed for husbandry such as ducks or chicken or could be used as fish-food (Anh et al. 2010; Da et al. 2012).

Multitrophic fish-culture is common and could include molluscivorous fishes (Figure 4) such as the Black Carp, *Mylopharyngodon piceus*, in parts of Asia (Hung et al. 2014), or certain cichlids in Africa (Chiotha et al. 1991; Makoni et al. 2005; Chimbari et al. 2007). Introducing non-native species (from outside the catchment area) should be avoided as there are several examples that introduced species have caused serious alterations of ecosystems (see below).

Raising pigs in family-based farms is profitable and therefore becoming more intensive, and this gives rise to problems with disposal of pig manure in excess of what could be added to fishponds (Tai et al. 2004). Excess pig manure could be used in family-based biogas digesters. Manure may contain a number of

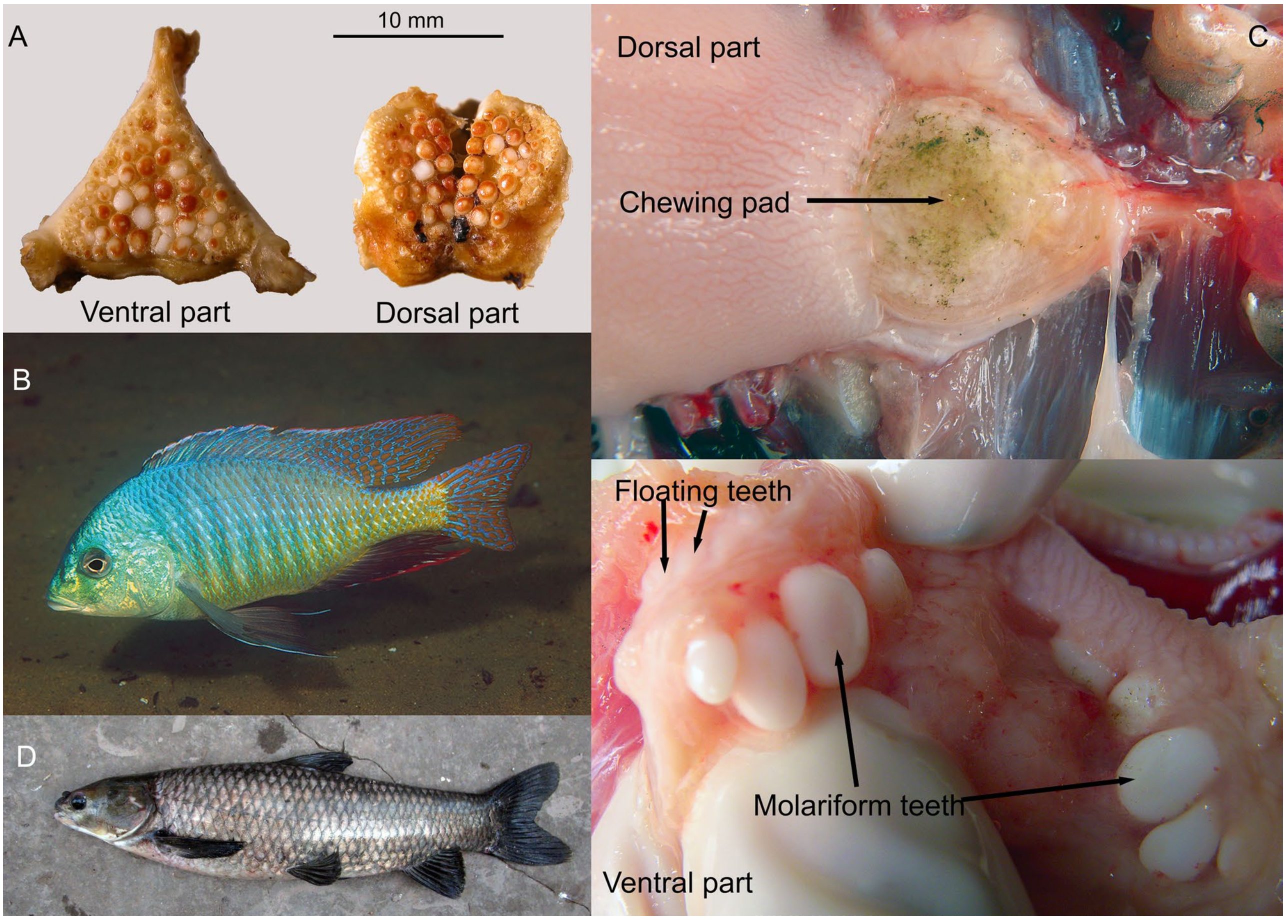

Figure 4. Fish preying on snails. (a) Pharyngeal bones of *Trematocranus placodon* (b) from Lake Malawi; (d) black carp, *Mylopharyngodon piceus* from Hanoi, Vietnam; (c) the crushing mill of the black carp.

potentially pathogenic bacteria (e.g., *Salmonella* spp.) that may cause human disease (e.g., Salmonellosis); and even the effluent from biogas digesters may contain pathogenic bacteria (Huong et al. 2014a, 2014b; Tram et al. 2022). Also, manure may contain eggs of several species of trematodes, thus management of manure becomes very important.

Aquacultural developments depends on a number of factors such as soil permeability, water availability, the ability of people to purchase aquacultural products, and food habits (Brummett 1999). What is possible depends on the specific conditions in the area of interest.

Problem areas in aquaculture and remediation

Pond fertilization using manure

Use of untreated manure (from humans or husbandry) for pond-fertilization can be problematic due to presence of eggs from parasites, pathogens (bacteria and viruses causing disease in people or fish), pollution with heavy metals, and possibly medicinal residues (Ström et al. 2018). The pathogens or parasites can be important either for both human-health or fish-health (Noga 2010).Various options are available for treatment of manure before using it for fertilization, e.g., composting (Dang et al. 2011) or anaerobic digestion in for example a biogas digester (Zeldovich 2021). Heat treatment can effectively reduce *Ascaris* eggs (Naidoo et al. 2020). The eutrophication in ponds may lead to cyanobacterial blooms that may release biochemically active metabolites some of which could be toxic to the aquacultural organisms or consumers or could have other negative effects (Smith et al. 2008).

Environmental impact

The main environmental impact of aquaculture is the organic loading of surrounding water bodies due to wastewater from ponds or cages (Bert 2007). Attempts should therefore be made to convert as much as possible of the organic loading and dissolved nutrients into useable biomass. Potential options include aquaponics production of vegetables, phytoremediation, bio-floc technology, multitrophic aquaculture, e.g., using filter-feeders such as certain species of snail or bivalve species.

Aquaponics

Aquaponics combines aquaculture with hydroponics (i.e., cultivating plants in water) whereby the nutrient-rich aquacultural water is fed to hydroponically grown plants, where nitrifying bacteria convert ammonia into nitrates (Baganz et al. 2022). As existing hydroponic and aquacultural farming techniques form the basis of all aquaponic systems, the size, complexity, and types of foods grown in aquaponic systems can vary as much as any system found in either distinct farming discipline.

Many plants are suitable for aquaponic systems, though which ones work for a specific system depends on the species, maturity, and stocking density and species of fish (Goddek et al. 2019; Pinho et al. 2021). These factors influence the concentration of nutrients from the fish-effluent and how much of those nutrients are made available to the plant roots via bacteria. Green leafy vegetables with low to medium nutrient requirements are well adapted to aquaponic systems, including Chinese cabbage, lettuce, basil, spinach, chives, herbs, and watercress. Other plants, such as tomatoes, cucumbers, and peppers, have higher nutrient requirements and will do well only in mature aquaponic systems with high stocking densities of fishes (Schmautz et al. 2016). Some plants (e.g., asparagus) are tolerant of salinity and could be used in conjunction with estuarine species. Floating beds of *Ipomoea* can improve quality of aquaculture wastewater (Zhang et al. 2014).

Bio-floc technology

Biofloc technology (BFT) is gaining traction as a strategic aquacultural tool for boosting feed conversions, biosecurity, and wastewater recycling (Bosma and Verdegem 2011; Crab et al. 2012; Hargreaves 2013). The significant aspect of BFT is aquaculture with highest stocking density and minimal water exchange. It not only improves the water quality of a system by removing inorganic nitrogen from wastewater but also serves as a suitable feed-supplement and probiotic source for cultured species. This technology is commonly used for culture of shrimp and tilapia and can be used for both semi-intensive and intensive culture systems (El-Sayed 2021; Nisar et al. 2021).

Manipulating the C:N ratio in aquacultural ponds encourages the uptake of the inorganic nitrogen into a microbial protein known as biofloc (Deng et al. 2018). If in the system, perfect balance of carbon and nitrogen in the solution exists, ammonium and other nitrogenous wastes will be converted into bacterial biomass (Ekasari et al. 2014; Abakari et al. 2022). Furthermore, by adding a carbohydrate source to a culture pond, microbial proteins assist heterotrophic bacterial growth and nitrogen uptake

(Avnimelech 2007). Biofloc systems work best with species that are able to derive some nutritional benefit from the direct consumption of floc (Hargreaves 2013). Biofloc systems are also most suitable for species that can tolerate high solids concentration in water and are generally tolerant of poor water quality (Hargreaves 2013). Species such as shrimp and tilapia have physiological adaptations that allow them to consume biofloc and digest microbial protein, thereby taking advantage of biofloc as food. Nearly all biofloc systems are used to grow shrimp, tilapia, or carps (Hargreaves 2013).

Phytoremediation

Wastewater from aquaculture should preferably not be discharged directly into natural waterbodies as this cause eutrophication. Treatment of wastewater from aquaculture could be done in artificial wetlands with dense growth of selected plant species (Zhang et al. 2014). Many plant species can remove heavy metals from soil and water, but for aquaculture the main remediation required will be removal of nutrients. Heavy metals may be reduced through phytoremediation (Wani et al. 2017). Phytoremediation treatment options offer an environmentally compatible, low technology approach that can be quickly integrated into existing aquacultural systems to provide management of contaminants (Etim 2012; Lanza et al. 2017). Integrated Aquaculture-Phytoremediation Systems (IAPS) will be highly site specific and will depend on local conditions including geomorphology, water sources, levels of ambient soil and water contamination, the aquatic species under aquaculture, and the type of culture system used. The IAPS design must provide a good balance of the removal of excess nutrients and other contaminants and an adequate supply of nutrients to support the growth of the aquacultural products. IAPS can greatly enhance the global production of plant and animal food particularly in developing countries with warmer climates and highly diverse plant communities. IAPS that effectively removes snail-vectored parasites (e.g., fish-borne zoonotic trematodes) are especially desirable because snails are often cultured for food in aquaculture systems along with fish and edible plants. Using carnivorous plants (e.g., *Utricularia* sp.) in IAPS may offer one solution. Species of *Utricularia* inhabiting wet soils and water are known to actively trap and consume aquatic animals, and it may be possible to use carnivorous plants to remove immature snails, snail eggs, miracidia, and cercariae as a treatment option in IAPS (Lanza et al. 2017).

Multitrophic culture including invertebrates

Some species of gastropods or bivalves can thrive in aquacultural ponds and although some of these serve as hosts of trematodes (see below) others should be seen as a valuable resource which could be utilized for human consumption or as feed for husbandry. Especially, filter-feeding species such as species of the Viviparidae and bivalves are important. These species would likely be able to exploit biofloc in ponds where this technique is employed.

Trematode transmission in aquaculture

There are several trematodes (Table 1) that cause disease in people or animals e.g., the most common being schistosomiasis, fascioliasis, echinostomiasis, opisthorchiasis, clonorchiasis, heterophyiasis, and paramphistomiasis. Many of these trematodes are zoonotic (Madsen and Stauffer 2022) and transmission may occur both in natural habitats and in man-made habitats, including aquacultural facilities.

Adult trematodes in the final hosts (humans and possibly reservoir hosts) deposit eggs which leave the host via feces or urine (Figure 5). Eggs that reach freshwater either hatch to a miracidium (e.g., schistosomes and fasciolids) that can subsequently infect a snail, or they are eaten by an appropriate snail (Table 1) inside which, it will hatch and develop. Through asexual multiplication a new infective stage develops inside the snail and upon release from the snail, cercariae can (1) infect the final host directly through skin penetration (e.g., schistosomes), (2) infect its second intermediate host such as fish (FZT) or crabs (*Paragonimus* spp.) where they turn into metacercariae, which are infective to the final host eating these second intermediate hosts, or (3) encyst on aquatic plants or grass submerged in water (Fasciolidae). Once eaten by a final host, metacercariae develop into adults flukes. The morbidity suffered by the final host differs considerably among species of trematodes and depends on the intensity of infection. Morbidity is either caused by physical damage caused by adult worms (*Fasciola* spp., FZTs) or by eggs that do not escape the body of the final host but lodge in various tissues (*Schistosoma* spp.) such as brain, prostrate/seminal vesicles, and lungs (Corachan et al. 1994; Cetron et al. 1996; Schwartz et al. 2000).

In the integrated fishponds, a common practice is to add floating aquatic macrophytes (for example duck weed) collected from other habitats as fish-feed and this was identified as risk factor for infection in fish

Table 1. Snail families involved as first intermediate hosts (a) for selected trematodes (flukes) causing disease in humans or domestic animals. Only certain species within a family are intermediate hosts for a given parasite. Animals or plants (b) that serve as second intermediate host and potential reservoir hosts (c) are also listed. Further details about the trematodes can be found in the references indicated in the footnotes.

	Schistosoma spp.[a]	Other schistosomes[b]	*Paragonimus* spp.[c]	*Clonorchis sinensis*[c]	*Opisthorchis* spp.[c]	Intestinal flukes[c]	*Echinostoma* spp.[c]	*Fasciola* spp.[c]	*Paramphistomum* spp.[d]
(a) First intermediate host									
Caenogastropoda[e]									
Amnicolidae			x			x			
Assimineidae			x	x					
Bithyniidae				x	x	x			
Cerithiidae		x				x			
Cochliopidae			x						
Hydrobiidae			x			x			
Littorinidae		x				x			
Pachychilidae		x	x	x			x		
Planaxidae[f]		x							
Pomatiopsidae	x		x			x			
Semisulcospiridae				×					
Stenothyridae						x			
Thiaridae		x	x	x			x		
Panpulmonata[e]									
Bulinidae	x	x							
Lymnaeidae		x					x		x
Physidae		x					x		x
Planorbidae	x	x					x	x	x
(b) Second intermediate host (vector)									
Vegetation								x	×
Crab/crayfish			x						
Snails							x		
Fish				x	x	x	x		
Other									
(c) Reservoir hosts									
Non-human primate	x								
Buffalo/cow	x							x	
Pig	x		x						
Dog/cat	x		x	x	x	x	x		
Rodents	x		x	x	x	x	x		
Bird		x				x	x		

[a] Littlewood and Webster (2016).
[b] Brant and Loker (2013).
[c] Chai and Jung (2022).
[d] Lotfy et al. (2010).
[e] Lydeard and Cummings (2019).
[f] Marine species.

(Phan et al. 2010). Similarly, ducks kept in such ponds may be fed snails, primarily viviparids or ampullarids, collected from outside the pond and this was a risk factor for infection in ducks (Anh et al. 2010). Snails may be crushed before being fed to the ducks.

Some experiments on management practices for reduced transmission of fish-borne zoonotic trematodes have been conducted in Vietnam (Clausen et al. 2015; Madsen et al. 2015). The interventions should attempt (1) reduction of egg of trematodes input to ponds, (2) reduction of abundance of the intermediate-host snails, and (3) prevention of cercariae or metacercariae from infecting people or reservoir hosts.

Probably, the most effective means of reducing egg contamination would be medical treatment of the final hosts (humans and reservoir hosts). Mass treatment of people as the sole intervention is not efficient (Lier et al. 2014) and needs to be reinforced by treatment of domestic animals and other measures against reinfection. This could involve sanitary improvements to reduce contamination of waterbodies with human or animal feces or urine; prevention of reservoir hosts to have access to the water bodies e.g., dogs, cats, and some wild birds for some of the fish-borne zoonotic trematodes. In aquaculture, the use of untreated manure from domestic animals can be a major way of introducing trematode eggs into ponds and manure treatment that inactivates contained trematode eggs would be important (Clausen et al. 2015). Cats and dogs are important reservoir hosts of fish-borne zoonotic trematodes and preventing surface run-off into the pond could help reduce egg contamination of the pond (Clausen et al. 2015). Some human practices such as washing intestines of slaughtered cats, dogs, and pigs in fishponds could be an important source

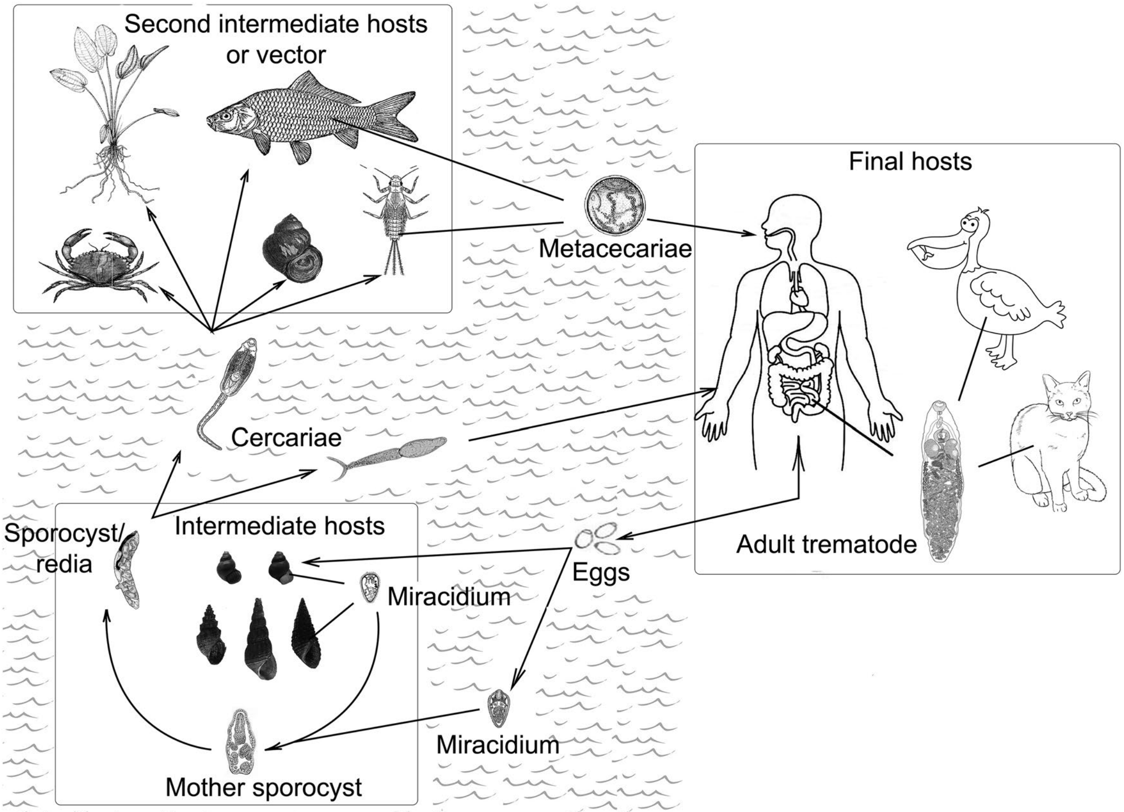

Figure 5. General life cycle of trematodes with medical or veterinary importance.

of eggs from trematodes and such behavior should be stopped.

Reducing the chance of eggs or miracidia infecting the first intermediate host (freshwater snail) is very important and this could be attempted through snail-control using either habitat modification, chemical control, or biological control (Hung et al. 2013b). Obviously, what is feasible depends on the type of habitat (Chiotha et al. 1991). Feeding fishes aquatic macrophytes collected from outside the aquaculture ponds constitute a risk of introducing intermediate host snails some of which could be infected (Phan et al. 2010).

There are various options available to prevent cercariae infecting people or the second intermediate host. For schistosomiasis, this could be through reducing water contact through supply of safe water. For FZT, there is probably little that can be done to reduce the infection success of cercariae into the fish that serves as second intermediate host. Hence, focus should be on preventing metacercariae infecting people or reservoir hosts and this would be attempted through behavioral changes, such as not eating raw fish, and cooking fish remains before feeding it to animals (pigs, dogs and cats). Preventing these animals from getting to the ponds is also a good preventive measure.

Controlling snails in aquacultural facilities using chemicals such as molluscicides, is problematic as most known compounds have piscicidal effect at molluscicidal concentrations (McCullough 1992). Niclosamide, a potent molluscicide (but also a piscicide) could be used in fishponds prior to stocking fish (Francis-Floyd et al. 1997). Niclosamide is metabolized quickly in water (Andrews et al. 1987) and would not show piscicidal effect after a few days. Biological control of snails is an alternative control method, and the employment of Black Carp, *Mylopharyngodon piceus*, which primarily feeds on mollusks has been shown effective in controlling snails in northern Vietnam (Hung et al. 2013b); and some cichlid species have similar control advantages in Malawi (Chiotha et al. 1991). There has, however, been much controversy about using molluscivorous fishes for biological control of snails. Fishes that do include snails in their diet are not necessarily good candidates for biological control (Marshall 2019) and species which in their natural habitat seem to specialize on snails, may change their diet when introduced in other habitats for snail-control (Slootweg et al. 1994; Slootweg 1995). Some cichlid fishes will not develop a strong pharyngeal bone and strong dentition when fed on a soft diet eventually rendering them unable to crush snail shells (Slootweg et al. 1994; Kefi et al. 2012). Also, the Black Carp, *Mylopharyngodon piceus*, had less developed dentition when from early life fed a soft diet than when fed a hard diet (Hung et al. 2015). If molluscivorous fishes are to be used in aquaculture ponds it is important to ensure that they have a well-developed pharyngeal dentition and this could be achieved by seeding wild-caught specimens, or by raising them in culture where they are forced to feed on a hard diet from their early life; once the dentition is developed, it will not regress. It also means that molluscivorous specimens should not be harvested from the pond. At least some species harvested from natural habitats can thrive under pond conditions, e.g., *Trematocranus placodon* from Lake Malawi (Kefi et al. 2012) and *Sargochromis codringtoni* from Lake Kariba, Zimbabwe (Chimbari et al. 2007).

Selection of fish for biological control, however, should be based on local species from the catchment area. Other methods of biological control of snails in aquaculture include duck keeping, other predators e.g. crustaceans (Lee et al. 1982; Sokolow et al. 2014, 2015), potential competitors such as for example viviparid species (Wang et al. 2020), parasite antagonism if parasite eggs are easily obtained (Joe et al. 1974a, 1974b).

Liming is an integral part of pond management and is undertaken for several reasons (Wurts and Masser 2004). The most common is ground magnesium limestone (GML), which is a mix of calcium and magnesium carbonate. Calcium oxide (quick lime) is also used, although not as frequently as GML. Most of these forms of lime, except quick lime, most likely have little effect on snails in aquacultural ponds. Hydrated lime, however, has been used as a molluscicide in culture of catfish in the USA (Terhune et al. 2003); the target snail is a planorbid snail, *Helisoma trivolvis*. Hydrated lime is applied along the margin of filled ponds at a concentration that is also toxic to the fishes if they came into this zone.

Introduced species

Introduction of foreign species for aquaculture or for high-value capture species in natural habitats should be discouraged as the species potentially could become invasive or could result in introduction of new parasites and/or diseases and the ecological consequences would be unpredictable. Many of the native fishes of Lake Victoria disappeared following the introduction in the 1950s and 1960s of Nile Perch *Lates niloticus* and Nile Tilapia *Oreochromis niloticus* (Bruton 1990; Ogutu-Ohwayo 1990; Balirwa et al. 2003).

Aquaculture has involved species that are especially suitable for propagation in aquaculture, for example high growth rate, tolerance to harsh environmental conditions or optimal feeding ability (Brummett 2007). Many species therefore have been translocated to aquacultural facilities outside their native range possibly with parasites (Minchin 2007). One example is *Oreochromis niloticus* which is used for aquaculture in many places outside its native range and has escaped into natural habitats, e.g., in crater lakes in Nicaragua (McCrary et al. 2008) and its potential introduction into Lake Malawi is a serious concern (Stauffer et al. 2022). A non-fish, example is the Golden Apple Snail (Figure 6), which was introduced in Asia for food production where it became invasive, and it has become a pest in rice fields (Madsen and Hung 2014). An overview of introduced species and where they have been introduced can be found in Database on Introductions of Aquatic Species (DIAS) at FAO (https://www.fao.org/fishery/en/topic/14786/en).

Prospect for development of aquaculture in Africa

Although Africa has a great potential for expanding aquaculture, it has been difficult to realize its high biophysical potential (Brummett et al. 2008). According to Brummett et al. (2008), aquacultural development

Figure 6. Apple snail, *Pomacea canaliculata* (a) and its characteristic egg masses (b, c).

in Africa has been hampered by ineffective institutional arrangements and donor-driven projects. African aquaculture however, has demonstrated its competitiveness (Brummett et al. 2008). Other constraints involve land-use issues and concerns for further aggravating schistosome-transmission. In some African countries such as Ghana and Sierra Leone, fish contributes or exceeds, 50% of total animal protein intake (FAO 2016). High cost of commercial aqua-feeds places a limitation on aquaculture production in Africa and search for locally available feeds is essential (Ocran 2020). The availability of antibiotics and their common use in agriculture increases the presence of Antibiotic Resistant Microbes (ARB) in African ecosystems. The expanding use of antibiotics in African aquaculture is a major concern (Limbu 2020).

Fish-borne zoonotic trematodes are not likely to become a major human health problem in most parts of Africa although several species are present; eating raw fish is not common in Africa. They might, however, be important in domestic animals and some of the trematodes also affect somatic growth in fishes (Bullard and Overstreet 2008; Noga 2010). The major concern in Africa, however, would be transmission of schistosomes (Slootweg et al. 1993) as aquacultural ponds and associated habitats could be excellent habitats for freshwater snails, *Biomphalaria* and or *Bulinus* species (Figure 7). Ozretich et al. (2022) reviewed the potential role of aquaculture in combined effort to produce food fish and fish for controlling schistosome-intermediate host snails in Côte d'Ivoire.

Studies in Malawi showed that the integrated pond-vegetable garden generates almost three times the annual net income from the staple maize crop and the homestead combined (Brummett 1999).

Examples for aquaculture development

In Lake Malaŵi, transmission of *Schistosoma haematobium* has established along open shorelines with sand or gravel sediment in the southern part of the lake. This is likely the result of overfishing resulting in a significant decline in densities of molluscivorous fishes (Stauffer and Madsen 2012) although other factors could play a role as well.

The southern part of Lake Malaŵi is an important area for tourism in Malaŵi, but the increased transmission of schistosomiasis and swimmers itch due to avian schistosomes in the Lake has reduced the influx of foreign tourists. Control of transmission within the

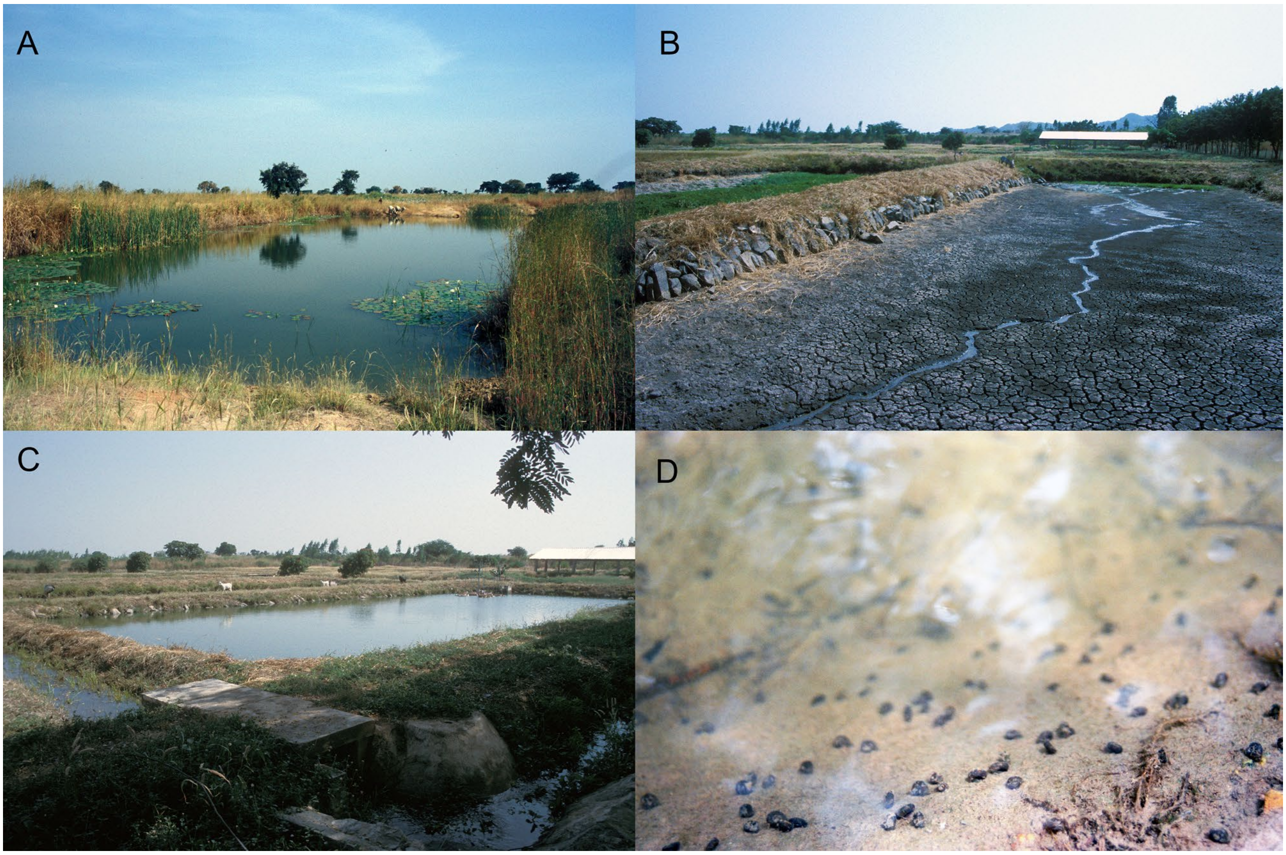

Figure 7. Aquaculture ponds in northern Cameroun, i.e. Lagdo area. (d) Very high density of *Biomphalaria pfeifferi* in drainage canal from the ponds.

lake, will be extremely difficult using traditional snail control. The only viable option appears to be protection of the natural fish populations. This, however, necessitates provision of alternative sources of fish-protein. Since transmission also occurs in the many streams and backwaters which constitute excellent habitats for *Bulinus globosus,* management of these inland waters might be important for controlling snails and transmission. Options include conversion of some of these habitats areas into aquacultural ponds, clearing vegetation in some, and possibly augmenting density of existing snail predators (Figure 8). Also aquacultural production of molluscivorous fishes, which in turn can be delivered to aquacultural ponds with non-molluscivorous fishes offers another option. This culture of molluscivores for seeding requires feeding the fry of these fishes locally available hard food types, to ensure development of the molariform pharyngeal teeth that enables them to consume snails. It should be noted that there are some cichlids that develop molariform teeth irrespective of their early diet; however, these fishes are not suited for aquacultural ponds, because once the snails are exterminated these fishes will starve. Thus, it is essential to use facultative molluscivores (e.g., *Trematocranus placodon*). Pond-based aquaculture could be established in many parts of Africa and although there are local adaptations required, the guiding principles should be the same.

More special situations are irrigation canals (Figure 9) such as those in the Office du Niger in Mali (Madsen et al. 1987) or the Gezira Managil Scheme in the Sudan (Madsen et al. 1988). Within the irrigation schemes, pond-culture could be established, but the largest canals might be utilized for cage-culture. The organic loading of the canal water might cause increased phytoplankton dominance in lower order canals, and this should help reduce snail populations.

Smaller order canals that do not dry could also be used for fish-production and at the same time species of fishes that are important as snail predators or efficient consumers of aquatic macrophytes (which create refuge for snails) should be augmented through provision of artificial shelters or breeding structures. One problem would, however, be poaching.

Aquaculture associated issues

Several possibilities exist that could be integrated with aquacultural development. Thus, horticulture and mini-livestock keeping should be considered,

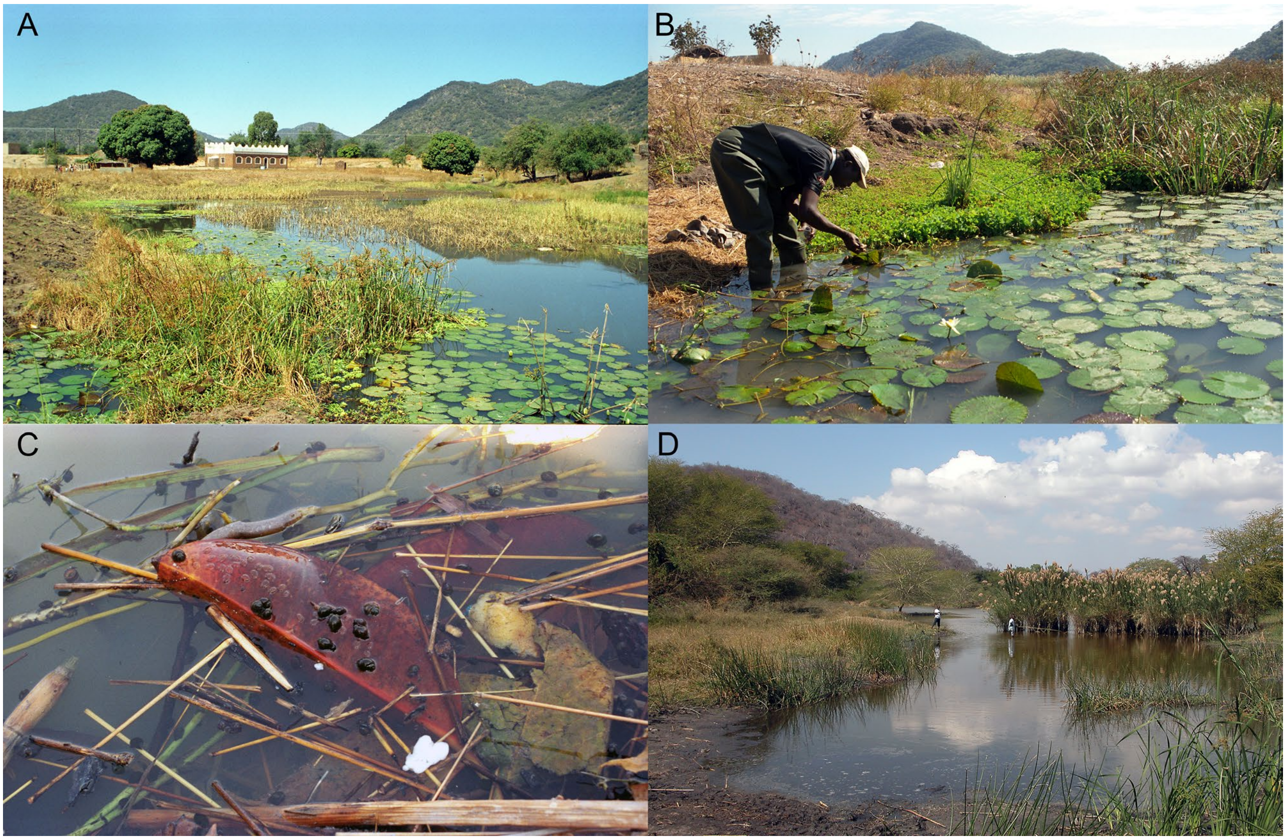

Figure 8. Inland habitats at the southern part of Lake Malawi that potentially could be used for aquaculture. Some of these are excellent habitats for *Bulinus globosus* (c) and may serve as transmission sites for *Schistosoma haematobium*.

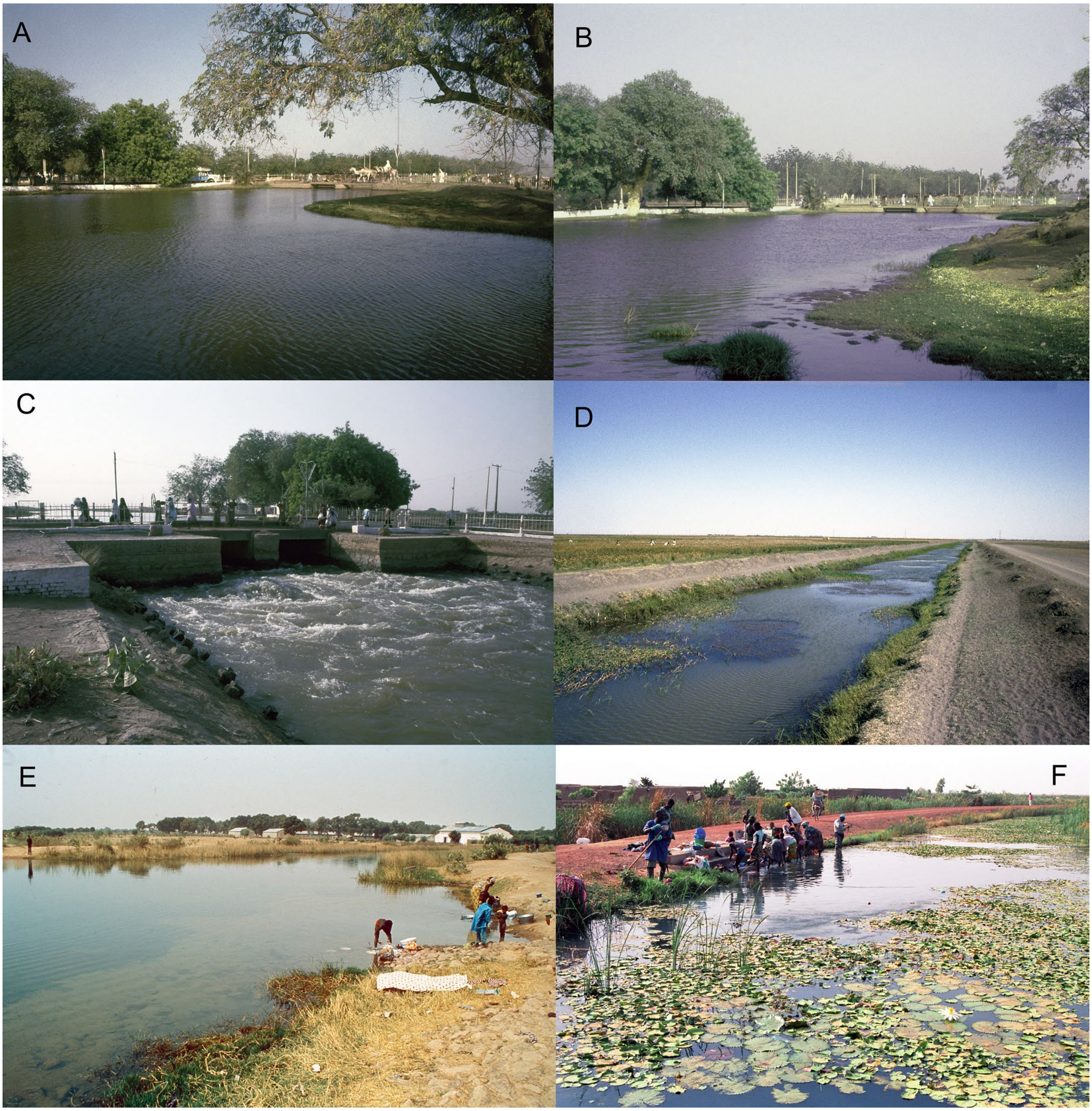

Figure 9. Possibility of using irrigation canals for aquaculture. (a–c) Main canal of the Gezira-Managil Agricultural Scheme in Sudan at Abu Ushar (about 170 km from the Sennar dam). The canal is large enough to support cage culture. (d) Minor canal in the same scheme. These canals are used for water storage within the scheme and they possibly could be used for aquaculture provided they continuously contain water. (e, f) Large irrigation canals in the niono area of the Office du Niger, Mali.

where pond sediment could be used to fertilize garden plots and other waste products from aquaculture might be used as feed for mini-livestock. Small-scale farms may not be able to sustain production of pigs or cattle and thus their diets often become based primarily on vegetable products. Until recently, it was assumed that plant proteins, when consumed in a balanced diet, can fully meet human nutritional requirements, and that animal proteins are not needed (Beets 1997). Recent research has shown, however, that in developing countries, unbalanced vegetarian diets regularly lead to nutritional problems, notably those caused by micro-nutrient and vitamin deficiencies. Consumption of small amounts of animal products can overcome these problems (Beets 1997). Under certain circumstances, there may be availability for livestock, particularly for small animals which are relatively efficient converters, or successful scavengers (Beets 1997).

Horticulture

Horticulture will be an important element as part of the integrated pond-system. Mud from ponds can be used as fertilizer and waste products from horticulture may be fed to husbandry or could be added to the pond. Households engaged in both homestead aquaculture and horticulture have the potential to improve the diet quality of households (Akter et al. 2020).

Poultry production

Smallholder poultry production is practised by most rural households throughout the developing world (FAO 2010). Production of ducks plays an important part in the agricultural economy of many Asian countries (Adzitey and Adzitey 2011). Ducks have better adaptation to various environmental conditions compared to chickens. They are hardy and can tolerate several diseases. They can also scavenge on their own and require less manpower to keep. Further, they can control snails in rice fields. They might also be able to control intermediate host snails of schistosome in fishponds and at the same time their excreta could serve to fertilize ponds and promote growth of both phytoplankton and zooplankton that serve as food for fishes. Obviously, there could also be problems with trematodes, especially echinostomes, becoming a disease of ducks.

Duck droppings can also promote the growth of aquatic snails, worms, and other aquatic fauna and flora that act as feed for ducks. This system has also been reported to increase productivity, ensure efficient use of water, spread economic risk of price fluctuation, has minimal environmental impact, and a good system for sustainable agriculture (Tai and Tai 2001). Under the traditional systems, ducks can scavenge on their own to obtain the necessary nutrients needed for their growth. By this feed supplementation (manufactured) can be avoided and subsequently reduction in feed cost.

Mini-livestock

Many small vertebrates and invertebrates are collected in the wild and used by man (Hardouin 1995). When bred under controlled conditions in captivity, these animals are called mini-livestock. To qualify as mini-livestock, animals must have a potential benefit either nutritionally for food or economically for animal-feed or revenue, and currently not being utilized to their full potential. Amongst mini-livestock species are several species of edible rodents, snakes, lizards, frogs, and invertebrates such as snails, earth or manure worms and various insects (Cicogna 1992). Obviously, not all potential species of mini-livestock would be easily integrated with aquaculture, but e.g., annelids living in litter and manure convert vegetable refuse to animal protein which could be used as feed for fish, pigs and poultry (Cicogna 1992; Brown et al. 2011). Land or freshwater snails offer another possibility as such snails could feed on waste products from horticulture or aquaculture. There is growing interest in rearing insects as these have the potential to serve as food and feed source globally with a lower negative impact on the environment (Govorushko 2019; Raheem et al. 2019).

Wild food has been upgraded due to the recognition that it has oxidants, vitamins, nutrients, polyunsaturated fatty acids, carbohydrates, and amino acids that are highly valued for healthy human nutrition (see review in Paoletti and Dreon 2005). The development of mini-livestock will contribute to meeting human needs and will also protect the environment from excessive harvesting (Hardouin 1995; Hardouin et al. 2003; Paoletti and Dreon 2005). Field collection of freshwater snails for food is practiced in many regions, but a problem is that in some locations, snails may bioaccumulate heavy metals or other chemicals (Agbolade et al. 2008; Bar 2020). A species like *Bellamya bengalensis* can be used as bioindicator for toxin and heavy metal contamination of water bodies (Bar 2020). Although production of freshwater snails in urban lakes that often are highly eutrophic can be high, there may also be concerns about accumulation of heavy metals or other pollutants in the snails and other organisms (Pham et al. 2007; Tao et al. 2012). Mini-livestock can be a major contributor of a more balanced diet for both rural and urban settlements (Barwa 2009). The attributes of mini-livestock gives it the potential of increasing household protein consumption as well as being a source of income. Production of mini-livestock can be practiced in rural and urban settlements considering its small size, low-cost management requirement, and low capital investment (Barwa 2009). Whilst promoting mini-livestock it should be noted that some of these small animals can represent a serious threat as crop pests and potential zoonotic implications, which need to be identified (Hardouin et al. 2003). Given the need, awareness and increasing information now available on mini-livestock species it is time for increased investment in this form of sustainable production (Hardouin et al. 2003).

Snails have been collected from wild populations, traded, and eaten in many parts of the world since time immemorial (Elmslie 2005). Terrestrial snail farming is not a way of producing cheap food for the masses but can produce a premium product when appropriate systems are used (Elmslie 2005). In West Africa, primarily Ghana and Nigeria, snail farming, primarily land snails of the genus *Achatina* or *Archachatina*, is a profitable undertaking and there are several research publications on methodologies for culture and nutritional composition of snail-meat (Elmslie 2005). The importance of snail-meat in supplying people with protein is well recognized (Eneji et al. 2008; Adeyeye et al. 2020; Meyo et al. 2021; Pissia et al. 2021).

Freshwater snails are easier to farm than terrestrial snails and edible species could be produced in multitrophic fishponds (Figure 10). Species of *Pomacea* are cultured for food in South America (Bocanegra

Figure 10. Snails as food. (a) Sorting snails collected from West Lake in Hanoi in 2005; (b, f) snail vendors in Hanoi markets; (c–e) live snails, *Pila polita* (d) and *Angulyagra polyzonata* (e); (g) enjoying a snail meal.

et al. 2002), Mexico (Mejía-Ramírez et al. 2020) and one species, *Pomacea canaliculata* was introduced into Asia (Ghosh et al. 2016, 2017, 2021), where it became invasive (Madsen and Hung 2014). In central and south Florida, there has been interest in culturing the Florida Apple Snail, *Pomacea paludosa*, for stock enhancement to help promote snail kite (*Rostramus sociabilis*) recovery (Garr et al. 2011). In Asia species of Viviparidae are frequently consumed by people, but there are relatively few places in Africa where freshwater snails are consumed. This could be because there are various taboos associated with eating snails (Ogbeide 1974).

For both freshwater and terrestrial snails, there are several hygienic aspects to consider if produced for human consumption (Giaccone 2005). Parlapani et al. (2014) showed that cultured snails had lower populations of *E. coli*/coliforms, *Enterococcus* spp. The absence of *Salmonella* spp. in cultured snails showed that the controlled conditions decreased the possibility of pathogen presence and contributed to food safety and public health. If snails are produced in excess, they can be utilized as feed for fish (Da et al. 2012; Sogbesan and Ugwumba 2008).

The role for (epi)genomics in fisheries management and aquaculture

Genetic resources are the building blocks for aquacultural breeding programs, biotechnology and conservation and there are legislative issues within countries for how these resources can be utilized and shared (Humphries et al. 2022). Use of exotic species to increase the rate of aquaculture in Africa may not be an efficacious strategy, while use of indigenous species avoids many environmental risks, facilitates brood stock and hatchery management at the farm (Brummett 2007). Selective breeding for genetic improvement of production traits has great potential to increase the efficiency and reduce the environmental footprint of aquaculture (Houston et al. 2020). According to Brummett (2007), the ICLARM genetically improved farmed strain of the Nile Tilapia, *Oreochromis niloticus* grew 20–70% faster than most other domesticated strains.

If focus is to use indigenous species for aquaculture, there may be a need to improve their performance in aquaculture using modern technologies. In contrast to the terrestrial livestock and crop sectors, aquaculture is based on a hugely diverse group of finfish and shellfish species, comprising an estimated 543 different animal species, including 362 finfish, 104 mollusks, 62 crustaceans, 9 other aquatic invertebrates and 6 frogs and reptiles (Houston et al. 2020). Despite their diversity, aquacultural species tend to share two key features that enhance their potential for genetic improvement, (1) they remain in the early stages of the domestication process which is linked to higher within-species genetic diversity and (2) they are highly fecund, with typically external fertilization (with the exception of some cichlids) (Houston et al. 2020). This feature of their reproductive biology allows for flexibility in breeding programme design and widespread dissemination of selectively bred strains to producers, often without the need for several tiers to multiply and disseminate sufficient numbers of genetically improved animals for production (Houston et al. 2020).

Aquacultural success may be challenged by the occurrence of microbial infections, notably those caused by antimicrobial-resistant pathogens (Canellas et al. 2022). In order to better forecast, prevent and deal with such adversities, new technologies need to be brought into action, such as the new "omics" technologies (Canellas et al. 2022). Omics technologies like genomics, transcriptomics, proteomics and metabolomics have received increasing recognition because their potential to unravel novel mechanisms in biological science (Mohanty et al. 2019). Omics technology is being used in a number of applications in the fisheries and aquaculture sector such as unraveling the mechanisms of disease and stress tolerance, selection of disease resistant varieties, fish disease diagnosis, vaccine development, species identification for fish food authentication, post-harvest value addition and many more (Mohanty et al. 2019; Tripathy et al. 2021). In the recent years, the genome sequencing of organisms has been adapted as a tool for understanding genetic variations affecting body functions, developing markers for tagging these variations useful in genome-wide association studies (Kumar et al. 2021).

Research of aquacultural genomics aims to develop a comprehensive understanding of the molecular basis of production-relevant traits such as growth rate, resistance to stress and disease, resilience with high temperature and low oxygen environments and others (Rise et al. 2019). Epigenetics has attracted considerable attention with respect to its potential value in many areas of agricultural production, particularly under conditions where the environment can be manipulated, or natural variation exists (Gavery and Roberts 2017). Environmental factors can exert influence on epigenetic changes to produce the phenotype and this effect can be passed on to the subsequent generations/offspring (Roy et al. 2021). This creates a huge possibility of epigenetic programming in animal husbandry/aquacultural sector for selection of the most favorable phenotypic traits and production enhancement (Roy et al. 2021). A recent review of these modern technologies in aquaculture is present in a book edited by Pandey and Parhi (2021).

As well as these technologies can be applied to the aquacultural species, they can be applied also to disease vectors or intermediate hosts. For example, whole genomes for some schistosome intermediate host species have been published (Adema et al. 2017). Studies have shown that the susceptibility of these snails to schistosome infection is more complicated than hitherto believed (Mitta et al. 2017; Castillo et al. 2020) and perhaps environmental change could cause epigenetic effects, such as increased resistance to infection (Bridger et al. 2018; Augusto et al. 2019).

Conclusions

The World faces huge challenges if the World Health Assembly target is to end world hunger and malnutrition by 2030. Aquacultural development could be a major contributor to achieve this goal by providing food rich quality protein, lipids and micronutrients. Diversifying food sources is especially important for maternal and child development. If properly implemented aquacultural production could play a major role in protecting biodiversity as well. Both commercial and small-scale family-based aquaculture should be promoted. There are several problems associated with aquaculture but there are possibilities for their potential mitigation. Obviously, the aquacultural activities should be adapted to prevailing local conditions and as experiences accumulate they can be perfected to make the aquacultural production more sustainable.

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