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# Safe and Sustainable Business Models for Water Reuse in Aquaculture in Developing Countries

Philip Amoah, Solomie Gebrezgabher and Pay Drechsel

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Philip Amoah, Solomie Gebrezgabher and Pay Drechsel

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## Collaborators

This research study involved collaboration among the following organizations:

International Water Management Institute (IWMI)

TriMark Aquaculture Centre (TAC), Ghana

Kwame Nkrumah University of Science and Technology (KNUST), Ghana

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# ACRONYMS AND ABBREVIATIONS

| ABBREVIATION | DEFINITION |
|---|---|
| BDT | Bangladesh Taka |
| BOD | Biological Oxygen Demand |
| Cd | Cadmium |
| COD | Chemical Oxygen Demand |
| FAO | Food and Agriculture Organization of the United Nations |
| GHS | Ghana Cedi |
| HACCP | Hazard Analysis and Critical Control Point |
| Hg | Mercury |
| HRT | Hydraulic Retention Time |
| IRR | Internal Rate of Return |
| IWMI | International Water Management Institute |
| KHC | Kumudini Hospital Complex (Bangladesh) |
| KMA | Kumasi Metropolitan Assembly (Ghana) |
| KNUST | Kwame Nkrumah University of Science and Technology (Kumasi, Ghana) |
| KWT | Kumudini Welfare Trust (Bangladesh) |
| MeHg | Methyl mercury |
| N | Nitrogen |
| Ni | Nickel |
| NPV | Net Present Value |
| O&M | Operation and Maintenance |
| P | Phosphorus |
| Pb | Lead |
| PPP | Public-Private Partnership |
| TAC | TriMark Aquaculture Centre (Ghana) |
| UN | United Nations |
| WE | Waste Enterprisers (Ghana, Rwanda) |
| WHO | World Health Organization |
| WSP | Waste Stabilization Pond |
| WTP | Willingness to Pay |

# SUMMARY

For many people, the nutritional benefits derived from pond-based aquaculture systems can be substantial. The use of wastewater can add additional environmental and financial benefits where freshwater is scarce and nutrients in the wastewater can be recovered as free fish feed instead of contributing to water eutrophication.

Wastewater-fed aquaculture has a long history, especially in Asia. While the planned use of wastewater appears to be declining due to increasing urbanization and the concomitant lack of space, unplanned and unsafe water reuse is common because of widespread water pollution. This report examines the win-win situations of planned integrated wastewater treatment and aquaculture production systems that support human nutrition and food security while contributing to the sustainability of wastewater treatment through cost recovery.

The report briefly reviews different wastewater-fed fish production systems and explores two empirical business cases from Africa (both public-private partnerships) and one from Asia (a nongovernmental organization and private sector partnership), which have been analyzed for their safety, value propositions, financial feasibility, socioeconomic and cultural acceptance, health risk reduction measures, as well as their scaling-up potential. The main section ends with special attention on the required standards for water quality monitoring given the importance of public health risks and risk perceptions.

From an aquaculture entrepreneur's perspective, the combination of fish farming and wastewater treatment in common waste stabilization ponds (WSPs) allows significant savings on capital (pond infrastructure) and running costs (wastewater supporting fish feed). On the other hand, the party who owns the treatment plant will have the benefit of a partner with high interest in taking direct or indirect care of the plant's operational and infrastructure maintenance.

Like other waste-based businesses, the success of wastewater-based aquaculture depends strongly on market perceptions and acceptance as well as compliance with the regulatory environment, in particular safety guidelines. In wastewater-based production systems, health concerns can relate to many parties, but most affected are the farm workers and fish consumers.

While in WSPs, fish are usually reared in the final maturation pond(s) to be followed by depuration and/or smoking of the fish as measures for risk reduction, an alternative model presented in the report limits the wastewater contact to broodstock. Fish eggs are extracted from the broodstock for the production of fingerlings which are raised in clean water. Another presented alternative is to produce fish feed (only) in the wastewater, such as duckweed, while fish are cultivated in clean water tanks as shown in the case study from Bangladesh.

The financial analysis of the presented systems shows profitable options for the fish farmer, operational and in part capital cost recovery for the treatment plant, and as the treatment plant operators can stop charging households a sanitation fee, eventually a triple-win situation for both partners and the served community.

The different models and partnership constellations can easily be replicated given the ubiquity of WSP systems, and emphasize the important role of an intersectoral dialogue for turning a highly subsidized waste burden into a potentially profitable business in support of a circular economy.

# 1. INTRODUCTION

Fish have been an important source of protein and other nutrients for humans throughout history. Half of the fish consumed today derives from controlled fish farming (SPORE 2013). Growing fish leapfrogs the normal crop-livestock based protein value chain and creates viable businesses, livelihoods and balanced diets (Edwards and Pullin 1990). However, not all farmed fish are produced in clean water, especially not in Asia. The rearing of fish in wastewater-fed ponds or lagoons has been practiced for a long time in several Asian countries (Edwards and Pullin 1990) taking advantage of human and animal waste to produce fish feed. On the other hand, rapid urbanization, coupled with regional freshwater scarcity, requires innovative solutions for food production which should include options for a circular economy, like wastewater treatment for safe reuse in agriculture and aquaculture (WWAP 2017).

The combination of wastewater treatment systems and water reuse through crop irrigation or aquaculture can support the functioning and sustainability of the treatment plant if the benefits are shared (Drechsel and Hanjra 2018). While a revenue stream might be difficult to arrange for crop irrigation downstream of a treatment plant (the water has to be released anyway), this does not apply to in-plant (in-situ) production of fish or fish feed within the treatment system. Such circular systems, if safe, can support food security while tackling human excreta, the ultimate food waste.

Where fish ponds contain raw or diluted wastewater, fish growth and the overall positive impact of such systems greatly depends on the quality of the water and its management. If these ponds are part of a treatment system, then the success of integrated fish farming depends on the performance of the treatment system, which implies that plant operators and fish farmers have to work closely together.

Promoting water reuse models in general, and water reuse for aquaculture in particular, requires the combination of strict health guidelines and innovative business models. A key driver for wastewater-fed aquaculture, apart from increasing competition for freshwater, is the limited availability of freshwater due to widespread water pollution in urban and peri-urban areas. Proximity to urban markets makes peri-urban areas particular hotspots for aquaculture initiatives, compounded by significant competition for land and safe water.

In combined aquaculture systems where part of the revenue is invested in wastewater treatment, the farmer benefits from access to existing infrastructure (pond systems) which minimizes capital costs, and access to free, nutrient-rich water in the ponds, which considerably reduces operational expenditures on fish feed. The development of such systems within public-private partnerships (PPP) can therefore be a win-win situation for fish farmers while recovering operational and even capital costs of the treatment plant (Drechsel et al. 2018) as the cases presented in this report will show.

Section 2 provides a short overview of wastewater-fed aquaculture in developing countries, seguing into Section 3 which presents waste stabilization pond-based fish production systems. Section 4 introduces wastewater treatment as an aquaculture business opportunity. Section 5 presents the three business cases from Ghana and Bangladesh, after overviewing the respective regulatory context. The chapter also examines the market environment and acceptance of fish reared in association with wastewater treatment. Section 6 addresses water quality and safety, and the importance of balancing production and health objectives. Section 7 provides concluding remarks and recommendations emerging from the comparison of the cases and their models.

# 2. WATER REUSE FOR AQUACULTURE IN DEVELOPING COUNTRIES

Several Asian countries have a long tradition of water reuse for aquaculture. Similar to wastewater use in crop irrigation there are modalities where (treated) wastewater or wastewater treatment systems are deliberately targeted; conversely there are situations where it is hard to avoid wastewater as all streams in urban and peri-urban areas either are polluted or receive treated or partially treated wastewater, including streams that feed ponds or wetlands. These circumstances are very common.

The East Calcutta Wetlands in India are the most frequently cited example. They have the largest wastewater-fed aquaculture ponds in the world with production of carp and tilapia estimated at 18,000 tons annually (Bunting 2007; Little et al. 2002; Mukherjee and Dutta 2016). Wastewater aquaculture is also widely practiced in Vietnam where one site is reported to produce 3,900 tons annually and in China where a review counted an area of 8,000 hectares (ha) producing 30,000 tons of fish per year (Bunting 2004). Due to the increase in industrial water pollution as well as disamenities caused by fish odor and phenolic taste issues, the practice in China is however declining (Bunting 2004).

Apart from fish production systems, aquatic vegetable production systems (aquaponics) in semi-intensive and intensive systems are also widespread and commercially significant around many cities in Southeast Asia. According to Phuong and Tuan (2005), in Hanoi, Vietnam, water spinach (*Ipomoea aquatica*) is produced throughout the year, while water mimosa (*Neptunia oleracea*) is cultivated only in the summer; water dropwort (*Oenanthe stolonifera*) and watercress (*Rorippa nasturtium-aquaticum*) are produced in the winter. Most production occurs in flooded fields, some of which are converted from rice production to generate higher income. Water spinach floating on canals within the city is also cultivated. In Hanoi, out of total vegetable consumption of 257 grams (g)/capita/day, the consumption of water spinach is about 77 g/capita/day (Anh et al. 2004). Water mimosa and water spinach production are also reported in peri-urban provinces around Bangkok (Yoonpundh et al. 2005). Consumers are usually not aware of the water quality used in vegetable production (Edwards 2005).

In the environs of Ho Chi Minh City, Vietnam, many farmers in Binh Chanh District have combined water mimosa cultivation with fish production in separate ponds; water mimosa provides daily income while the fish consume the duckweed (*Lemna* spp.) that grows beside the mimosa (Hung and Huy 2005). Duckweed production in waste stabilization ponds (WSPs) to feed poultry or fish cultivated in treated wastewater or clean water tanks has been reported, for example, from India and Bangladesh (Islam et al. 2004; FAO 1998; Patwary 2013). A major challenge for wastewater-fed aquaculture is the limited land availability around rapidly expanding cities (Edwards 2005), pushing the systems away to more distant sites (Nguyen et al. 2012).

In contrast to freshwater aquaculture, wastewater-based systems are practically unknown in Latin America and are not overly common in Africa (WHO 2006). In Africa, publications refer to experimental studies as well as business cases, with reports coming from Egypt, South Africa, Ghana and Tanzania for instance (Tenkorang et al. 2012; Ampofo and Clerk 2003; Abdul-Rahaman et al. 2012; Mkali et al. 2014).

Apart from aquatic systems where water pollution is very common and wastewater use is difficult to avoid there are also wastewater-fed farming systems where farmers approach treatment plant operators for approval to use their treatment ponds. **These systems are the focus of this report** as they offer a win-win situation for fish farmers and the treatment plant operators unless consumers reject the produce as reported for example from Egypt (Mancy et al. 2000). To ensure that fish produced in wastewater aquaculture systems are acceptable to consumers, great care must be taken when introducing the fish on the market and informing consumers about the water source of the offered food.

Kaul et al. (2002), Bunting (2004), Costa-Pierce et al. (2005) and WHO (2006) provide a more detailed overview of the geography and characteristics of wastewater use in aquaculture.

# 3. TREATED WASTEWATER AQUACULTURE PRODUCTION SYSTEMS

The most common system for the planned cultivation of fish with treated wastewater takes place at the end of a pond-based treatment system, such as WSPs. WSPs are a cascade (interconnected series) of ponds designed for wastewater treatment to reduce organic content and remove pathogens from wastewater. Untreated wastewater enters at one end of the WSP cascade and exits at the other end as treated effluent, after spending several days in the system. The presence or absence of oxygen varies among and within these ponds which are classified as anaerobic, facultative and maturation ponds according to the biological activities occurring in them (Ramadan and Ponce 2016). The production of fish is usually limited to the last pond(s), i.e. the maturation ponds, while aquatic plants can also be grown in other ponds where they contribute to the water treatment by extracting nutrients from the water and transforming them into biomass.

Within a WSP system, the **anaerobic pond** is the first and smallest unit in the series with depths ranging from 2 to 5 meters (m). The pond receives raw wastewater with high organic loads resulting in a strong reduction of dissolved oxygen (i.e. high biological oxygen demand [BOD] of over 3,000 kilograms (kg)/ha/day for a depth of 3 m). The pond thus contains no dissolved oxygen and no algae (Mara 2004). The primary function is to reduce the organic load (BOD reduction) through sedimentation and anaerobic digestion in the resulting sludge layer. The process of anaerobic digestion is more intense at temperatures above 15°C (Kayombo et al. 2010). Therefore, in cold climates, anaerobic ponds mainly serve as settling ponds. The Hydraulic Retention Time (HRT) for anaerobic ponds is about 1 to 3 days (Mara 2004; Van der Steen 2014). Before entering the first pond, a coarse mesh helps to remove large objects such as trash and textiles from the inflow which could subsequently harm the system and processes. After coarse screening, a grit chamber can be useful to slow down the flow so that solids such as sand will settle out of the water before it enters the anaerobic pond. Heavy metals are precipitated as metal sulfides and many organic toxicants are altered into nontoxic forms.

The second treatment step within the WSP system involves provision of **facultative ponds**. There are two types of facultative ponds (Mara 2004): the primary facultative pond receives raw wastewater after screening and grit removal; the secondary facultative pond receives settled wastewater, usually the effluent from anaerobic ponds, septic tanks, primary facultative ponds and shallow sewerage systems. They are usually 1.5-m (1.0 to 1.8 m) deep and further reduce BOD on the basis of relatively low surface loading (100 to 400 kg BOD/ha/day) to permit the development of a healthy algal population as the oxygen for BOD removal by the pond bacteria is mostly generated by algal photosynthesis. The HRT of the ponds varies between 5 and 30 days (Mara 1997). The ponds are usually dark green due to the algae that grow naturally and profusely. The word 'facultative' is derived from the fact that the top layer of facultative ponds is aerobic due to oxygen production by the algae and the bottom layer is anaerobic due to the absence of algae activity. The level of dissolved oxygen is high during the day (oxygen production) and low at night (algae consume oxygen) which correlates with a similar pH fluctuation, important for bacterial die-off. Waste stabilization in these ponds is the result of both oxidation of organic matter by aerobic and facultative bacteria as well as anaerobic processes in the anaerobic bottom layer.

**Maturation ponds** are usually 1- to 1.4-m deep and are entirely aerobic. A minimum of 3 days HRT for a maturation pond is recommended, although at temperatures below 20°C, 4 to 5 days are preferable (Mara 1997). The size and number of ponds are governed mainly by the required bacteriological quality of the final effluent; their primary function is to remove excreted pathogens. *E. coli* reductions of 6 log units are possible (Mara 2004). Kaul et al. (2002) recommended two ponds in a series, each with a retention time of 7 days to produce a final BOD of under 25 mg/L. The algal population in maturation ponds is much more diverse than that of the facultative ponds and the diversity generally increases from pond to pond along the series (Mara 2004; Kayombo et al. 2010). Because of the photosynthetic activities of pond algae, there is a diurnal variation in the dissolved oxygen concentration. The principal mechanisms for fecal bacteria removal in maturation ponds are time and temperature, high pH (> 9) and high light intensity, combined with high dissolved oxygen concentration (Mara 2004; Kayombo et al. 2010). The use of paddle-wheel aerators at times of low oxygen levels can significantly support fish production (Sey et al. 2021) but should be solar-powered to avoid increased operational costs.

In view of fish farming, WSP systems support different options (Table 1).

**TABLE 1.** VARIATIONS OF WSP-BASED FISH PRODUCTION SYSTEMS.

| Production target | Brief description | Sources |
|---|---|---|
| Fish farming | Fish cultivation in the maturation ponds of the WSP system. | Amoah et al. (2018) |
| Fish farming and irrigation | Fish production within the [facultative and] maturation ponds; treated effluent used for crop irrigation. | Kumar et al. (2015) |
| Broodstock production for external fish (and crop farming) | Broodstock cultivation in the maturation ponds of the system; while fingerlings and fish for sale are grown in clean water tanks. Crops are grown with wastewater from the fish tanks. | This report |
| Aquatic plants to feed externally cultivated fish | Aquatic plants grow within the ponds, absorb nutrients, and are either sold or used internally e.g. as fish feed for fish reared in separate clean water ponds, or ponds using treated wastewater. | Drechsel et al. (2018)<br>FAO (1998) |

Compared with other treatment systems, WSPs are considered to be efficient, robust and low-cost (no electricity costs) treatment systems for tropical countries where space is not a limitation. WSPs, however, require regular (unsophisticated) maintenance to perform properly. This includes ensuring that debris is removed from the mesh, cleaning the grit chamber, preventing debris buildup in influent or effluent pipes as well as those between the ponds, keeping the pond surfaces clear, attenuating the growth of vegetation in and around the ponds and maintaining the HRT. However, given the unsophisticated nature of pond maintenance, such maintenance is often disregarded or not budgeted for, leaving WSPs unsupervised and in a poor state (Murray and Drechsel 2011).

Production of fish, fish feed and/or crops within or adjoining a WSP system could effectively capture the economic value of the treated water and its nutrients; some of the generated revenue could be used to support operation and maintenance (O&M) of the treatment facilities. This concept dubbed 'design for reuse' (Murray and Buckley 2010; Tenkorang et al. 2012) builds the conceptual backbone of the business cases presented in this document.

In addition to WSPs, fish and aquatic crops are also produced within other systems which are not designed treatment systems, but support treatment through natural processes, such as wastewater-fed lakes, channels, lagoons and wetlands (Table 2). In such natural systems, farmers usually target areas close to the wastewater inflow as there is a strong positive correlation between the organic load (BOD), savings on fish feed and significant fish growth (Mukherjee and Dutta 2016). The water in such fish production systems should not be classified as 'treated'.

**TABLE 2.** OTHER WASTEWATER-FED PRODUCTION SYSTEMS USED FOR FISH OR AQUATIC PLANT PRODUCTION.

| Fish farm location | Brief description of the aquaculture system | Source |
|---|---|---|
| Lakes in urban vicinity serving as natural treatment systems (mostly unplanned) | An example is the Beung Cheung Ek Lake near Phnom Penh, Cambodia, that receives largely untreated wastewater from the city. The lake employs biological treatment of wastewater – recapturing nitrogen (N) and phosphorus (P) to produce aquatic vegetables like morning glory (water spinach) for human and animal consumption. | Kuong et al. (2006)<br>Leschen (2018) |
| Wastewater drains and irrigation channels, paddy fields and farmer-generated ponds | Treated and untreated wastewater is directed through a network of channels. From Hanoi three systems have been described: (i) fish culture alone, (ii) fish-rice rotations and (iii) fish-rice-vegetable rotations. In Ho Chi Minh City, a network of smaller less-defined wastewater channels supports the growth of different aquatic plants for human or animal consumption, as well as ornamental fish and fish for consumption. | Minh Phan and Van de Pauw (2005)<br>Hung and Huy (2005)<br>Tuan and Trac (1990) |

(Continued)

**TABLE 2.** OTHER WASTEWATER-FED PRODUCTION SYSTEMS USED FOR FISH OR AQUATIC PLANT PRODUCTION. (CONTINUED)

| Fish farm location | Brief description of the aquaculture system | Source |
|---|---|---|
| Wastewater-fed wetlands which function as treatment systems | Natural wastewater-fed ponds and lagoons, which receive diluted or raw wastewater from the city for treatment. Wetland ponds are usually large and can be 40-50 ha in size. The 12,500 ha of wastewater-fed wetlands in Calcutta, India, are considered the largest operational system in the world where fish are cultured in ponds or cages. | Leschen (2018)<br>Leschen et al. (2005)<br>Mukherjee and Dutta (2016) |
| River deltas | Deltas can show a large variety of aquaculture, including coastal fisheries, brackish water aquaculture (like shrimp farms) and riverside prawn collection. Other systems combine aquaculture with rice production and/or animal husbandry. Water quality is affected by upstream pollution, saline water intrusion and agricultural intensification (including impacts from pond effluent). Examples are the Nile, Mekong, Indus and Ganges deltas. | Oczkowwski and Nixon (2008)<br>Nguyen (2017)<br>SourceTrace (2018) |

# 4. WASTEWATER AQUACULTURE AS A BUSINESS MODEL

This section provides a general description of a wastewater-fed aquaculture business using the business model canvas approach (Osterwalder and Pigneur 2010). The basic wastewater-fed aquaculture business centers around the coupling of wastewater treatment in a WSP and fish farming, usually represented in a partnership between a public and a private entity.

The combination has the following advantages for the fish farmer:

- Access to existing infrastructure (ponds) which saves on capital costs.
- Access to a location in an urban (market) vicinity where normally land prices are high.
- Access to nutrient-rich water which reduces the need for fish feeding, which can be the largest operational cost factor.

It also entails disadvantages, such as:

- Limited support where these systems operate within a policy and regulatory grey area.
- The need to comply with additional food safety regulations and risk monitoring.
- The variety of fish species will be limited to those that can be cultivated in (treated) wastewater.
- The possibility of negative consumer perceptions, including short-term perception changes as experienced under the Covid-19 pandemic, for example.

The advantages for the treatment plant operator are the possibility of cost savings and recovery through leasing the ponds and/or asking the farmer to arrange for the maintenance of the pond system. From a public sector perspective, leasing ponds to farmers or sale of fish, aquatic plants and/or irrigation water[1] represent interesting opportunities to offset at least the operational costs of wastewater treatment, if not the capital costs, as shown in India and Bangladesh for example (Kumar et al. 2015; Drechsel et al. 2018).

Successful implementation of such a possible win-win system needs the involvement of at least two to three entities. With the exception of larger hotels, most wastewater treatment plants in low-income countries are managed by the public sector (such as municipalities, universities, hospitals, army barracks). A PPP can be established if a municipality has no interest/capacity to engage in fish farming on its own. The fish farming can be outsourced to an entrepreneur or for larger pond systems, to a farmer cooperative (Nandeesha 2002). Experience shows that it is useful to involve a research and development partner who can support laboratory services and assistance to implement safety standards and obtain public health approval (Figure 1).

[1] In some locations, official water-pricing policies might not support charging farmers for treated wastewater (Nguyen et al. 2012) but society for the treatment process.

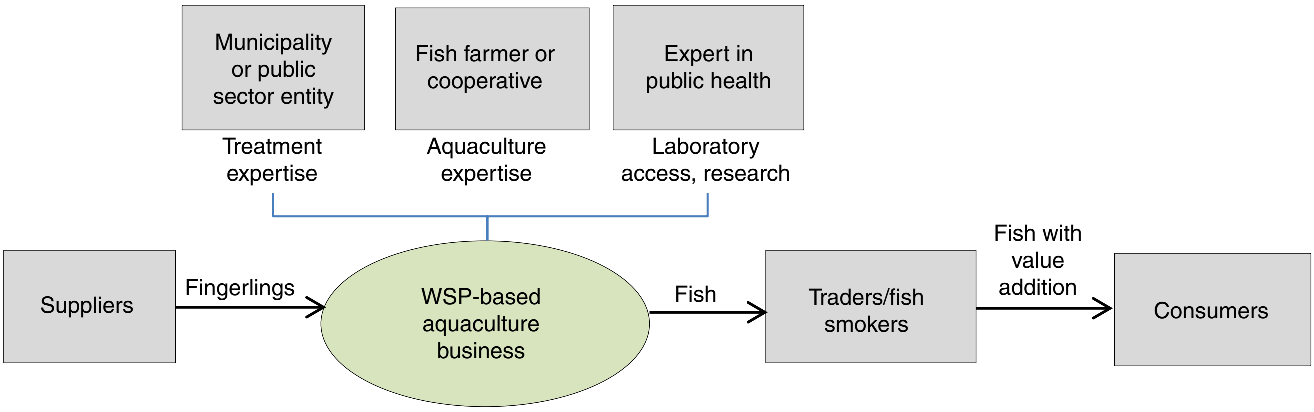


**FIGURE 1.** INTEGRATED WSP AND AQUACULTURE SYSTEMS – KEY PARTNERS AND PRODUCT FLOW VALUE CHAIN.

Osterwalder and Pigneur (2010) suggested the visual presentation of a business model through its basic building blocks, namely, customers, value proposition, key activities and so forth as shown in Table 3 for a wastewater-fed aquaculture business assuming a PPP relationship (see also Drechsel and Hanjra 2018).

The key value proposition from the PPP perspective is providing a high-value protein (fish) or crop to meet the specific demands of consumers. Ideally, the product will be certified to show its consumer safety. The second value proposition is the increased sustainability of wastewater treatment efficiency as parts of the revenues are invested in O&M of the treatment system (e.g. through a pond usage fee, rent, lease).

The private entity will generate revenue from sales of the fish or crops produced from the systems. The aquaculture business model is based on a strong partnership with key actors involved in sanitation and fish production for sale in identified markets through a network of fish or crop sellers, or otherwise sold directly to individual consumers. The success of the business model depends on the scale of and the value addition to the harvested fish as well as consumers' acceptance of the fish reared in treated wastewater. A better understanding of fish consumers' perceptions of and attitude towards fish reared in treated wastewater is key to ensuring that fish produced in wastewater aquaculture are acceptable to consumers. Great care must be taken when introducing fish reared in treated wastewater into areas where wastewater has not been traditionally used.

To optimize water treatment and fish production under the local wastewater quality conditions and to assist in certifying fish safety, collaboration with a local university would be advantageous.

**TABLE 3.** BUSINESS MODEL CANVAS OF A WASTEWATER-FED AQUACULTURE PPP.

| Key partners | Key activities | Value proposition | Customer relationships | Customer segments |
|---|---|---|---|---|
| • Public treatment plant operator<br>• Private enterprise, farmer group or cooperative<br>• Input suppliers (plant seeds/fingerlings, extra feed)<br>• Safety certification body<br>• University partner for accompanying research | • Production of fish/ crop in treated wastewater ponds<br>• Product certification<br>• Sale and distribution of fish<br>• Treatment plant O&M<br>• Research and development | • High-value protein fish and/or crops which are safe and certified<br>• Increased sustainability of quality wastewater treatment<br>• Low-cost fish production and wastewater treatment | • Network of fish/ crop sellers | • Traders in markets and restaurants<br>• Private households and individuals |
| | **Key resources**<br>• Capital<br>• Treated wastewater pond systems<br>• Labor<br>• Technical competency | | **Channels**<br>• Direct sales | |
| **Cost structure**<br>• Capital investment (fingerlings, …)<br>• O&M of pond system (internal transaction)<br>• O&M of fish farming (marketing, packaging, distribution, sale)<br>• Management costs or share | | | **Revenue streams**<br>• Sales of fish/crops (private partner)<br>• Pond rent/lease (internal transaction)<br>• Savings on feed and capital costs | |
| **Social and environmental costs**<br>• Possible human health hazard from contact with treated wastewater for workers (only if the safety plan is violated)<br>• Possible risks to consumers from fish consumption (if safety measures are not observed) | | | **Social and environmental benefits**<br>• Reduced public costs of treating wastewater<br>• Higher sustainability of the treatment process (reduced pollution and health costs) | |

# 5. SELECTED BUSINESS CASES

The selected business cases came from Ghana and Bangladesh where fish is a well-accepted part of the diet and a key source of animal protein (GLSS 2019; BBS 2017). A significant difference between both countries is that fish farming has a much longer tradition and significance in Bangladesh compared to Ghana. Bangladesh ranks globally among the top countries in view of aquaculture production, with fish farming having a share of over 50% of the country's total fish production, while in Ghana the share is about 15% (FAO 2014; Cobbina and Eiriksdottir 2010; Amenyogbe et al. 2018).

In both countries, rearing of fish in treated wastewater ponds is not addressed in current policies and strategies, and remains a grey area without direct support or limitations, or entry in any official statistics. Ghana's Environmental Sanitation Policy describes solid and liquid wastes as 'materials in transition' in support of value creation and reuse, but there is no legislation that explicitly promotes or bans the use of wastewater for aquaculture. Existing aquaculture regulations focus (only) on the possible negative impact of fish farming on the environment. For example, commercial fish farming needs an environmental impact assessment to obtain approval from the Fisheries Commission, which in its National Aquaculture Guidelines and Code of Practice (2014) sets minimum standards for operators in the aquaculture value chain to prevent any possible harm to the environment, in line with the Fisheries Regulations, 2010 and Fisheries Act, 2002 (Act 625).

In Bangladesh, aquaculture is supported by the National Aquaculture Development Strategy and Action Plan 2013-2020 which is aligned with and draws guidance from the National Fisheries Policy, Country Investment Plans and the National Fisheries and Livestock Sector Development Plan. The action plan calls for an integrated environmental monitoring system to ensure aquaculture safety and to minimize aquaculture impacts on surrounding ecosystems. However, the existing legislation does not address linkages among sanitation and aquaculture, wastewater-fed aquaculture or the production of fish feed in treatment ponds. However, the National 3R Strategy for Waste Management recommends that one facility's waste (energy, water or materials) becomes another facility's feedstock which supports the idea of wastewater-based fish farming (DoE 2010).

From a consumer perspective in both countries, no negative response related to wastewater-fed fish cultivation has been reported. Consumer surveys conducted, for example, in 2014 and 2018 in Kumasi (Ghana) showed that product attributes that influence consumers' fish-buying decisions were related to product price, size and perceived fish quality while the source of the fish was among the least important product attributes (Gebrezgabher et al. 2015; Sey et al. 2021), similar to results from Nigeria (Adeola et al. 2016) or the purchase of potentially wastewater-irrigated vegetables (Keraita and Drechsel 2015). In Ghana, where the irrigation water in and around cities is severely polluted, the limited interest in the water source has been attributed to low education and health risk awareness (Drechsel and Keraita 2014). However, another reason, in particular for fish farming in Africa, is that wastewater-fed aquaculture is still a largely unknown activity and the link is not identified. This is very much in contrast to the wide acceptance of wastewater-grown vegetables in Asia, which appears to be based on the long tradition of the practice and capacity to manage possible risks (Leschen et al. 2005).

In Kumasi, an analysis of consumers' willingness to pay (WTP) showed a higher probability of consumers buying fish farmed in treated wastewater if they are less expensive than fish from other sources. The mean WTP for both fresh tilapia and smoked catfish with wastewater origin was comparable to their respective (freshwater) market prices (Gebrezgabher et al. 2015). Interestingly, among households in treatment plant proximity, 66% of the respondents were not concerned about the source of the fish and those with knowledge of the plant and fish preparation had an even higher probability of buying them than consumers living elsewhere in the city (Sey et al. 2021). It appears that having some knowledge of the water treatment process and the facility made consumers more comfortable with eating the fish (Howell 2021).

More details about the local settings, opportunities and challenges are presented in the following business cases which are all based on the integration of fish farming within a wastewater treatment facility:

Business case 1: The Waste Enterprisers (WE) aquaculture model, Kumasi, Ghana.

Business case 2: The TriMark Aquaculture Centre (TAC) model, Kumasi, Ghana.

Business case 3: The PRISM Kumudini Hospital model in Mirzapur, Bangladesh.

## 5.1 Business Case 1: The Waste Enterprisers Aquaculture Model in Kumasi

### 5.1.1 Context and Background

In early 2010, Waste Enterprisers (WE), a nonprofit organization, entered into a PPP with the Kumasi Metropolitan Assembly (KMA) to set up a wastewater-fed aquaculture business model in the Ahinsan and Chirapatre wastewater treatment plants located in Kumasi. Both treatment plants were built in the late 1970s to each serve more than 200 houses in their respective communities with about 1,500 residents in Ahinsan and 1,800 in Chirapatre. The houses were connected to a communal sewerage network which was channelled to the respective WSPs for treatment (Tenkorang et al. 2012). Over time, the maintenance of these facilities became a challenge for the KMA due to inadequate funds and the poor fee collection system for the households served by the treatment plants, a situation common across the country (Murray and Drechsel 2011; Tenkorang et al. 2012).

Following extensive research and testing to ensure the quality and safety of fish, WE decided to cultivate African catfish *(Clarias gariepinus)*. This species was chosen for its ability to grow well under the conditions of the maturation pond and safety reasons as it is normally consumed smoked in the region and not eaten fresh.

The institutions involved in the establishment of the PPP and subsequent operation comprised:

- The KMA as the public entity that provided access to the land and WSP. It was also involved in monitoring of the aquaculture plant and facilitation of business implementation.

- WE as the private entity in charge of O&M of the aquaculture plant and marketing of fish.
- The local university, Kwame Nkrumah University of Science and Technology (KNUST), which provided technical guidance and research on feeding, stocking and food safety.
- The Fisheries Commission which provided guidance on safety and health aspects of fish reared in treated wastewater.
- The International Water Management Institute (IWMI) as a research partner providing advice on the market and facilitating the PPP agreement.

After operating the WSP for 2 years, WE had the opportunity to engage in a larger sanitation challenge and handed the plant back to the city of Kumasi, before TAC came into the picture in 2017 (see section 5.2).

### 5.1.2 Waste Enterprisers Business Model

The partnership between WE and the KMA was founded on the notion that the partnership would result in benefits for both parties (Table 4). WE would obtain access to the WSP land and infrastructure as well as nutrient-rich water at no cost for WE to cultivate fish under strict safety standards in the two maturation ponds. In return, WE would use half of its profits from selling catfish to ensure regular O&M of the treatment plants, which would (a) remove the sanitation fee burden from the houses served by the treatment plant, and (b) lower public health expenditures as better treated wastewater would be released into the environment. In the system setup, WE sold its products to wholesalers who smoked the fish or sold it to local fish smokers. Wholesalers were contacted and notified of harvest times.

To support the health and safety of the fish, WE's operations on feeding, stocking and food safety were informed by research conducted by the Department of Fisheries and Watershed Management, KNUST and IWMI to optimize the system (Amoah and Yeboah-Agyepong 2015a, 2015b).

**TABLE 4.** BUSINESS MODEL CANVAS FOR THE WASTE ENTERPRISERS AQUACULTURE BUSINESS.

| Key partners | Key activities | Value proposition | Customer relationships | Customer segments |
|---|---|---|---|---|
| • KMA<br>• KNUST<br>• IWMI<br>• Fingerling and feed suppliers | • Maintain wastewater treatment functions<br>• Production of fingerlings and fish<br>• Fish marketing, sale and trust building<br>• Research and development | • Fish production at competitive prices<br>• Improved wastewater treatment at no cost for the authority | • Personal contact with wholesalers at harvest<br>• PPP contract with KMA | • Wholesalers/ fish smokers |
| | **Key resources** | | **Channels** | |
| | • Wastewater, land, treatment ponds<br>• Labor, capital<br>• Fingerlings, extra feed<br>• Aquaculture expertise, laboratory access | | • Direct sales to wholesalers | |
| **Cost structure** | | | **Revenue streams** | |
| • Capital investment (max. 30%)<br>• Regular fingerling purchase<br>• Pond O&M (subcontracted)<br>• Fish harvest, marketing, sales<br>• Fish-farming research and development cost<br>• Management cost or overhead | | | • Fish sales | |
| **Social and environmental costs** | | | **Social and environmental benefits** | |
| • Potential health risks to plant workers and to consumers through fish consumption if the monitoring system failed<br>• Potential risk to biodiversity if fish escaped | | | • Improved wastewater treatment and public health<br>• Increased protein supply<br>• Connected households exempted from WSP (maintenance) fees | |

*Source:* Amoah et al. (2018).

### 5.1.3 Waste Enterprisers Setup and Business Value Chain

The wastewater from housing estates was channelled to the WSPs, which were publicly owned but operated by WE under the PPP agreement. Initially, O&M of the WSPs was dependent on the fees collected by a maintenance contractor from houses served by the WSPs (Figure 2, option 1). With the new business model, WE paid (via the KMA) for O&M (option 2) or if this did not work out, WE paid the O&M provider directly (option 3). Fish were sold directly to consumers or to wholesalers or fish smokers. As parts of the revenue generated from selling of fish were used for O&M of the WSPs, there was no longer a need to charge low-income houses served by the plants, making the model a triple-win situation.

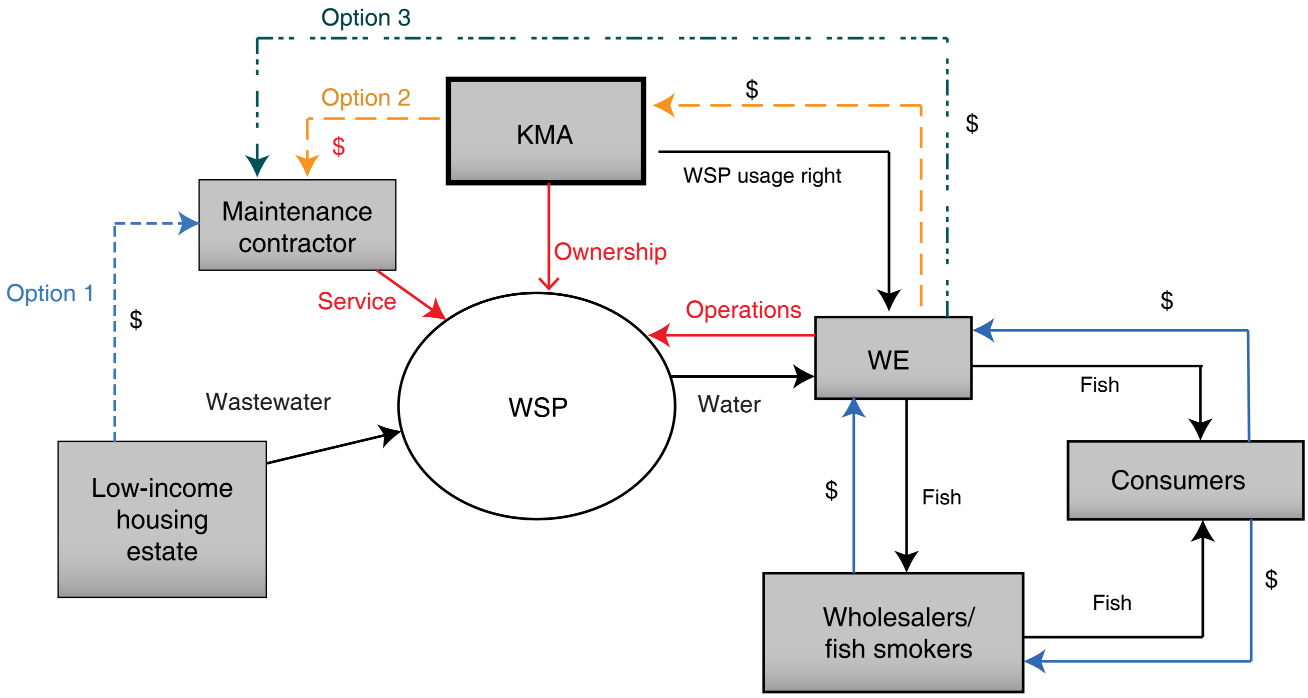


**FIGURE 2.** WASTE ENTERPRISERS' AQUACULTURE VALUE CHAIN (*SOURCE:* MODIFIED FROM AMOAH ET AL. 2018).

### 5.1.4 Technology and Process

Figure 3 shows the WSP system at Ahinsan with an initial grit chamber, a screening chamber, an influent chamber, two inspection chambers and four treatment ponds (an anaerobic pond, a facultative pond and two maturation ponds). The last two ponds were used to cultivate catfish that have relatively high tolerance to low levels of dissolved oxygen. Phosphorus and nitrogen provided with the wastewater are essential to facilitate the production of natural microscopic plants and plankton as food for the fish. There were two growing seasons per year. About 3 fingerlings/m$^2$ were stocked in both maturation ponds per season, targeting average annual production of about 1 ton per pond or 2 tons of fish per treatment plant with a survival rate of about 80%. Most fish were directly sold to wholesalers who were contacted during harvest periods.

### 5.1.5 Financial Analysis

Table 5 shows the financial analysis of the WE aquaculture system assuming two scenarios: a) the management of one WSP system, and b) the management of two WSP systems. As existing infrastructure was used for the aquaculture business, this provided huge capital cost savings for WE. The initial investment cost was thus mostly for rearing infrastructure for fingerlings. The aquaculture business had two annual harvests from the WSP systems which were sold fresh and the fish mortality rate was estimated to be 20%. Direct labor cost formed the bulk of the total production cost accounting for 57% of the total production cost followed by the cost of fingerlings accounting for 21% of the total production cost. The aquaculture business resulted in a gross margin of 78% in both scenarios; operating one WSP system resulted in a negative operating profit while with two WSP systems the business could break even. This indicated that the gross profits were not high enough to cover the indirect costs, such as management, if the team was only managing one plant. Scenarios for up to five plants showed that the share of the administrative cost as a percentage of total revenues could drop from 64, to 51 to 43% if the enterprise extended its operation to three, four or five plants, respectively. The Net Present Value (NPV) and Internal Rate of Return (IRR) became positive with more than three plants (Amoah et al. 2018).

Options to make just one WSP system viable were also possible based on an improvement of fish survival (e.g. through artificial pond aeration) and the sale of smoked fish (i.e. not to outsource the smoking) which would allow for higher revenues, as demonstrated in the accompanying research by KNUST and IWMI.

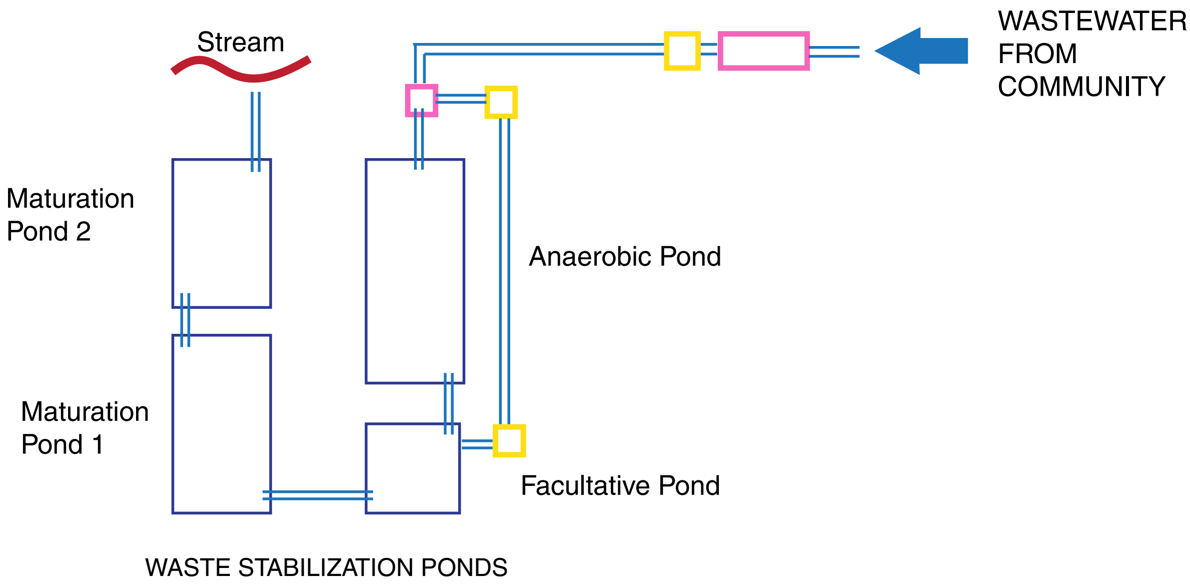


**FIGURE 3.** TREATMENT PROCESSES OF THE WSP SYSTEM AT AHINSAN, KUMASI, GHANA.

**TABLE 5.** FINANCIAL ANALYSIS OF THE WASTE ENTERPRISERS AQUACULTURE BUSINESS MODEL.

| Item | Amount in GHS per year | |
|---|---|---|
| | One WSP system | Two WSP systems |
| Investment cost | 3,436 | 6,873 |
| Revenue: | | |
| Total revenue | 9,720 | 19,440 |
| Production cost: | | |
| Fingerlings | 450 | 900 |
| Fish feed (supplement) | 140 | 280 |
| Pond/tank maintenance | 330 | 660 |
| Direct labor cost | 1,200 | 2,400 |
| Total production cost | 2,120 | 4,240 |
| Gross margin | 7,600 | 15,200 |
| Indirect labor (management) | 15,000 | 15,000 |
| Other costs (National Health Plan) | 40 | 60 |
| Profit before tax | (7,440) | 140 |

*Source:* Amoah et al. (2018).
*Note:* Exchange rate: USD 1.00 = GHS 1.5 (2012).

After operating the WSP for 2 years and successful proof of the concept, WE had the opportunity to engage in another sanitation challenge in Ghana and later Rwanda and discontinued the aquaculture business in 2012. The sites were later transferred to a research project until 2015 and operation of the Chirapatre WSP was later taken over by TAC in 2017 (see Business Case 2 for more details).

### 5.1.6. Socioeconomic, Health and Environmental Impact

Water reuse for aquaculture has the potential to improve wastewater treatment and public health while improving protein supply to consumers. However, wastewater aquaculture practices should satisfy health and hygiene guidelines and standards. The Sanitation Safety Planning manual of the World Health Organizaton (WHO) is based on the Hazard Analysis and Critical Control Point (HACCP) system that allows monitoring of all practices with a possible pathogen transmission threat and calls for compliance with recommended safety procedures to reduce or eliminate potential health risks, for consumers, traders and workers (Amoah and Yeboah-Agyepong 2015a, 2015b; WHO 2015). According to various tests, fish cultured in the locations under study did not pose health risks to consumers in view of heavy metal and microbial contamination (Yeboah-Agyepong et al. 2019). Heavy metal concentrations in both fish and water were all within acceptable limits for human consumption according to the Food and Agriculture Organization of the United Nations (FAO) and WHO limits. Microbial concentrations were high on the skin and gut of the fish as expected, however a protocol for depuration and smoking was developed which reduced the microbial concentrations significantly making the fish safe for human consumption (Yeboah-Agyepong et al. 2019). Similar results were found for selected emerging contaminants (Asem-Hiablie et al. 2013). However, this result should not be generalized as the treatment plants under study had mostly wastewater of domestic origin as sources. Another potential impact is related to the release of pond effluent, rich in fish excreta. This risk is however manageable, as in an optimized wastewater-fed aquaculture system, farmers will monitor the nutrient balance via visual indicators as excess nutrients should support feed production and not eutrophication and a decline in dissolved oxygen (WHO 2006).

### 5.1.7 Scaling-up and Scaling-out Potential

The triple-win business model implemented by WE is also used in other countries, where, depending on the number of ponds, fish might also be grown in a facultative pond unless the oxygen level gets too low (Kaul et al. 2002). With the right technical expertise, the model has a significant potential for replication in other municipalities and/or regions where there are WSP systems. Success of the model depends, however, on a positive market perception (or at least no objection) which has to be supported by compliance with national (or international) safety guidelines such as those issued by WHO (2006) given that the fish are in direct contact with the (treated) wastewater. The general drivers for success of the business are:

- Wastewater of largely domestic origin to avoid industrial contaminants.
- Supportive regulations and policies, like for resource recovery from wastewater.
- Increased awareness and capacity of key stakeholders on water reuse potential.
- High local demand for catfish and favorable consumer perceptions.
- Win-win PPP attracting entrepreneurs with high skills but limited capital and operational cost requirements.
- Aquaculture expertise and/or research partnership to monitor and optimize system safety and productivity.

## 5.2. Business Case 2: TriMark Aquaculture Centre (TAC)

### 5.2.1 Context and Background

In 2017, the KMA revived the successful PPP contract with WE, with a new private entity, TriMark Aquaculture Centre (TAC), at Chirapatre in Kumasi, Ghana, for one of the plants where between 2010 and 2012 WE had successfully piloted its aquaculture model (see Business Case 1). TAC's business was initially supported by the Netherlands Ghana WASH Window with subsequent support from other donors after the business started operation.

Chirapatre Estate in Kumasi has a population of about 1,800 residents and the houses in the community are served by a network of sewer lines, which are channelled to the community WSP system. The pond system attracted TAC's interest. In the TAC model, the KMA provides access to the WSP while the TAC operates and maintains the WSP through an integrated system of wastewater treatment and aquaculture. Scientific support was again sought from KNUST and IWMI.

### 5.2.2 Business Model

TriMark's business model initially used the same setup as WE, but this subsequently evolved after consultations with relevant authorities such as the Fisheries Commission of Ghana. To address possible concerns related to the water source, the eventually adopted model only places the parent fish (broodstock) in the maturation pond; after extraction of their eggs, the catfish are raised from fingerlings in safe groundwater in concrete tanks. This combined wastewater-freshwater model minimizes the safety risks associated with the final product as the fingerlings are cultured in freshwater without contact with treated wastewater. The freshwater is derived from a well of about 10-m depth, which has no water quality issues. This change informed the production system which aimed at improving the quality of fish to address possible negative perceptions, although the accompanying research did not indicate any health risks (Yeboah-Agyepong et al. 2019). As a result, the operational and capital costs have increased with the loss of free feed and the need for concrete tanks (Figure 4).

*Photo source:* Pay Drechsel.

**FIGURE 4.** CONCRETE PONDS USING WELL WATER FOR CATFISH PRODUCTION.

As thousands of fingerlings can be produced from a few catfish, one of the TAC's major revenue streams is the sales of fingerlings produced from broodstock reared in the treated wastewater system. Another major revenue stream for the center is selling table-size smoked catfish to consumers. These table-size catfish are cultured in a concrete tank using freshwater and value addition through smoking is also done on site. Currently, the aquaculture center has three different product lines that cater to different end-user needs and preferences (Table 6):

- ***Broodstock:*** Parent fish for egg or fingerling production and retail to other fish farmers.
- ***Fingerlings:*** Produced from broodstock but cultured in concrete tanks using freshwater from a well. They are targeted for other farmers engaged in catfish grow-out.
- ***Table fish:*** These are cultured in concrete tanks using freshwater and are targeted for consumption, also in smoked form.

TABLE 6. BUSINESS MODEL CANVAS FOR THE TRIMARK OPERATIONS.

| Key partners | Key activities | Value proposition | Customer relationships | Customer segments |
|---|---|---|---|---|
| • KMA<br>• KNUST<br>• IWMI<br>• Fisheries Commission<br>• Fingerling and feed supplier | • Maintain the wastewater treatment plant<br>• Production of fingerlings and fish<br>• Establish an on-site hatchery<br>• Establish an on-site fish smoking system<br>• Fish marketing, sale and trust building<br>• Research and development | • Fish farmers have reliable supply of broodstock for fingerling and/or fish production<br>• Fish farmers obtain safely produced catfish fingerlings<br>• Consumers obtain wholesome smoked catfish and recently also food crops from the greenhouse | • Personal (on-site) contact with all customer segments | • Fish farmers engaged in fingerling production<br>• Fish farmers engaged in catfish grow-out<br>• Consumers |
| | **Key resources**<br>• Wastewater, land, ponds<br>• Labor, capital<br>• Fingerlings, feed<br>• Expertise, laboratory access | | **Channels**<br>• Direct sales to all customer segments | |

| Cost structure | Revenue streams |
|---|---|
| • Capital investment – concrete freshwater ponds, fish-smoking equipment<br>• Consumables – fish feed, fuel for pumping water to hatcheries and concrete tanks; fuel for smoking fish<br>• Pond O&M<br>• Research and development cost<br>• Labor – field attendant, technician, accountant, management | • Sales of fingerlings<br>• Sales of broodstock<br>• Sales of wholesome catfish<br>• Sales of crops<br>• Electricity off-setting biogas (ongoing) |

| Social and environmental costs | Social and environmental benefits |
|---|---|
| • Potential health risks to plant workers if monitoring and the HACCP system fail | • Improved wastewater treatment and public health<br>• Increased protein supply<br>• Poor households exempted from sanitation fees |

A new revenue stream for the TAC is the establishment of an aquaponics system. The TAC has set up a greenhouse in this respect within the compound of the wastewater treatment plant to produce high-value crops (e.g. vegetables). The source of water for the greenhouse (Figure 5) is not the human wastewater but the equally nutrient-rich (fish manure) water generated from the hatchery and from the concrete tanks, as suggested by Mara (2004).

*Photo source:* IWMI.

**FIGURE 5.** GREENHOUSE SECTION OF TAC: USING WATER FROM THE FISH TANKS FOR IRRIGATION AND ENERGY FROM THE BIOGAS **DOMES.**

### 5.2.3 Aquaculture Value Chain

The TAC can be thought of as a vertically integrated business as it is involved in the production, selling and value addition of its different product lines. It manages all the activities across the value chain from research, supply of inputs, value addition to final sales of its products to different end-users. Broodstocks are produced in treated wastewater, which are then used for the production of fingerlings. The fingerlings are grown to an average size of about 5 g in concrete tanks and most of them are sold to other farmers (Figure 6). Some (mostly the jumpers) are used to restock the treated wastewater ponds to continue the broodstock production cycle. The rest of the fingerlings are cultured in concrete tanks fed with clean water from wells and/or harvested rainwater and grown to table-size fish for processing and consumption. Some of the broodstock is also sold to other farmers for fingerling and fish production in grow-out ponds.

Water generated from the hatchery and the on-site concrete fish culture tanks is channelled to an aquaponics system in the greenhouse for vegetable crop production.

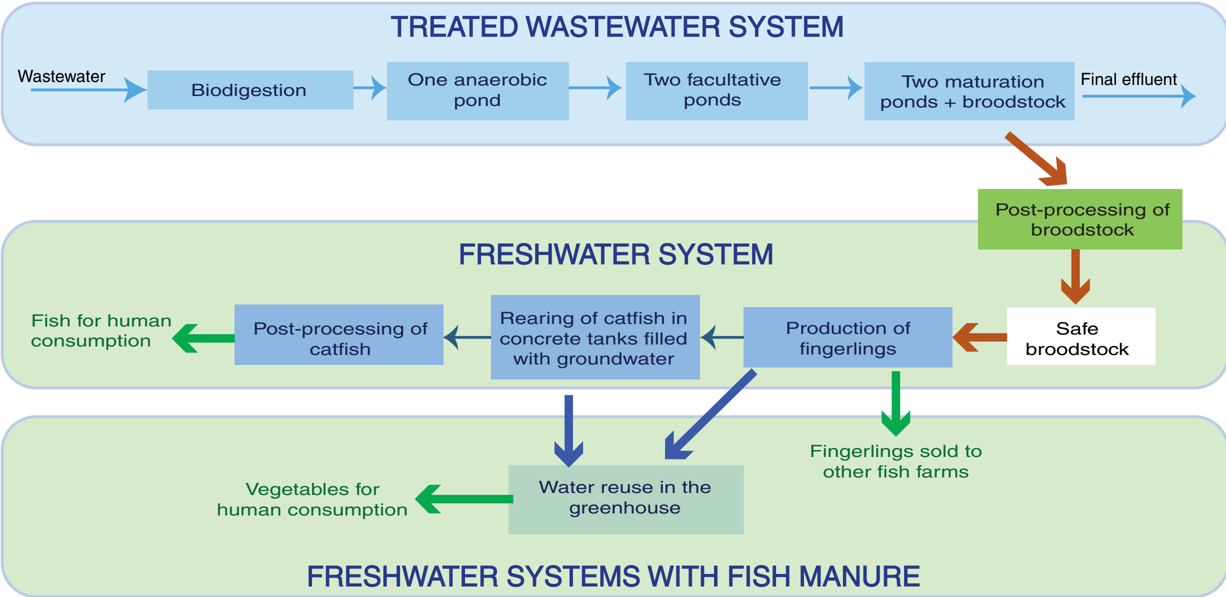


**FIGURE 6.** THE TAC PRODUCTION PROCESS AND VALUE CHAIN AS OF 2020.

### 5.2.4 Technology and Process

The Chirapatre wastewater treatment plant used for the TAC business is one of five small-scale wastewater treatment plants within the Ashanti region of Ghana. The wastewater is mostly of domestic origin and channelled through sewer pipes directly to the WSPs. The treatment plant has five initial chambers (grit, screening, influent and two inspection chambers) as well as one anaerobic, two facultative and two maturation ponds in sequence for further treatment (Figure 7). As the wastewater passes through the ponds, different chemical and biological reactions occur in the treatment process. The maturation ponds, where the broodstock is cultured, each has a surface area of about 225 m$^2$ with a depth of 1 m around the inlet and about 0.5 m around the outlet.

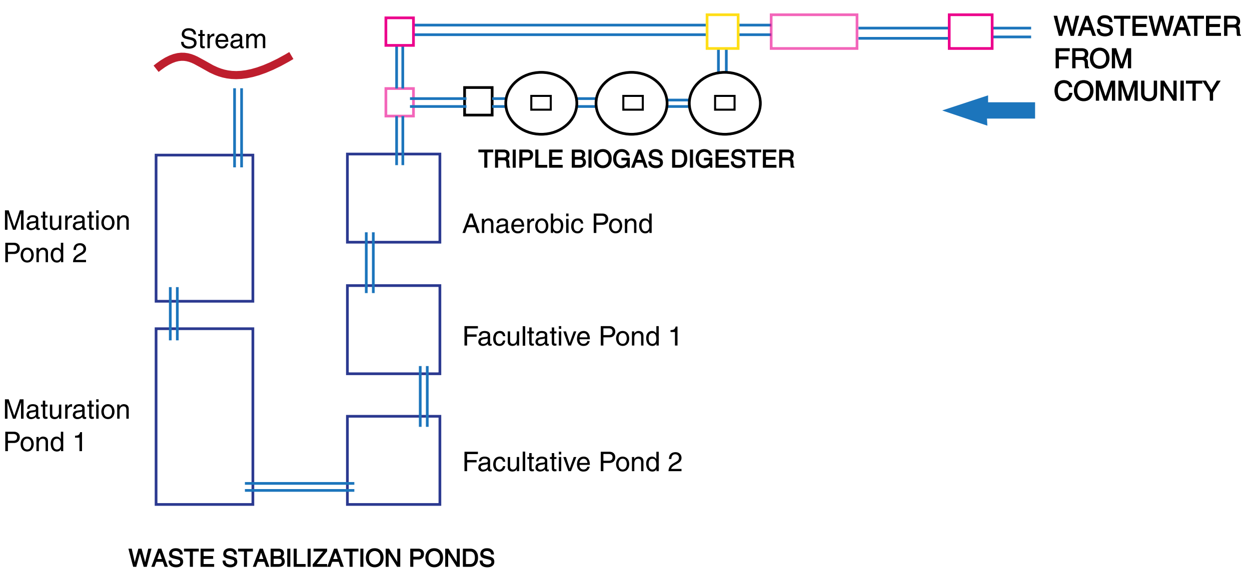


**FIGURE 7.** TREATMENT PROCESSES OF THE WSP SYSTEM AT CHIRAPATRE, KUMASI, GHANA (*SOURCE:* MODIFIED FROM YEBOAH-AGYEPONG ET AL. 2019).

The water quality in the plant meets international standards for wastewater-fed aquaculture. This is supported by a solar-powered aerator for both maturation ponds (Figure 8). Earlier research, when the ponds were still used for the whole cycle of fish farming, had shown that additional aeration was important for the viability of such a system (Sey et al. 2021). More recently, the treatment plant has been re-engineered to include a triple biogas digester to further improve the incoming water quality.

*Photo source:* Pay Drechsel.

**FIGURE 8.** PADDLEWHEELS USED BY TRIMARK.

### 5.2.5 Financial Analysis

As part of the PPP agreement with the KMA, the TAC uses existing infrastructure which reduces the initial investment cost. However, before the start of the aquaculture operation, an initial investment of GHS 29,348 (USD 1.00 = GHS 4.5 in 2018) was made for the construction of the hatchery, concrete ponds, a fish-smoking shed, acquisition of fish-smoking equipment and solar powered aerators and generators for pumping water. Table 7 shows the production and sales data for the two product lines for 2018 and 2019. For the first year of operation (2018), the center produced 34,600 fingerlings and achieved fingerling survival rate of 42%. From the total surviving fingerlings, 62% was sold to other farmers at an average price of GHS 0.46/fingerling. In the second year of operation, fingerling production increased by 28% and the survival rate improved to 56%. While the production and survival rates improved in 2019, the sales rate decreased slightly to 56% compared to 62% in 2018. Similarily, table fish production showed an increase of 21% in 2019 while the sales rate decreased slightly from 40% in 2018 to 37% in 2019. The unit price of table fish was GHS 8/kg.

**TABLE 7.** PRODUCTION AND SALES DATA OF THE TAC.

| Items | Years of operation | |
|---|---|---|
| | Year 1 (2018) | Year 2 (2019) |
| ***Fingerling production:*** | | |
| Fingerling production (number of fingerlings) | 82,000 | 105,000 |
| Fingerlings survived (number of fingerlings) | 34,600 | 58,500 |
| Survival rate (%) | 42% | 56% |
| Number of fingerlings sold | 21,000 | 33,000 |
| Unit price of fingerlings (GHS/unit of fingerling) | 0.46 | 0.5 |
| Proportion of fingerlings sold (%) | 61% | 56% |
| ***Table-size fish production:*** | | |
| Quantity stocked (number) | 21,000 | 25,500 |
| Quantity harvested (number of fish) | 16,800 | 20,400 |
| Weight of fish harvested (kg) | 0.5 | 0.5 |
| Total weight of fish harvested (kg) | 8,400 | 10,200 |
| Total weight of fish sold (kg) | 3,400 | 3,800 |
| Unit price of table fish (GHS/kg) | 8 | 8.95 |
| Proportion of table-size fish sold (%) | 40% | 37% |

*Note:* Exchange rate: USD 1.00 = GHS 4.5 in 2018 and GHS 4.8 in 2019.

For the first year of operation, total production costs, which included fish feed, fuel for pumping water from the well to hatcheries, cost of firewood for smoking fish and direct labor cost were estimated to be GHS 8,425 and indirect labor costs such as management were estimated to be GHS 7,200 while the corresponding figures for 2019 were GHS 15,805 and GHS 12,600 respectively (Table 8). In the first year of operation, direct labor cost formed the bulk of the total production costs accounting for 64% of the total production costs while fish feed accounted for 26% of the total production costs. In the second year of operation, the share of fish feed in the total production costs increased to 43% due to the change of fish cultivation from the ponds to freshwater tanks. In other words, in the first year of operation, the TAC relied on the wastewater to supply feed for the fish, an advantage which was lost for enhanced safety in the revised business model. This change was accepted as the business continued operating at a profit, achieving a gross margin of 69% in the first year of operation and 45% in the second year. An important component for the growth of fish in the maturation pond is additional aeration (Figure 8) (Sey et al. 2021).

**TABLE 8.** FINANCIAL SUMMARY OF THE TAC.

| Items | Amount (GHS) | |
|---|---|---|
| | 2018 | 2019 |
| **Investment cost[1]:** | | |
| Hatchery | 12,600 | |
| Concrete ponds | 3,600 | |
| Solar powered aerators | 7,600 | |
| Generator for pumping water | 1,548 | |
| Fish-smoking shed | 4,000 | |
| Total investment cost | 29,348 | |
| **Revenue:** | | |
| Sales of fingerlings | 9,660 | 16,500 |
| Sales of table-size fish | 27,200 | 34,010 |
| **Total revenue** | **36,860** | **50,510** |
| **Production cost:** | | |
| Fish feed | 2,885 | 11,935 |
| Fuel for pumping water | 900 | 1,250 |
| Fuel for smoking fish | 325 | 1,055 |
| Direct labor cost | 7,200 | 13,500 |
| Total production cost | 11,310 | 27,740 |
| Gross margin | 25,550 | 22,770 |
| Indirect labor (management, etc.) | 7,200 | 12,600 |
| Profit before tax | 18,350 | 10,170 |

*Notes:* Exchange rate: USD 1.00 = GHS 4.5 in 2018 and GHS 4.8 in 2019. [1] Excluding the biogas domes (constructed 2019/2020) and greenhouse (built in 2020).

In 2020, TriMark's operations and finances were significantly affected by the Covid-19 pandemic: (i) The government-ordered lockdown of restaurants interrupted a major income source for the whole sector (Okai 2020); (ii) staff were not allowed to resume work and maintain the system; and (iii) authorities feared that wastewater which potentially carries the virus might not be safe for aquaculture[2]. The economic break was used by TriMark to set up its greenhouse. As of 2021, TriMark was re-initiating all of its production components.

## 5.2.6 Socioeconomic, Health and Environmental Impact

The TAC produces over 100,000 fingerlings and about 10,000 kg of catfish annually which support local fish demand and protein intake. To ensure food safety and minimize exposure risks for workers, the following protocols are followed: 1) the treatment plant (including all ponds) is properly maintained for optimal treatment and water quality; 2) the concrete tanks where the fish are cultivated are regularly cleaned and the (well) water is changed frequently; 3) harvested fish are (depending on demand) smoked which helps to eliminate pathogens and also to improve taste[3]; and 4) workers have to follow strict hygiene instructions.

The wastewater-freshwater business model ensures regular maintenance of the treatment plant to adequately treat the wastewater before its release into the environment. As a result, pollution of the receiving surface water is as low as possible and better than that from a poorly maintained plant. Water quality is better than in the model run by WE as the last pond has significantly less fish-borne excreta. Moreover, the new biogas digester supports energy recovery (Figure 9) while the new greenhouse helps to safely dispose of the water from the concrete tanks which is rich in fish manure, turning its nutrients into biomass.

[2] SARS-CoV-2 RNA tests by Ghana's Water Research Institute could not confirm risks for fish consumers.

[3] According to Sey et al. (2021), consumers' preference for smoked catfish is because (a) it is considered a healthy source of meat due to the long hours of smoking which reduce the fat content of the fish, and (b) its competitive price compared to other protein sources, like meat.

Creating value through the reuse of water for aquaculture has the potential to create employment and enhance livelihoods along the product value chain. TAC employs about eight staff members (including technical and nontechnical staff) directly in charge of the maintenance of the treatment plant, fish culture and the greenhouse operations. Fingerlings and table fish are sold to fish farmers and about 30 fish traders, providing direct employment and enhanced livelihoods for them. Substantial employment is generated in larger treatment plants and systems through reuse of water treated to 'fit-for-purpose' levels and in a range of water-dependent sectors, especially agriculture.

*Photo source:* IWMI.

**FIGURE 9.** BIOGAS DOMES AT TRIMARK BETWEEN WATER INFLOW AND THE FIRST POND.

### 5.2.7 Scaling-up and Scaling-out Potential

The TAC aquaculture model has significant potential for replication and scaling up in other regions of Ghana as well as other countries because consumer risks have been eliminated. However, farm workers' compliance with national or international safety guidelines such as those of WHO (2006) has to be assured. In 2019, the TAC-KMA PPP won different prizes in a competitive 'Sanitation Challenge for Ghana' (Danquah 2019). The TAC system in Kumasi received an award as the overall best innovative liquid waste management initiative in Metropolitan, Municipal and District Assemblies. The KMA won first place in the 'Metropolitan and Municipal Assembly Category' and TAC won first place in the 'Private Partners' category. The cash prize money enabled TAC to invest in business expansion such as establishment of the aquaponics (greenhouse crop farming) system. Public recognition contributes to enhancing the awareness and willingness of stakeholders and donors to adapt and implement similar models in other municipalities.[4] With full compliance with safety regulations and policy support, the model is easily transferable, as pond-based treatment systems are very common in developing countries, especially where space is not yet a limitation.

Some of the challenges faced when implementing this business model in particular concerned the process of reaching a mutually beneficial PPP agreement. These included:

- Lack of awareness of water reuse potential and the technical capacity of stakeholders.
- Agreement on a benefit-sharing mechanism with full protection for partners.
- Changes in government resulting in important personnel or staff changes and loss of communication, including changing political interests.

Thus, for this model to be successful certain conditions had to be met:

- Presence of WSP systems that would benefit from better maintenance.
- The interests of each partner needed to be aligned for a win-win PPP, targeting long-term sustainability based on benefit-sharing mechanisms.

[4] https://thefishsite.com/articles/overflowing-with-opportunity-ghanas-wastewater-catfish-farms

- If needed, the development and implementation of supportive regulations and policies to avoid a regulatory vacuum.
- Increased awareness and capacity among key stakeholders on water reuse potential.
- Regular interactions among partners and key stakeholders.
- High local demand for catfish resulting in higher sales and thus allowing profit sharing among the partners.
- Research partnership to monitor and optimize system safety and productivity.

## 5.3. Business Case 3: Kumudini Hospital, Mirzapur, Bangladesh

### 5.3.1 Context and Background

Mirzapur town (with a 2011 population of about 28,000 inhabitants) lies in central Bangladesh. In 1993, a plug-flow system for the local Kumudini Hospital Complex (KHC) started full operation till it was decommissioned 20 years later and replaced in 2015 by a more compact treatment plant. However, during its lifetime, the treatment plant and its interlinked aquaculture system proved to be highly successful, recovering operational and capital costs by supplying the population of Mirzapur over its whole operational period with a reliable, twice weekly harvest of carp and free-of-charge wastewater treatment service for the hospital, related schools and the staff housing complex. The system received raw sewage and greywater which would otherwise flow untreated to a nearby river. The treatment involved duckweed-based phytoremediation on a 0.6-ha zig-zag plug-flow system. No fees were charged for the treatment, no subsidies were received from the government and no water was sold, but fish were reared on the harvested duckweed in adjacent tanks fed by groundwater and topped up with treated wastewater. Perennial crops such as papaya and bananas were grown along the pond perimeter providing additional income. The fish and crops produced were sold on site.

Kumudini Hospital is a private hospital that is funded and managed by the Kumudini Welfare Trust (KWT) and provides free healthcare. The PRISM Bangladesh Foundation is a nonprofit voluntary development organization established in 1989 in the name of PRISM Bangladesh. The relationship between the two entities was specified under a succession of mutual agreements. At a later stage, PRISM's involvement was phased out, while the treatment system continued to operate till 2013 when the Indian Government financed a new treatment plant for the hospital complex which was inaugurated on June 7, 2015.

### 5.3.2 Business Model

The overall value proposition of the Kumudini model was high quality wastewater treatment paid through the production of fish feed, crops and fish at competitive market prices, making the system independent of fees and tariffs. The enterprise employed a value-driven and for-profit, end-sales model whereby even larger value was derived from environmental and social responsibility impacts (Table 9). Essential for the business model was the partnership with PRISM which brought duckweed[5] and aquaculture expertise into the partnership. This ensured that two important economic values were created: (i) wastewater that was treated to an advanced level at no extra cost to the hospital, thus adding value for the hospital in terms of avoided costs for financing improved treatment, and (ii) a reliable and guaranteed supply of fish feed (to cultivate fish outside the treatment system) benefiting from the nutrients the wastewater supplied at no extra costs. The symbiosis between the nonprofitable wastewater treatment and the highly profitable fish production made the so-called 'Agriquatics' model financially viable, not only to break even, but also to pay back the initial loan taken for the setup of the treatment system.

PRISM inherited a defunct pond system which was redesigned for fish production while its capital investment went into the duckweed zig-zag plug treatment system. Land, fish tanks, water and nutrients were effectively free. Since conventional fish feed was scarce and (consequently) prices were high, the use of alternative sources of quality fish feed was very attractive.

[5] Duckweed grown on nutrient-rich water can have a high concentration of protein (35-43%), trace minerals, K and P and pigments, particularly carotene and xanthophyll, that make duckweed meal an especially valuable supplement for poultry and other animals, and it provides a rich source of vitamins A and B (Leng et al. 1995).

**TABLE 9.** BUSINESS MODEL CANVAS OF THE AGRIQUATICS SYSTEM IN MIRZAPUR.

| Key partners | Key activities | Value propositions | Customer relationships | Customer segments |
|---|---|---|---|---|
| • KHC/KWT<br>• PRISM<br>• Local community | • Treatment of wastewater<br>• Growing and harvesting of crops, duckweed, fish<br>• Fish and crops sales<br>• Technical advice | • High quality wastewater treatment paid through the production of fish feed, crops and fish at competitive market prices, making the system free of fees or tariffs | • Recurrent purchase based on customer satisfaction (low price and availability)<br>• Contractual relationships<br>• Strong (nonfinancial) public support | • Fish buyers (incl. KHC)<br>• Crop buyers<br>• KWT (demanding wastewater treatment) |
| | **Key resources**<br>• Land-use rights; operational ponds<br>• PRISM technical expertise<br>• Capital access<br>• Fingerlings | | **Channels**<br>• Direct selling on site<br>• Contracts and direct interaction of partners at the hospital site | |
| **Cost structure**<br>• Capital investment (loan and land lease)<br>• Regular fingerling purchase/breeding costs<br>• O&M (mostly labor employed for duckweed farming, fish feeding, harvest and sale; and crop irrigation, harvest, sale); debt repayment; management overheads | | | **Revenue streams**<br>• Sales of fish<br>• Sales of crops | |
| **Social and environmental costs**<br>• Laborers' health risk due to contact with wastewater<br>• Possible human health hazard from consumption of results in reduced environmental pollution fish if contaminants are transported via duckweed to the fish and not destroyed by fish cooking | | | **Social and environmental benefits**<br>• Wastewater efflux from the hospital is treated which<br>• Employment and protein supply for the local community<br>• Cheap food supply to the hospital supporting its free service to the poor<br>• Nutrient uptake by the harvested duckweed reduces eutrophication after final water release | |

*Source:* Modified from Drechsel et al. (2018).

### 5.3.3 Aquaculture Value Chain

The two partners provided the business with its most critical resources (wastewater, treatment ponds, technology and expertise). Having these in place, the business was positioned to buy its other inputs such as fingerlings and seeds from up-chain suppliers and sell its products (fish and crops) directly to end-users (local fish consumers; Figure 10). A notable portion of the fish and crops produced was bought by the hospital complex. Additional profits from water sales were not realistic in the local context as there was no market for the treated water due to the availability of adequate freshwater for agriculture, even in the dry season.

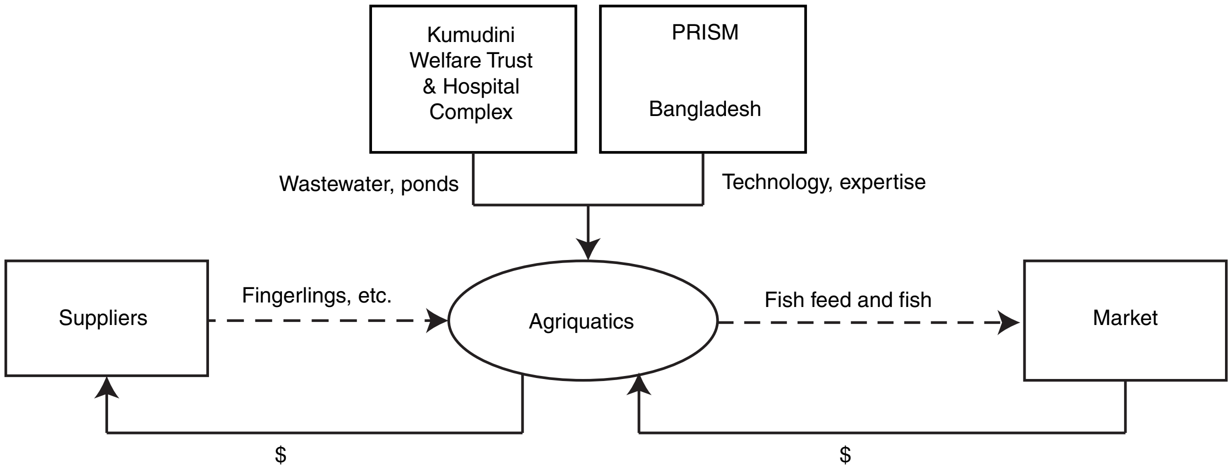


**FIGURE 10.** VALUE CHAIN OF THE KUMUDINI BUSINESS MODEL (*SOURCE:* DRECHSEL ET AL. 2018).

## 5.3.4 Technology and Process

The project inherited a defunct four-pond WSP system and added to it a 0.6-ha plug-flow duckweed wastewater treatment system. Only the first of the four ponds remained connected to the wastewater treatment system serving as a primary wastewater receiving and settling tank (Figure 11). The other three ponds were converted to fish production tanks, fed by groundwater and topped up by the final effluent of the plug-flow system (Iqbal 1999).

The wastewater moved by gravity to and through the whole treatment system from the initial 0.25-ha pond with a hydraulic retention time of 2 to 4 days, followed by the duckweed-covered plug-flow lagoon constructed as a 500-m long nonaerated serpentine channel with seven bends. For this, the depth of the lagoon increased gradually from 0.4 to 0.9 m. The system was fed with a mixture of hospital, school and domestic (staff residencies) wastewater from a population of about 3,000 to 4,000 people with per capita production of wastewater estimated at around 100 liters/day, or 350 m$^3$/day for 3,500 people.[6] The hydraulic retention time in the plug-flow wastewater-fed duckweed lagoon was estimated by different authors as 15 to 22 days. The lagoon was covered by a floating bamboo grid to contain the standing (100% cover) duckweed mat (Figure 12), at least in the first part of the system which was naturally the richest in nutrients. Data suggested that the system produced 220 to 400 tons of fresh duckweed/ha/year (about 17 to 31 tons dry weight/ha/year) reconfirming its enormous and fast growth potential (UNEP 2002). Duckweed was harvested manually with nets, drained in bamboo baskets, weighed and then placed in one of 12 floating feeding stations distributed evenly across the surface of the originally three 0.25-ha fish tanks. Fish were fed additionally with rice bran and oil cake (Edwards 2005).

Part of the treated water was eventually used to top up the fish tanks. Analysis by the International Center for Diarrheal Disease Research, Dhaka, Bangladesh, verified that indicator pathogen transmissions to fish or workers were similar to control groups and within safety margins (Gijzen and Ikramullah 1999; Islam et al. 2004).

[6] The compact plant which started operation in 2015 served about 5,000 residents with a handling capacity of 840 m$^3$ sewage/day plus an even larger capacity for greywater (https://backend.videshapps.gov.in/node/1000).

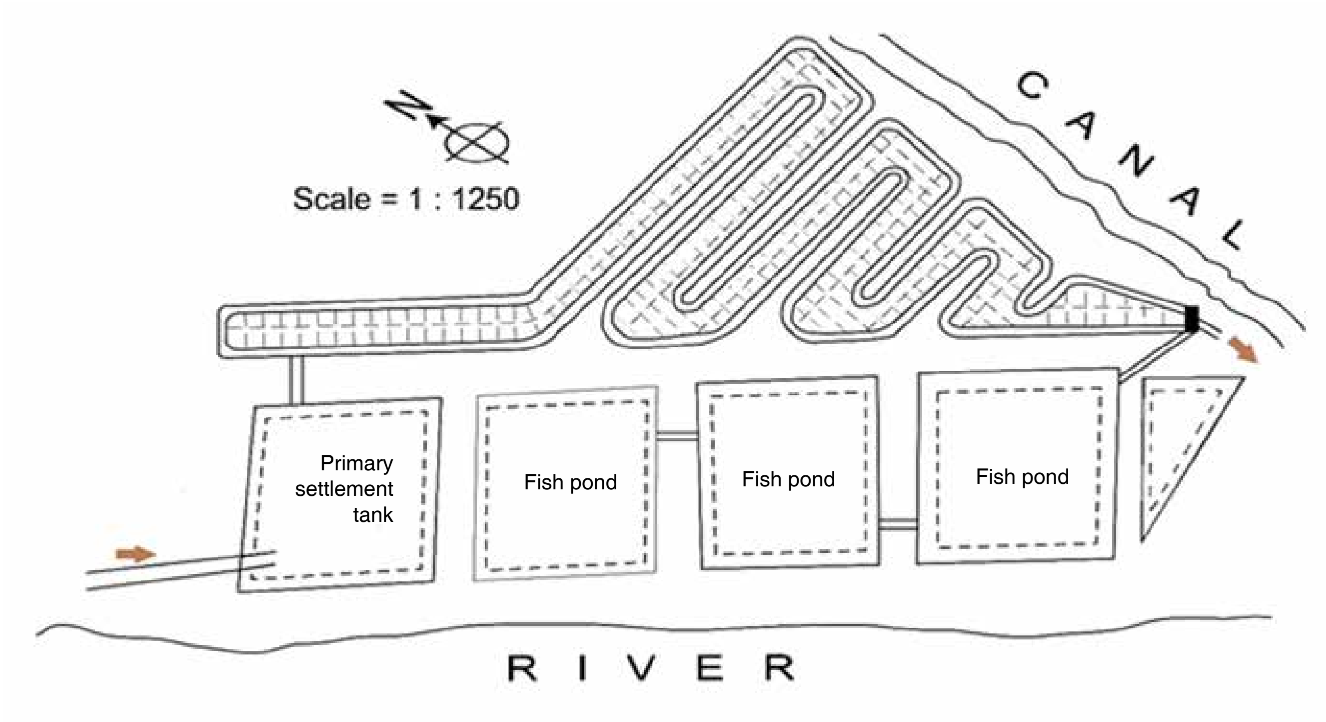


**FIGURE 11.** LAYOUT OF THE WASTEWATER TREATMENT SYSTEMS AND FISH-FARMING COMPONENTS AT AGRIQUATICS. (*SOURCE:* DRECHSEL ET AL. 2018, AFTER IQBAL 1999).

*Photo source:* Patwary (2013)

**FIGURE 12.** DUCKWEED-COVERED PLUG-FLOW LAGOON OF THE KUMUDINI HOSPITAL WASTEWATER TREATMENT PLANT.

The fish tanks were stocked with approximately 10,000 to 14,000 fingerlings at the onset of the monsoon season. The polyculture included Indian major carps (mrigal 25%, catla 20%, rohu 15%) and Chinese carps (silver carp 10%, mirror carp 20%, grass carp 10%). Tilapia were not stocked but fingerlings entered the tanks accidentally (UNEP 2002). Fish were usually harvested twice a week. The production numbers varied between an average of 7.5 tons/ha/year to a maximum of 15 tons/ha/year (of which a share was usually stolen). Wind movement across the surface was mitigated by strategic placement of crops such as bananas, taro, papaya and lentils along the perimeter. These crops also contributed to the income of the system.

## 5.3.5 Financial Analysis

Agriquatics had the advantage that wastewater collection and channelling were already in place so the defunct pond system was redesigned for fish production. The land was leased on favorable terms but capital investments for the labor-intensive construction of the plug-flow system were limited. Financial support was provided by the United Nations Capital Development Fund.

In view of operational cost recovery, a portion of the fish produced was bought by the hospital which provided financial security. Both initial partners (KWT and PRISM) had obvious interests in the effective operation of the system: KWT to achieve the effective treatment and proper disposal of its wastewater; PRISM to promote the duckweed technology while generating financial returns. Based on audited records from the first 8 years (Table 10), revenues allowed a pay back of the initial loan from PRISM within about 6 years. Subsequently, the wastewater-fed duckweed–fish system generated an annual net profit of about USD 2,000 to USD 3,000 which was larger per hectare than that from rice, the major agricultural crop in the area. The IRR was calculated as approximately 26% (Gijzen and Ikramullah 1999; UNEP 2002; Patwary 2013).

**TABLE 10.** AVERAGE ANNUAL INCOME AND EXPENDITURES, 1993 TO 2000 IN BDT.

| Description | Year 1 (BDT) | Year 2 (BDT) | Year 3 (BDT) | Year 4 (BDT) | Year 5 (BDT) | Year 6 (BDT) | Year 7 (BDT) | Year 8 (BDT) | 8-year average |
|---|---|---|---|---|---|---|---|---|---|
| **1. Recurring operational cost** | | | | | | | | | |
| Land rental (2 ha) | 26,000 | 26,000 | 26,000 | 26,000 | 26,000 | 26,000 | 26,000 | 26,000 | 26,000 |
| Staff salaries and wages | 85,600 | 92,020 | 98,922 | 106,341 | 114,317 | 122,891 | 129,036 | 136,480 | 110,701 |
| Field supplies (duckweed) | 10,000 | 12,000 | 13,500 | 14,300 | 15,200 | 15,960 | 15,678 | 16,512 | 14,144 |
| Field supplies for agriculture & fish | 28,000 | 29,000 | 30,000 | 31,000 | 33,000 | 32,300 | 34,000 | 33,600 | 31,363 |
| Energy/fuel cost (pump) | 43,500 | 45,500 | 47,900 | 50,430 | 55,720 | 58,500 | 62,400 | 63,100 | 53,381 |
| Maintenance | 13,700 | 14,000 | 14,500 | 15,200 | 16,720 | 17,556 | 18,375 | 18,500 | 16,069 |
| Miscellaneous | 6,285 | 6,580 | 7,000 | 7,350 | 7,700 | 7,900 | 7,500 | 7,720 | 7,254 |
| **Subtotal annual operation cost** | **213,085** | **225,100** | **237,822** | **250,621** | **268,657** | **281,107** | **292,989** | **301,912** | **258,912** |
| Depreciation of loan (10 years) | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 |
| Management overhead (7.5%) | 15,981 | 16,833 | 17,837 | 18,797 | 20,149 | 21,083 | 21,974 | 22,643 | 19,412 |
| Financial costs (9.5% on working capital) | 10,450 | 10,925 | 11,590 | 12,350 | 13,300 | 13,352 | 13,916 | 14,340 | 12,528 |
| **Subtotal admin & finance costs** | **51,431** | **52,758** | **54,427** | **56,147** | **58,449** | **59,435** | **60,890** | **61,983** | **56,940** |
| **Total annual recurring costs** | **264,516** | **277,858** | **292,249** | **306,768** | **327,106** | **340,542** | **353,879** | **363,895** | **315,852** |

(Continued)

**TABLE 10.** AVERAGE ANNUAL INCOME AND EXPENDITURES, 1993 TO 2000 IN BDT. (CONTINUED)

| Description | Year 1 (BDT) | Year 2 (BDT) | Year 3 (BDT) | Year 4 (BDT) | Year 5 (BDT) | Year 6 (BDT) | Year 7 (BDT) | Year 8 (BDT) | 8-year average |
|---|---|---|---|---|---|---|---|---|---|
| **2. Income from farm revenue** | | | | | | | | | |
| Sale proceeds from duckweed-fed fish | 128,778 | 253,800 | 316,509 | 402,231 | 404,982 | 445,702 | 419,440 | 413,354 | 348,100 |
| Sale proceeds from agriculture & fruits | 25,000 | 30,000 | 34,000 | 44,000 | 65,000 | 58,250 | 56,667 | 60,223 | 46,643 |
| Miscellaneous sales | 3,600 | 4,400 | 4,600 | 5,200 | 5,400 | 5,200 | 5,100 | 5,600 | 4,888 |
| **Total income from sales** | **157,378** | **288,200** | **355,109** | **451,431** | **475,382** | **509,152** | **481,207** | **479,177** | **399,631** |
| **3. Operational profit** | **-55,707** | **63,100** | **117,287** | **200,810** | **206,725** | **228,045** | **188,218** | **177,265** | **140,719** |
| **4. Net profit before taxes[1]** | **-107,138** | **10,342** | **62,860** | **144,663** | **148,276** | **168,610** | **127,328** | **115,282** | **83,779** |

*Source:* Modified from Patwary 2013.

*Note:* USD 1.00 = BDT 40-50 in this period; [1]No tax on agricultural production (tax holiday).

### 5.3.6 Socioeconomic, Health and Environmental Impact

The duckweed recovered a significant portion of the nutrients in the wastewater, but in the last part of the zig-zag plug system its growth was minimal due to low nutrient content. The nutrient removal had a positive impact on the effluent-receiving waterbody and its water quality, reducing potentially human health-related costs in the vicinity. Nitrogen as ammonium and nitrate was not only efficiently captured through phytoremediation, but through the duckweed, was also transformed into protein-rich biomass. Based on water quality data (BOD, COD, N, P, fecal coliforms) the treated wastewater was fit for unrestricted vegetable irrigation according to the WHO 1989 standards (UNEP 2002).

While the harvest of duckweed significantly exposed workers to wastewater and its pathogens, scientific monitoring could not determine a cause-effect relationship between incidences of worker diarrheal disease infection and their working at the site (Gijzen and Ikramullah 1999). Also fish were tested for safe consumption. However, while duckweed absorbs nutrients, it also absorbs heavy metals, and if it is used as herbivorous fish feed, the metals can be bio-accumulated as was locally verified (Parven et al. 2009). There was also the possibility of gastroenteritis pathogens occurring in the treatment system that could have spread to fish (Rahman et al. 2007). In a similar system in India, fecal coliforms were found in the guts and gills of fish fed on sewage, but none in fish muscle. To prevent cross-contamination hygienic gutting will be imperative. In the case of Bangladesh, the risk of pathogen transfer to human consumers was considered low as fish are generally not eaten raw (Gijzen and Ikramullah 1999). Unfortunately, there are no data on other potential contaminants of relevance for fish or humans such as pharmaceutical residues.

### 5.3.7. Scaling-up and Scaling-out Potential

Over its lifetime, the Agriquatics system recovered its investment costs several times, which remains unique in the domain of wastewater treatment. The key drivers for the success of the business were:

- Availability of land.
- Limited capital cost with several profitable revenue streams for high-value products resulting in fast payback.
- The low-tech and cost-treatment system supported by a mutually beneficial partnership ensuring availability of nutrient-rich water and expertise in

duckweed and fish production as well as system maintenance.

- Profit incentive for treatment of wastewater that obviated the requirement for external supervision and control.

It is important to note that the positive financial performance of the wastewater treatment and aquaculture system was the result of a mutually beneficial partnership which created beneficial conditions, such as no major costs for wastewater collection and channelling, and favorable terms for capital investment, land lease and cost recovery. The prospects of cost recovery were also confirmed from a related system set up on 0.5 ha in the city of Cuttack, Orissa, eastern India, where 1 million L/ per day of primary treated sewage were channelled into ponds containing duckweed, followed by ponds stocked with carp and prawns. After five days, water quality had improved to the point where it could be used for irrigation. The sale of fish fattened in the sewage ponds for 8 to 12 months almost offsets the operating cost of the plant, leaving a net cost of about USD 385 (FAO 1998).

A pillar of the success of the duckweed system was value creation in terms of fish culture, i.e. capitalizing on increasing revenues with movement up the value chain, compared to treatment plants that only provided treated water, e.g. for crop irrigation. On the other hand, the requirement for a suitably large land area for the combined treatment and aquaculture system is a common constraint within towns and cities. The plant which eventually replaced the zig-zag plug system in 2015 was a much more compact one. Land constraints are especially significant in Bangladesh with its very high population density, land speculations and rising opportunity cost of land, in particular within urbanizing areas (Edwards 2005).

While the system in Mirzapur was set up at a hospital, data on emerging contaminants such as pharmaceutical residues, estrogens and antibiotics were not available. A safe replication of the system is therefore recommended for locations where the wastewater derives only from domestic settings with minimal risk of pharmaceutical or industrial contamination, not hospitals.

Given the rapid decomposition of duckweed following harvest, fish or poultry have to be close by if the plant is used as feed.

# 6. THE ROLE OF WATER SAFETY IN BALANCING FISH PRODUCTION AND WATER TREATMENT

While in the case of Bangladesh, the cultivated duckweed could tolerate a broad range of water quality as long as it was rich in nutrients,[7] key challenges in the two cases from Ghana were that the quality of water in the ponds used for fish farming had to provide: (a) the fish with optimal living conditions, (b) the consumer with a safe product, and (c) the environment with a well-treated final effluent. All three targets were interlinked as water quality affects feed efficiency, and as such fish growth rates, health and survival (Isyagi et al. 2009). The water quality requirements vary among species and have to be balanced between the mutually exclusive objectives of optimizing both water treatment and fish production. While high organic loading will reduce dissolved oxygen and limit the number of fish species which can be cultivated, suboptimal organic loading can result in too low levels of nutrients to grow sufficient phytoplankton which is the major source of natural food in a fish pond (Kaul et al. 2002). From the fish farming perspective, ponds should be designed based on the concept of ‘minimal treatment for maximal production of microbiologically safe fish’ (Mara 2004).

Locally appropriate fish can be selected depending on their availability and the characteristics of the treated wastewater. African catfish, *Clarias gariepinus*, for example, is very adaptive to the environmental conditions found in WSPs and can live in wide ranges of pH and dissolved oxygen. In waste treatment systems with artificial aeration, species like tilapia, carps and prawns are grown in India, Vietnam and China.

Thus, apart from the water source, water quality also depends on pond management and mismanagement will hinder the success of treated wastewater aquaculture systems or even lead to failure. Many water quality parameters fluctuate daily due to pond dynamics, which include local weather (temperature) conditions, photosynthetic activities of aquatic plants and so forth.

The key water quality parameters for pond production are temperature, oxygen, pH, alkalinity, hardness (amount of dissolved calcium and magnesium) and certain nutrient levels. Ammonia, for example, can be directly toxic to

[7] Duckweed is temperature-sensitive and grows best between 20 and 30°C and at a pH of 5 (6.5) to 7.5, but it can tolerate temperatures up to 35°C and a pH between 3 and 10 (5 and 9) according to different sources (Skillicorn et al. 1993; Leng 1999; Vymazal 2008).

fish (the fish's own excretion of ammonia is impaired) or support the growth of toxin-producing cyanobacteria (Isyagi et al. 2009; WHO 2006). It is important to note that different species can have different water quality requirements and that the concentrations of many parameters vary with changes in temperature, salinity, hardness, pH and stocking density for example. Dissolved oxygen is a common example of a factor that can vary significantly with temperature, as well as among species and fish age. Unlike tilapia, African catfish have accessory organs that enable them to breathe atmospheric oxygen, and thus, they are better able to survive in water at (for short periods) low oxygen levels. However, this ability does not apply to juvenile catfish which depend on the dissolved oxygen in the water (Isyagi et al. 2009), i.e. an oxygen deficit might not affect adult fish growth but prevent their reproduction. Thus, before stocking fish in a treated wastewater pond, fingerlings should be raised in clean water to the required size (for catfish about 50 g) for a survival rate of 80 to 90% (Isyagi et al. 2009). Table 11 shows desirable water quality values recommended by various sources for fish farming. The ranges where fish can survive might be larger but might affect growth or reproduction. Tilapia, for example, can tolerate a pH from 3.7 to 10.5, but below pH 5, they are stressed and will not eat (WRC 2010).

**TABLE 11.** DESIRABLE WATER QUALITY RANGES FOR WASTEWATER-FED AQUACULTURE (WARM WATER SPECIES).

| | Kaul et al. (2002) | Isyagi et al. (2009) | PHILMINAQ (2008) | Asmah et al. (2016) | BC MOE (2019) | DWAF (1996) |
|---|---|---|---|---|---|---|
| pH (comfort zone) | 7.5-8.5 | 6.5-9.0 | 6.5-9.0 | 6.5-9.0 | 6.5-9.0 | 6.5-9.0 |
| Temperature (°C) | 26-33 | 26-32 | | 22-38 | | 28-30 |
| Dissolved oxygen (DO) (mg/L) | 3-10 | >4 | ≥5 | 3.7-9.0 | 5-11 | 5-8 |
| Alkalinity (mg/L) as $CaCO_3$ | | >20 | >20-100 | 54-200 | >20 | 20-100 |
| Ammonia-nitrogen (mg/L) | <0.25 | 0.3 | | <0.5 | 0.1-1.2[1] | 0-0.3 |
| Dissolved reactive phosphate (mg/L) | | | 0.05-0.1 | <1.5 | | <0.1 |

*Note:* [1]Depending on pH (pH 6.5: 1.2; pH 9.0: 0.1; for 20°C).

In view of chemical risks for fish and the food chain, the general recommendation is that industrial effluents should be avoided, or at least be adequately pretreated to remove chemicals if they enter the same streams as municipal wastewater. However, these treatments rarely occur in many low-income countries. Thus, where water might contain industrial effluent with potentially toxic chemicals (Table 12), bioaccumulation is possible and its use in fish farming is discouraged. However, there are differences in the risk between possible hazards: In WSPs, most heavy metals are precipitated under the anaerobic conditions in the first WSP or lose solubility under increasing pH in the maturation pond(s). Algae can accumulate various heavy metals but, with the possible exception of mercury, fish raised in sewage-fed ponds have not been observed to accumulate high concentrations of possible toxic substances in edible parts (Pescod 1992). One reason is that fish are usually harvested young, and any possible bio-accumulation of toxic metals remains limited. As such, the risks from most heavy metals to human health from fish raised in sewage-fed waste stabilization ponds have been assessed as low (WHO 2006), similar to consumption risks from pesticides or antibiotics even in high-input aquaculture (Murk et al. 2018).

**TABLE 12.** GENERAL ACCEPTABLE LEVELS OF SELECTED HEAVY METALS FOR A FRESHWATER ENVIRONMENT.

| Country | Freshwater (µg/L) | | | |
|---|---|---|---|---|
| | Hg | Pb | Cd | Ni |
| Australia, New Zealand | <1.0 | <1-7.0 | <0.2-1.8 | <100 |
| Kenya | 5.0 | 10 | 10 | 300 |
| Philippines | 2.0 | 50 | 10 | NA |

*Source:* PHILMINAQ (2008).

In the case of mercury, its methyl mercury (MeHg) fraction poses the most danger and the threshold for the commonly analyzed total Hg amount has to be adjusted when the MeHg share increases. In the Canadian Guidelines from British Columbia, the average concentration of total mercury should not exceed 0.02 µg/L (20 ng/L) when the MeHg fraction is ≤ 0.5% of the total mercury concentration. When the share of MeHg is greater than 0.5%, the guideline should be stricter, as indicated in Table 13, to prevent undesirable accumulation of mercury from water to the food chain that may harm the most sensitive consumers (e.g. avian species) or aquatic life (BC MOE 2001).

**TABLE 13.** GUIDELINE FOR TOTAL HG AS A FUNCTION OF THE PERCENTAGE OF METHYL MERCURY.

| % MeHg (of total Hg) | Upper threshold (ng/L total Hg) |
|---|---|
| Up to 0.5 | 20.0 ng/L |
| 0.6-1.0 | 10.0 ng/L |
| 1.1-2.5 | 4.0 ng/L |
| 2.6-5.0 | 2.0 ng/L |
| 5.1-8.0 | 1.25 ng/L |

*Source:* BC MOE (2001).

In view of human health risks from fish farming, most attention is given to pathogens, in particular food-borne trematodes and schistosomes (Table 14) which are endemic in certain geographic regions. Food-borne trematodes present risks where fish is eaten raw, while schistosomiasis (bilharzia) is transmitted through water-skin contact where snail hosts are present in aquaculture ponds.

**TABLE 14.** MICROBIOLOGICAL QUALITY TARGETS FOR WASTEWATER AND EXCRETA USE IN AQUACULTURE.

| Media | Viable trematode eggs (number per 100 ml or per gram of dry excreta | *E. coli* (arithmetic mean per 100 ml or per gram of dry excreta) | Helminth eggs (arithmetic mean per liter or per gram of dry excreta) |
|---|---|---|---|
| **Product consumers** | | | |
| Pond water | Not detectable | $<10^4$ | <1 |
| Wastewater | Not detectable | $<10^5$ | <1 |
| Treated excreta | Not detectable | $<10^6$ | <1 |
| Edible fish flesh or plant parts | Infective metacercariae not detectable or noninfective | Codex Alimentarius Commission HACCP specifications | Not detectable |
| **Aquaculture workers and local communities** | | | |
| Pond water | Not detectable | $<10^3$ | <1 |
| Wastewater | Not detectable | $<10^4$ | <1 |
| Treated excreta | Not detectable | $<10^5$ | <1 |

*Source:* WHO (2006).

For a sustainable wastewater aquaculture business, the risk of pathogens in general and trematode infections in particular should receive priority monitoring to safeguard human health. There are two key risk groups:

- **Workers** on the fish farm should receive training on the risks associated with wastewater-fed aquaculture. There should be measures in place to address them, such as light protective clothing, facilities to bathe/shower, means to maximize personal hygiene, as well as provisions for medical treatment; in proven endemic areas there must be regular prophylaxis action. As aquatic snails serve as intermediate hosts for Schistosoma, snail monitoring and environmental snail control (e.g. removing vegetation from ponds and their surroundings) are important safety procedures.

- For **consumers**, the key questions are whether the selected fish will be (1) cooked, or (2) eaten raw or insufficiently cooked. If fish are to be cooked, then pathogenic consumption risks are very low and there should be no objection to the water source (FAO and WHO 2019).[8] Where fish is not cooked but eaten raw, further risk reduction measures are needed between 'farm and fork', ideally in combination. This also applies to fish grown in 'treated' wastewater of WSP maturation ponds or any purchased fish (of any origin) as contamination can also occur in markets or restaurants. Implementing such a multibarrier system reduces the pressure on farmers to seek perfectly clean water, which is in many regions simply not feasible (WHO 2006). Such additional safety measures include:

**Fish depuration** before harvesting: Batches of living fish are placed (for at least 2 to 3 weeks) in clean water ponds after being taken from the treated wastewater-fed ponds, to allow external and internal removal of biological contaminants, odor and physical impurities. The water in the depuration ponds should belong to a flow-through system and be changed regularly. Relatively short depuration periods of one to two weeks do not appear to remove bacteria from the fish digestive tract. There has been significant research on the effectiveness of depuration for removing sewage-associated bacteria in shellfish; however the removal of viruses has not been satisfactory (Lees et al. 2010).

**Fish gutting**: After rinsing the harvested fish under running tap water, it is important to prevent cross-contamination of the fish flesh with the gut contents. Thus, the intact gut of the fish should be removed before removing the fish muscle and the gut cavity should be rinsed with safe/clean water. It is very important to use a different knife for cutting the flesh after removing the gut content. Knives used to process the raw fish should not be used for other purposes such as cutting cooked fish or vegetables.

**Fish smoking**: Fish smoking in Ghana is predominately carried out by women (Gebrezgabher et al. 2018) and can contribute to pathogen removal (Yeboah-Agyepong et al. 2019). It is generally done using two methods – cold smoking and hot smoking. Cold smoking requires temperatures between 30 and 40°C and hot smoking between 80 and 90°C. Almost all microbes except some pathogenic bacteria are destroyed due to hot smoking because the fish are cooked and dried completely. However, smoked fish can also be a source of microbial hazards if fish handling, marketing, gutting and storage do not follow hygiene standards (Dutta et al. 2018).

**Change of business model**: As this report reveals aquaculture can benefit from nutrient-rich wastewater in several way and not all require direct contact between wastewater and fish. The options are:

- Shifting to another fish species which is not consumed raw, but cooked, smoked or grilled.

- Only growing fingerlings in treated wastewater, but adult fish in clean water. This results in significantly less contamination. However, precautions must be taken to prevent trematode infection because trematodes remain viable as long as the host is alive.

- Only growing broodstock with wastewater, from which eggs are extracted for the production of fingerlings. The fingerlings are cultured in clean groundwater. This process minimizes hazards associated with the final product as the fingerlings do not have direct contact with the treated wastewater.

- The production of fish feed, such as fast-growing duckweed, in the ponds which turn the nutrient load of the wastewater into protein-rich biomass, while fish are cultivated in safer water outside the WSP system.

There are many more actions that can be taken to improve the safety and quality of fish at different levels from consumers (e.g. the four steps to food safety: clean, separate, cook, chill) to fish businesses, governments and donors (adoption and promotion of food safety regulations and standards (such as the Codex Alimentarius Commission standards) including good handling practices, good manufacturing practices, good hygiene practices, etc. (Mahmoud et al. 2019).

[8] The assumption is that the treated wastewater does not show chemical contaminants above permitted thresholds.

# 7. CONCLUSIONS AND RECOMMENDATIONS

The empirical business cases presented in this report showcase that different business models can be designed to implement safe water reuse for fish production, with different levels of fish-water contact in view of safeguarding public health. The TAC business model can be seen as an extension of the WE business model, which evolved and adapted to respond to food safety and market-related needs (Table 15). Both Kumasi-based business models were implemented by setting up a PPP model. In the Bangladeshi case, the plant was owned by a private hospital and the partner was an NGO with expertise in duckweed production and fish farming. These different constellations can be perceived as representative of most of the water reuse for aquaculture models and emphasize the important roles that intersectoral partnerships have for turning a highly subsidized treatment plant into a resource recovery center and potentially profitable business.

**TABLE 15.** OVERVIEW OF THE THREE PRESENTED BUSINESS CASES.

| | Waste Enterprisers | TriMark Aquaculture Centre | Kumudini Hospital |
|---|---|---|---|
| **Technical/general data** | | | |
| Status | Aquaculture component closed; now operated by TriMark (case 2) | Treatment plant and aquaculture component running | Treatment plant decommissioned and replaced after 20+ years of operations |
| Scale (per year) | • 2,000 kg of catfish | • 10,000 kg of catfish<br>• 100,000 fingerlings | • 7,500 kg of carp<br>• Papaya and bananas |
| Supply of inputs | • Wastewater from housing estates | • Wastewater from housing estates | • Wastewater from the hospital complex |
| Technology/process | • WSP system | • WSP system | • Zig-zag plug flow treatment system |
| Product lines | • Catfish | • Broodstock; fingerlings<br>• Table fish (smoked catfish)<br>• Greenhouse crops | • Duckweed to feed externally cultivated carp<br>• Crops |
| Main clients | • Wholesalers | • Fish farmers<br>• Consumers | • Local community |
| Key partners | • KMA, KNUST, IWMI, WE | • KMA, KNUST, IWMI, Fisheries Commission, TAC | • PRISM Bangladesh, KWT/ KHC |
| **Safety measures put in place** | | | |
| Measures to mitigate health risk to consumers | • Depuration of fish in freshwater<br>• Smoking of fish | • Only broodstock cultured in wastewater<br>• Fingerling culture in freshwater (no direct contact of fish for sale with treated wastewater)<br>• Smoking of fish | • No direct contact of fish with treated wastewater<br>• Only fish feed cultivated in the treatment system |
| Water quality measures | • Fish turning nutrients from wastewater into protein and fat | • Solar-powered aerators in maturation ponds<br>• Triple biogas digester | • Duckweed absorbing nutrients and turning them into biomass and protein |
| Financial success | Positive NPV and IRR when operations are optimized or cover three or more WSPs | Profitable, especially if fish ponds are aerated | Profitable, with a recovery of operational and capital investments |

The financial analysis of the empirical systems shows profits for the fish farmer, operational and, in part, capital cost recovery for the treatment plant as the treatment plant operators can stop charging households a sanitation fee; eventually a triple-win situation for both partners and the community.

The examples showed several drivers or barriers which can play an important role in outscaling of wastewater-fed aquaculture systems: 1) a supportive policy environment; 2) land and water (of limited risk) availability; 3) management able to address operational constraints; and 4) the risk of changing public health perceptions.

## 7.1 Providing a Supportive Policy Environment

The safe use of treated wastewater for agriculture or aquaculture requires support through policies, legislations, institutional frameworks and regulations. So far, the national adoption of international guidelines by WHO (2006) for instance remains low, although broader pledges in support of circular systems and waste reuse are on the increase. The Environmental Sanitation Policy of Ghana, for example, supports safe resource recovery and reuse. The philosophy of 'materials in transition' seeks to create awareness about changes of attitude towards the handling and disposal of all types of waste by demonstrating that there is value in all waste components (NESSAP 2010). As there are no clear rules and regulations governing the use of treated wastewater for aquaculture in most countries, this is creating a policy vacuum and potential conflict between those in charge of food safety and those in support of a more circular economy. Policy support is also needed for credit access and to back public sector treatment plant operators to engage in PPP, which is a driving factor for the success of the studied business models. To support wastewater aquaculture with appropriate guidelines, the opportunities for safe resource recovery (also in the form of fish protein) from treated wastewater sources should be communicated effectively to policy-makers. In developing such policies or guidelines, an inclusive approach is critical for the identification and involvement of the principal stakeholders from public health services, agriculture and waste management sectors.

## 7.2 Urbanization, Land and Water Availability

Urban growth increases the demand for land in urban vicinities for purposes other than farming. Public space for larger pond-based treatment plants is declining. This limits the future for wastewater aquaculture in many cities in developing countries unless planners and policy-makers are developing strategies to ensure that suitable facilities are protected from increasing urbanization and its related demands. As WSPs are as effective as they are unsophisticated in their operation, they remain a perfect fit for municipalities with limited institutional capacities in other types of sewage treatment plants. Another challenge of rapid urbanization which has often outpaced urban planning, is the mix of domestic and industrial land use and as a result mixed domestic and industrial wastewater streams. While risks from domestic wastewater are relatively easier to manage and control, industrial wastewater can be harmful to fish and its impact on the food chain more difficult to predict and manage.

## 7.3 Operational Constraints

Treated wastewater aquaculture, especially in Africa or Latin America, is relatively new and therefore it is likely that farmers will miss appropriate support from agricultural extension services and face operational constraints that will affect their production and hence the business. There is considerable literature on duckweed cultivation in treatment systems, aquaculture in general as well as the cultivation of particular fish species suitable for wastewater-based systems, although not all guidelines are as farmer-friendly as Isyagi et al. (2009). These constraints should be addressed through the design of tailored training manuals that include: (i) information on wastewater as a medium and related risks and opportunities for fish farming; (ii) the water quality requirements of fish and aquatic plants and related monitoring needs; and (iii) recommendations for risk reduction for workers and consumers based on WHO (2006, 2015), for example. At a more advanced level, bio-economic modelling could add value as it allows comparison of treatment effects, productivity and financial returns associated with different designs for lagoon- or pond-based treatment and aquaculture reuse systems (Bunting 2007).

## 7.4 Addressing Public Health Perceptions

Available market demand and perception studies showed that the actual water source used in fish production is usually not a decision-making criterion, partly because wastewater-fed aquaculture is largely an unknown activity, or has a long tradition or risk awareness is limited. It is, however, important to acknowledge that consumers' awareness (not only where fish are sold at the farm-gate) can change (e.g. as witnessed under Covid-19) and their decisions to buy fish and crops produced in treated wastewater can become negative, despite low levels of contamination (Bunting and Little 2003). Full compliance with good handling and hygiene practices should therefore be certified (including product quality assurance) by a Standards Authority to assure consumers of the safety of the water and produce, as well as to raise awareness on the environmental benefits of the combined systems.

The WHO (2015) sanitation safety plan manual based on the HACCP system, which was extended to commercial aquaculture (Lima dos Santo 2002), can help in identifying potential problems along the production chain to develop strategies to minimize associated risks for workers (Figure 13), communities and consumers. It is evident that local government and nongovernment agencies have important roles in monitoring such systems.

*Photo source:* IWMI.

FIGURE 13. FISH FARM WORKERS AT TRIMARK, KUMASI, USING PERSONAL PROTECTION GEAR.

A video about TriMark's work in Kumasi can be accessed here: https://www.youtube.com/watch?v=S2dU0OcyVoA

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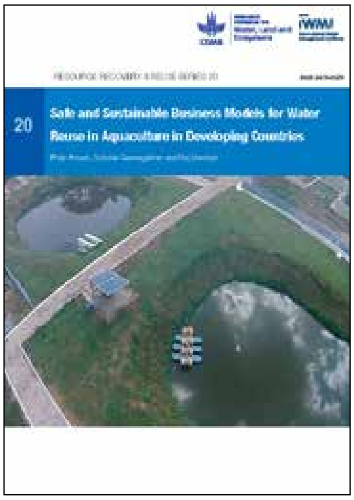


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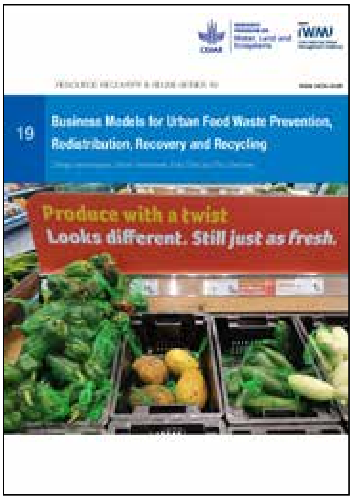


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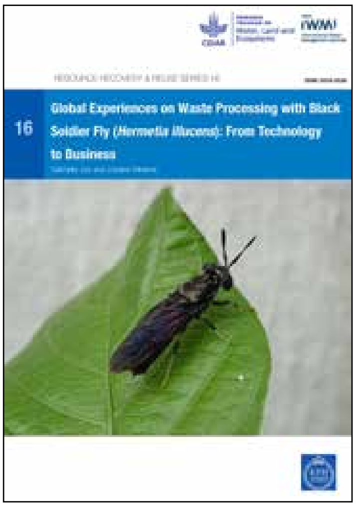


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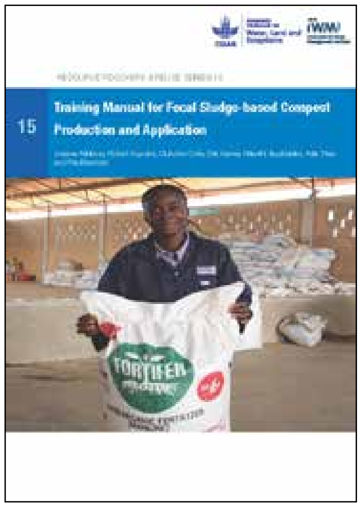


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RESEARCH PROGRAM ON Water, Land and Ecosystems

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**Resource Recovery and Reuse (RRR)** is a subprogram of WLE dedicated to applied research on the safe recovery of water, nutrients and energy from domestic and agro-industrial waste streams. This subprogram aims to create impact through different lines of action research, including (i) developing and testing scalable RRR business models, (ii) assessing and mitigating risks from RRR for public health and the environment, (iii) supporting public and private entities with innovative approaches for the safe reuse of wastewater and organic waste, and (iv) improving rural-urban linkages and resource allocations while minimizing the negative urban footprint on the peri-urban environment. This subprogram works closely with the World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), United Nations University (UNU) and many national and international partners across the globe. The RRR series of documents presents summaries and reviews of the subprogram's research and resulting application guidelines, targeting development experts and others in the research for development continuum.

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