Fish, roots, tubers and bananas: opportunities and constraints for agri-food system integration

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Abstract

Agri-food system integration has the potential to increase and add value to agricultural production, reduce cost of and dependency on external inputs, generate additional income to farmers, and encourage the diversification of outputs and diets. Agri-food system integrations such as livestock-fish, poultry-fish, crop-livestock and rice-fish farming have been well documented in academic literature. However, information on fish and root, tuber and banana (RTB) crops integration is scarcely available, despite their worldwide cultural, dietary, and economic importance. This article, which is informed by a narrative literature review and ground-truthing through key informant interviews, documents existing linkages between two agri-food systems—fish and RTB—and identifies opportunities and challenges for strengthening their integration. We found that recorded instances of fish-RTB integration are limited and predominantly discuss production-related activities. Nevertheless, initial evidence suggests that there are important livelihood-enhancing opportunities as well as environmental, nutrition and food-security related benefits, which need to be considered. These include the potential to improve the nutritional status of vulnerable populations and lower the cost of fish production and thus improve the livelihoods of small-scale fish farmers. Further field-based research is recommended to explore these outcomes in more detail.

Keywords: integrated agriculture-aquaculture; agri-food systems; roots; tubers; bananas; nutrition; fish feed; nutrition-sensitive programmes.

Introduction

Agri-food system integration has the potential to increase and add value to agricultural production, reduce cost of and dependency on external inputs, generate additional income for farmers, and encourage the diversification of outputs and diets (Brummett and Jamu, 2011). Agri-food system integration can be loosely defined as the diversification of agricultural production – from the landscape level to the diversification of smallholder plots. The term is used broadly to include farm management practices like crop rotation and intercropping and encompasses the integration of agricultural subsystems, including crop production, livestock husbandry, and aquaculture (Edwards, 1998).

Integrated agriculture-aquaculture (IAA) is one typology of an integrated agri-food system that refers to the combined production of finfish, shellfish or other aquatic animals (hereon referred to as fish), crops, and in some instances livestock. The composition of IAA systems is context-specific; the particularities of IAA systems vary between regions and depend on many factors, including financial resources available to the farmer, climatic conditions, ecological attributes, individual and cultural consumptive preferences, market orientation and opportunities, availability of labour, land tenure, management objectives, and agricultural knowledge (Mohri *et al.*, 2013). More holistic conceptualisations of IAA, used to guide this investigation, extend the focus from relatively simple two-component systems (i.e. the concurrent production of fish with livestock) to multi-component systems that include sequential, in addition to concurrent, linkages between subsystems. This approach includes the use of off-farm resources and agricultural by-products, produced at separate locations and by different people. It also encompasses linkages between agricultural and human activities, for example, the re-use of human excreta in agricultural production (Prein, 2002; Little and Edwards, 2003; Ahmed, Ward and Saint, 2014). Integration can develop at a variety of scales: at the homestead level, agri-food system integration can refer to the effective management of resources and by-products such as the utilisation of livestock manure in crop production or the use of household food waste as fish feed; and at a landscape level, agri-food system integration can involve collaborations between food producers, national policy coordination and coherence, and multifarious partnerships. Integrated agri-food systems are designed to increase synergies between systems, minimise negative externalities and trade-offs, and ultimately deliver ‘triple-wins’: improved livelihoods, efficiently managed natural resources, and boosted agricultural production (Edwards, 1998; Mamun, Nusrat and Debi, 2011).

Agri-food system integration (e.g. livestock-fish, poultry-fish, crop-livestock, and rice-fish farming) has been practiced in countries like China, Vietnam, Cambodia, Indonesia, and Malaysia for centuries (Little and Edwards, 2003; Phong *et al.*, 2008; Ahmed, Ward and Saint, 2014). Such systems have been well documented in academic literature and advocated for by organisations such as the International Rice Research Institute (IRRI), the FAO, and WorldFish, as an effective approach to increasing agricultural income and promoting nutrition-sensitive agricultural practices among small-scale farmers. However, the integration of fish, and root, tuber, and banana (RTB) crops[1] has, so far, received little attention, despite the importance of these crops to small-scale farmers. Globally, more than a billion people eat potato as a staple food. Cassava is considered to be the third most widely consumed food crop in the tropics (CIP FOODSTART+, 2018; International Potato Center, 2018). Orange-fleshed sweetpotato (OFSP) is a nutritious and well-accepted biofortified root crop that contains high levels of vitamin A, phosphorus, and potassium, which are often lacking in poor quality diets (Low *et al.*, 2017). Due to their popularity and nutritional quality, OFSP have potential to reduce the global prevalence of vitamin A deficiency. Furthermore, RTB crops are often drought-tolerant, which can help farmers adapt to climate change and related extreme weather events (Prain and Naziri, 2020). Equally, fish, especially small fish, are a source of essential micronutrients - including calcium, iron, zinc, vitamin A, and vitamin B12 - amino and fatty acids (Longley *et al.*, 2014). Fish are often the cheapest available animal source food in developing countries (Finegold, 2009; The World Bank, 2012). Data suggest that at least one billion people depend on fish as their main source of animal food (Genschick *et al.*, 2015). Yet, the importance of fisheries in local and global food systems, and its contribution to livelihood, nutrition, and health, is often overlooked and undervalued (Thilsted *et al.*, 2016). Hence, there are clear opportunities to enhance the contribution of fish and RTB agri-food systems to sustainable development.

Collaboration and coordination between agricultural sectors, across the food system, are required to achieve functional food systems that contribute to multiple economic, social,

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[1] Including, but not limited to, cassava, sweetpotato, potato, cocoyam, banana, and plantain.

and environmental objectives. Thus, research that seeks to identify how, and to what extent, agri-food system integration can bring about so-called triple-wins is warranted.

The objective of this paper is to present the key findings of a literature review that was conducted to a) document existing linkages between fish and RTB agri-food systems at the point of consumption (e.g. in diets) back to food production (e.g. farm management practices); b) identify opportunities for, and challenges to, strengthen integration of fish and RTB agri-food systems; and c) identify research gaps and provide policy recommendations that support effective agri-food system integration.

Methodology

Literature review

Publications were first sourced through databases, including Google Scholar, Scopus, Web of Science, and PubMed. Relevant literature was searched for using multiple key terms (Table 1), which were generally used in combination e.g. “fish-feed” AND “sweetpotato.” Next, we searched the webpages of pertinent governmental organisations, development organisations, and research institutions, including WorldFish and the International Potato Center (CIP), for grey literature. The reference lists of all publications were then consulted to find additional publications that did not appear through our initial search methods. Reviewed literature was also identified through the ‘cited by’ function on many of the aforementioned databases.

Document review and analysis

The review is narrative; it intends to document and discuss the current state of literature on the integration of fish and RTB agri-food systems and on-the-ground evidence of such linkages. Papers were considered if they were published from 2000 to 2019.

Eligible papers were coded using the qualitative coding software NVivo (version 12.2.0) and categorized according to publication date, research methodology, location of study, and focus crops. Extracts of text were coded into topics and themes for analysis. The development of themes was guided by the food systems framework presented by the High Level Panel of Experts on Food Security and Nutrition (2017) and included the following thematic codes: nutrition and health outcomes, dietary diversity, food processing, production systems, economic impacts, environmental impacts, social impacts, and drivers of food systems (socio-cultural, political, economic, biophysical, and demographic). Categorising references according to this framework first demonstrated active areas of integration presented in peer-reviewed and grey literature and, second, helped shed light on opportunities for further fish-RTB integration. This analysis was the basis for determining research gaps and shortcomings in our current knowledge of the topic.

Primary data collection

In order to validate the preliminary findings of the literature review, semi-structured interviews were conducted with academic professionals, fish feed manufacturers, fish feed dealers, fish farmers, RTB farmers, and households in four divisions of Bangladesh; Dhaka, Mymensingh, Sylhet, and Rangpur. Integrated farming systems are prevalent in Bangladesh, particularly the co-production of rice and fish. Integration is widely acknowledged in the country as an effective mechanism to increase agricultural production, incomes, and promote nutrition-sensitive agricultural practices, especially in areas with resource limitations and poor access to cultivatable lands (Ahmed and Garnett, 2011). However, from the literature, specific instances of RTB crop and fish integration are indistinguishable. There is a general lack of detail about the crops grown in IAA homegardens; and very few publications evidenced the consumption of fish with roots, tubers, or bananas in traditional dishes, and complementary feeding practices. Primary data collection was expected to reveal such instances, if any.

A total of 22 semi-structured interviews were carried out during a two-week field visit to Bangladesh. Key informants from WorldFish, CIP, the Bangladesh Agricultural University, and the Bangladesh Fisheries Research Institute, among others, were selected by purposive sampling for their topical knowledge (Bryman, 2012). Fingerling producers, fish farmers, RTB farmers, and project beneficiaries were also purposively sampled (Table 2). These respondents were selected because they were known to have integrated fish and RTB crop production, potentially use alternative aquafeed ingredients including RTB crop by-products, and/or could provide contextual insight into the fish and RTB food system in Bangladesh.

Results

The various search methodologies produced 45 eligible documents, of which 33 were peer-reviewed journal articles and the remaining twelve documents consisted of books or book chapters (3), institutional reports and working papers (7), and conference proceedings (2).

Much of the available literature on this topic (n=39) is concentrated at the production end of the food system and includes the concurrent production of fish with RTB crops (n=9) and the development, testing, and utilisation of RTB crop residues as fish feed (n=30)[2]. An additional six documents detailed the traditional consumption of fish with RTB crops (n=2) and studies on the nutritional enhancement of i) conventional cereal-based complementary food for infants and young children with RTB crops and fish (n=3), and ii) the diets of primary-school children with yellow cassava combined with small dried fish (n=1).

A large number (n=20) of the literature published on this topic focuses on the Nigerian agri-food system. Seventy percent of these papers (n=14) discuss the use of RTB crop residues in fish feed. Other countries featured in the published literature include Bangladesh (n=3), Thailand (n=2), Indonesia (n=2), Vietnam (n=3), Cambodia (n=1), Papua New Guinea (n=1), Ghana (n=1), Malawi (n=3), Kenya (n=3), Tanzania (n=1), Rwanda (n=1), and Uganda (n=1).

Co-consumption of fish and RTB crops in the diet

Fish is a common accompaniment to traditional cassava-based food products, such as *garri*[3], in West African countries like Nigeria and Ghana (Sharma, Njintang, Singhal, and Kaushal,

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[2] The development, testing and utilisation of RTB crop residues as fish feed is broadly categorised at the point of production because interventions in this area concern improving or altering fish production practices.

[3] *Garri* is a popular cassava-derived product in Nigeria, and other West African countries like Ghana, Benin, and Togo (Onyemauwa, 2010). To make *garri* cassava roots are peeled, washed then grated or crushed or ground. Afterward, the substance is left to ferment and then pressed in a porous bag, often between a jack, to remove excess starchy water. This process can take between 1 hour to 3 days. The cassava is then sieved and roasted. This process is known as garification. In some cases, palm oil is also added to the cassava and creates yellow

2016). In mid-western Nigeria, *kpokpo garri*, a variation of regular *garri,* is often eaten with dried or smoked fish, groundnut, and/or coconut kernel (Sharma *et al.*, 2016). *Konkonte,* a traditional Ghanaian dish, made with cassava flour added to boiling water to form a smooth, thick paste, is often served with ground pepper and fish and is considered a customary dish for lactating mothers, particularly among the Krobo people in eastern Ghana (Sharma *et al.* 2016).

There is growing evidence that fish, in addition to their intrinsic nutrient content, contributes to improved nutrition by facilitating the uptake of iron and zinc from dietary components of vegetable origin (Belton and Thilsted, 2014). In Eastern Kenya, Talsma *et al.* (2018) conducted an assessment of the nutrient adequacy of primary school children when vitamin A-rich biofortified yellow cassava was added to school lunches. This study concluded that adding two servings of small dried fish per week to the yellow cassava school lunch optimised the overall nutrient adequacy of the diet of primary school children.

Small dried fish have also been recommended in combination with orange-fleshed sweetpotato (OFSP) by Bogard *et al.* (2015) as a complementary food product for enhancing nutrition in the first 1000 days of life. The complementary food product developed by Bogard *et al.* (2015) is based on the traditional rice-based porridge consumed in Bangladesh. To enhance the nutritional quality of this traditional porridge, OFSP was added. OFSP was selected because it is a rich source of vitamin A and was found to be acceptable in initial studies (Bogard, *et al.*, 2015). Dried darkina fish (*Esomus danricus*), a small indigenous fish

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garri. The resultant dry granular *garri* can be ground or pounded to make flour (Sharma *et al.*, 2016). *Garri,* the flour*,* is then used to make various dishes including *fufu*, and *eba*.

species, was selected due to its high iron, calcium, and zinc content. The proposed serving sizes, exceeded 100% of estimated required calcium intakes for all age-groups as well as vitamin A, iron, and zinc requirements for children 12 to 23 months. Moreover, the fish-based complementary food contributed substantially to essential fatty acid requirements (Bogard, *et al.*, 2015). Similarly, Nandutu and Howell (2009) used OFSP and skinned fillets of Tilapia to develop a nutritionally-dense complementary food for infants in Uganda. The complementary food developed in the study favourably compared with commercial complementary food products available in the market in terms of consistency (i.e. thickness and texture of the food product) and nutritional value (Nandutu and Howell, 2009).

Production: concurrent and sequentially integrated fish and RTB production systems

The reviewed literature suggests that bananas (*Musa spp.*) are the most commonly recorded group of RTB crops integrated with fish. Systems that incorporate fish production into cassava, sweetpotato, potato, yam, and cocoyam cropping systems were documented, but to a lesser extent (Table 3). Six of the nine publications describe fish-RTB integrated production systems in South and South East Asia.

In traditional Javanese homegardens, locally known as *Pekarangan*, crops, livestock, and fish are concurrently cultivated and reared (Mohri *et al.*, 2013). Banana plants are grown alongside other food and cash crops including coconut, orange, mango, jackfruit, rice, maize, sweetpotato, cassava, yam, and leafy vegetables. Fish and livestock, specifically chickens, cows, goats, and sheep, also represent an important feature of Javanese homegardens (Mohri *et al.*, 2013). According to Mohri *et al.* (2013), 20% of the total area of West Java is occupied by homegardens. These homegardens vary in size from a few square metres to hectares, with an average area of 0.4 – 0.6 hectares. In Bangladesh, in 2011, over 1000 hectares of land was under pulse or potato-fish cultivation (Dey *et al.*, 2012). Here, potatoes or pulses are grown during the dry season followed by fish culture in the wet season, and, unlike in Javanese homegardens, the production of fish and potatoes in this system is not simultaneous, but still considered as ‘integrated’.

Reclaiming, re-cycling, and re-using nutrients and organic ‘waste’ produced on, or off-farm is often cited as a defining feature of integrated production systems and appears as a resource management strategy in many of the fish-RTB production systems identified in this study. For instance, water from the pond is used to irrigate the various crops, including RTB crops (e.g. Miller *et al.*, 2006; Nagoli *et al.*, 2009; Mohri *et al.*, 2013). Oribhabor and Ansa (2006) report that farmers in the Niger Delta region of Nigeria have tactically planted valuable cash crops such as banana and guava on the perimeter of their ponds to take advantage of the water that seeps from the pond into the surrounding soil. In areas without adequate irrigation and in drought-prone agro-ecological zones, ponds are an especially important source of water (Pant, Demaine and Edwards, 2004; Al Mamun, Nusrat and Debi, 2011). In addition, excess pond silt is often used by farmers as a fertiliser and applied to fields to boost crop productivity (Oribhabor and Ansa, 2006; Al Mamun, Nusrat and Debi, 2011).

Vegetable waste is, in some cases, reclaimed to assist fish production (Al Mamun, Nusrat and Debi, 2011). In Northeast Thailand, cassava leaves, banana leaves and stems were just some of the recorded vegetable and crop by-products applied to ponds (Pant, Demaine and Edwards, 2004). Pant, Demaine and Edwards' (2004) research in Northeast Thailand revealed that over 50% of the 234 IAA practicing households interviewed applied crop by-products, including RTB crop residues, to their ponds. In Bangladesh, *Musa spp.* leaves are used as a major source of feed for Grass carp specifically. According to one fish farmer in Mymensingh, green banana leaves are applied to the pond, with grass cuttings, every 10 to 15 days (MRICE08). Through key informant interviews, Bangladeshi farmers reported on occasions feeding potatoes to fish (RBARI05; CIP23). Farmers are known to boil potatoes that were harvested in the previous year and not consumed before the new harvest period in order to feed them to cows, poultry, and fish (RBARI05; CIP23).

Nevertheless, key informants interviewed in Bangladesh, explained that the re-purposing of agricultural by-products is not as popular as it was twenty years ago (WF21; WF22). People are thought to have acquired better management practices and use improved and more efficient technology and inputs to increase production (WF22). Use of agricultural by-products is actually discouraged by most aquaculture extension officers (WF21; WF22; MBFRI12). Furthermore, the commercial fish feed sector in Bangladesh, is believed to be quite domineering and arguably use their relatively powerful positions to influence pond owners to purchase commercial compound feed (MBFRI12).

RTB crop residues as an ingredient in commercial compound fish feed

In addition to being used by small-scale fish farmers, RTB crop residues are increasingly regarded as a viable ingredient for commercial compound fish feed. Abu *et al.* (2010b) reported that cassava root meal is of comparable quality to conventional energy sources, such as maize, and is cheaper and more readily available in certain locales than other energy sources. Additionally, Solomon, Okomoda, and Oloche (2015) indicated that sweetpotato peels contain important micronutrients such as vitamin C and iron. Furthermore, plant leaves, especially cassava and sweetpotato leaves, are high in protein and can have relatively high amino acid profiles and micronutrients, including vitamins A, C, E, and riboflavin (Adewolu, 2008; Olusola and Olaifa, 2018)

Research on the integration of RTB crops in fish feed over the last twenty years has been dominated by quantitative lab-based feed trials. The majority of these feeding trials explored the incorporation of cassava or sweetpotato into Tilapia or Catfish diets (Table 4).

These studies were primarily designed to investigate the effects of replacing a proportion of conventional protein or energy sources used in commercial fish feed by RTB peels, leaves, or meal on fish growth and efficiency in feed utilisation. The results of the feeding trials are not easily summarised, and no conclusive evidence of the effectiveness of such an intervention was found, since most of the studies varied, either according to the a) crop, b) crop part, c) fish species, d) life stage of a particular fish species, or e) the processing techniques applied to the feed ingredient. However, tentatively, it seems that conventional energy sources such as maize can, to a degree, be replaced effectively by the trialled RTB crop residues and leaves in the diets of African Catfish and Nile Tilapia. Only one study (Lawal *et al.*, 2012) concluded that it was not favourable to replace maize in the diet of Catfish fingerlings. In contrast, Dada *et al.* (2015); Ojukannaiye *et al.* (2013); and Tachia, Ataguba, and Abuh (2016) found that replacing maize with cassava peel did not result in statistically significant reductions in growth performance. Two of these articles suggest that cassava peel can almost or completely substitute maize at a replacement level of 97% and above in the diet of Nile Tilapia (Ojukannaiye, Mogali and Asuwaju, 2013; Dada, Adeparu and Malomo, 2015).

Moreover, Ojukamaiye, Mogali, and Asiwaju (2013) found that fish fed a diet with 100% replacement level of maize by cassava peel meal (15% of formulated diet) recorded the highest mean weight gain (significantly different to other treatments) and specific growth rate.

Evidence regarding the effectiveness of replacing conventional protein sources such as fishmeal and soybean with RTB crop residues, are less promising. Though, studies suggest that fermentation could improve the value of RTB crop residues as a source of protein in fish feed. Ubalua and Ezeronye (2008) found that fermented cassava peel compared favourably with the trialled fishmeal-based diet. Using a microbial sourced from palm wine, these authors recorded an increase in the crude protein value of the cassava peel from an initial crude protein value of 5.4 to 17.2% after fermentation (Ubalua and Ezeronye, 2008). Nile Tilapia fingerlings fed fishmeal-based diets and fish fed diets containing soybean meal as the primary protein source performed better overall, based on various growth parameters including mean weight gain and specific growth rates, than fish fed fermented cassava peel but these differences were not statistically significant ($p>0.05$). Moreover, Oboh (2006) showed nutrient enrichment of cassava peels using a mixed culture of *Saccharomyces cerevisae* and *Lactobacillus spp* in a solid media fermentation technique. This research demonstrated that the fermentation of cassava peels with pure strains of *Lactobacillus delbruckii* and *Lactobacillus coryneformis* improved their protein, cyanide and phytate contents to 22%, 6.2 mg/kg and 789.7 mg/100 g, respectively. However, the fermentation of cassava peel is still costly and requires pure strains of bacteria that are not readily available in a developing country such as Nigeria. Thus, new approaches to improve the nutritional value and digestibility of the nutrients contained in the cassava peels are still worth investigating.

In addition to the effects on growth performance and feed utilisation, a few studies identified in this review explore the economic implications of replacing conventional feed ingredients with RTB crop residues and leaves. Sine *et al.*, (2017) detail that it would almost reduce by half the costs of Tilapia feed for farmers in Papua New Guinea if conventional commercial Tilapia feed ingredients such as fishmeal, meat and bone meal, soybean meal, maize, and rice bran were completely replaced by cassava and sweetpotato meal. Abu *et al.*, (2010b) conducted a cost-benefit analysis of replacing conventional energy sources with whole cassava root meal. They concluded that although RTB-based replacements may not perform as well as conventional feed ingredients such as maize or fishmeal, replacing maize with whole cassava root meal in the diet of hybrid Catfish led to up to 100% higher net profits, with the highest profit achieved with a 66% replacement level. However, this study was specific to the hybrid Catfish species and also regionally specific to Nigeria. Since commodity prices vary regionally, these findings are not universally representative.

Discussion

This review has revealed important instances of integrated fish-RTB agri-food systems. Whilst the global extensiveness of these particular interactions is fairly unclear, and detailed accounts are limited, agri-food system synergies including fish and RTB crops are relevant in West Africa, particularly Nigeria, and South East Asia. The evidence available to date is bounded and concentrated upon the effectiveness of integration at the point of production.

Nevertheless, there are important livelihood-enhancing opportunities and environmental, nutrition and food-security related benefits that should be considered. Integrated fish-RTB agri-food systems have the potential to improve the nutritional status of vulnerable populations (Bogard *et al.*, 2015) and lower the cost of fish production and thus improve the livelihoods of small-scale fish farmers (Sine et al. 2017; Abu et al. 2010b). Though, there are significant challenges and potential trade-offs linked to the integration of fish-RTB agri-food systems that also need to be examined.

Pathways for improving diets

Integrated agri-food systems are thought to improve dietary diversity directly through increased consumption and indirectly through increased household income from additional agricultural sales (Prein and Ahmed, 2000; Sibhatu, Krishna and Qaim, 2015). It is hypothesised that when a smallholder household produces a greater variety of agricultural products, then barriers to accessing a diversity of foods decrease and household consumption increases. Jones (2017) found that, of the 21 identified studies, 90% of studies analysing the association between agricultural biodiversity and dietary diversity found a positive association.

Jahan and Pemsl (2011) and Brummett and Jamu (2011) have recorded increased household fish consumption associated with the adoption of aquaculture into agricultural systems when culturally-appropriate behaviour change communication was included. Jahan and Pemsl (2011), who studied the impact of long-term IAA training in Bangladesh, found that average per capita consumption of fish, vegetables, and potato increased significantly during the project period as compared to a control group. Similarly, Brummett and Jamu

(2011) reported a 208% increase in fresh fish consumption and a 21% increase in dried fish consumption as an outcome of IAA adoption in Malawi.

An annual assessment of the ‘Suchana’ project[4], and their nutrition-sensitive horticultural and aquaculture interventions, including the promotion of OFSP and fish cultivation in homestead gardens, in North East Bangladesh, conducted by WorldFish (2018), revealed significant increases in the proportion of produced vegetables used for family consumption, and improved dietary diversity of women of reproductive age, and young infants and children (6-23 months old). In particular, Suchana promoted Mola, a small indigenous fish with great potential to reduce micronutrient deficiencies (Keus *et al.*, 2017) but whose market price can be high in comparison to larger, and more commonly cultured species like Pangasius Catfish (personal observation, March 3, 2019)[5]. Therefore, the project, supported the culture of Mola in homestead ponds along with Tilapia and Carp (*spp.*) as a direct and relatively cheap source of micronutrients. In addition, expanded income from the sale of a diversified set of agricultural products is also believed to indirectly contribute to increased dietary diversity as households can also purchase diverse foods from the market with this income (Sibhatu, Krishna and Qaim, 2015). Whilst the size of homegardens in Bangladesh are relatively small and generally range from 0.004 to 0.08 hectares, homegardens can be highly productive and contribute significantly to household food security (Ferdousy *et al.*,

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[4] Suchana ‘Ending the cycle of under-nutrition in Bangladesh’ is a multi-sectoral, six-year project led by Save the Children, supported through a consortium of partners including WorldFish, Helen Keller International, International Development Enterprises, FIVDB, RDRS, and CNRS; and funded by UKAID and the European Union (WorldFish, no date). The project aims to address regionally high rates of malnutrition, in the Sylhet and Moulavibazar districts in the North East of the country, through nutrition-sensitive and nutrition-specific interventions including the promotion of nutrition-sensitive horticulture, including the promotion of OFSP, and fish production (Save the Children, no date; WorldFish, no date).

[5] Market prices for fish species were observed in Trisal Fish Market, Mymensingh, Bangladesh.

2018). Moreover, since women are the main caretakers of homegardens in Bangladesh, nutrition-sensitive interventions that focus on enhancing and diversifying homestead production are said to have empowering impacts for rural women, specifically increased participation in household decision-making related to production, harvesting, and utilisation of aquaculture and agricultural products – given that they are at the very least gender sensitive[6] (Ferdousy *et al.*, 2018).

In addition to improved household production, fish-RTB integration through programmatic and institutional health interventions can also improve the nutritional status of micronutrient deficient populations. Complementary feeding refers to the timely introduction of safe and nutritious foods and is recommended to begin when the infant is six months of age (World Health Organization, 2008). In low-income countries, most infants are given cereal-based complementary foods (Amagloh *et al.*, 2012). However, the most desirable complementary foods are prepared using a variety of foods and include animal source foods. Improving complementary feeding practices is considered a food-based approach to improving the diet of children during the first 1000 days; defined as point of conception up to two years old (WHO, 2008). Fortification - the addition of micronutrients during processing of plant-based, commercially produced complementary foods - is one approach to achieve desired nutrition densities. But not all families have access to or the means to buy these products (Bogard, *et al.*, 2015). Home-based approaches, such as encouraging the inclusion of local, culturally acceptable, nutrient-rich ingredients, including animal source foods, in complementary feeding practices is also a valuable approach.

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[6] Gender sensitive interventions attempt to redress existing gender inequalities through addressing gender norms, roles and access to resources (UN Women, no date).

Fish, are rich in high quality, readily digestible protein and energy; and are a good source of readily absorbable and bioavailable micronutrients including calcium, iron, zinc, and vitamin A (Neumann *et al.*, 2014). For these reasons, fish, especially small fish, can be utilised instrumentally, to create micronutrient-dense complementary foods for infants that can contribute to the alleviation of the multiple burdens of malnutrition. Equally, OFSP can provide high levels of vitamin A to vulnerable populations. Future research should identify additional micronutrient-rich combinations of fish and RTB products that are relevant to other geographical regions with populations suffering from micronutrient deficiencies and develop social and behaviour change communication materials that educate caretakers of the nutritional benefits of feeding children these ingredients as a combination.

Economic opportunities and livelihood enhancement

Mamun, Nusrat and Debi (2011) position IAA as a ‘resource management strategy’ since diversifying land use through the integration of crops, aquaculture, and often livestock optimises the per unit production. Mohri *et al.* (2013) found that in Vietnam, garden-pond-livestock systems were more productive than rice monocropping and generated a collective income almost fifteen times higher than rice farming. Increases in income are also likely influenced by reductions in the volume and cost of off-farm inputs (Nagoli *et al.*, 2009). Dey *et al.* (2010) attributed IAA-associated increases in productivity and profitability in Southern Malawi to synergistic interactions between various farm enterprises, specifically the use of pond water for the irrigation of crops, including banana plants. Additionally, this integration allowed small-scale farmers to increase cropping intensity and enabled farmers to grow higher value crops (Dey *et al.*, 2010). For these reasons, integrated production systems are positioned as particularly appropriate for small-scale, resource-poor farmers (Nhan, Bosma and Little, 2007; Ahmed, Ward and Saint, 2014). Integrating crop production, especially micronutrient rich RTB crops, and fish cultivation in homegardens in North East Bangladesh has a particularly high potential where landlessness is prevalent (about 62% of farmers are landless in the Sylhet division), and where nutritious foods are locally available but not necessarily affordable, especially for the poorest households (in the Sylhet division, 68% of the population live below the international poverty line of US$ 1.25 a day) (WorldFish, 2017; Ferdousy *et al.*, 2018). Similarly, in the Khulna region pond-dike cropping is a particularly common farming strategy. Here, a large proportion of the land in this region is saline and somewhat unsuitable for agricultural production (Abdullah *et al.*, 2017). Strategic pond-dike infrastructure provides an elevated growing area unaffected by increasingly saline soil conditions (Kabir *et al.*, 2016). Hence, ponds are being constructed with wider dikes to plant crops, or adapted in response to environmental change, regardless of their size and market orientation (Kabir *et al.*, 2017). This response to unfavourable cropping conditions is an opportunity to further fish-RTB integration into production systems, for instance by building on recent effort by CIP to develop saline-tolerant potato and sweetpotato varieties in Bangladesh.

However, temporal and spatial challenges exist. For instance, residues from crop harvests, which can be used as pond inputs, might only be available at specific times of the year, yet are required throughout the entire fish cultivation period (Prein, 2002). Moreover, as Prein (2002) explains, small-scale rural farms are often fragmented. Homesteads, crop plots, and fishponds can be based at different locations and are not necessarily located within a convenient proximity of one another for easy transport of crop residues, kitchen waste, and manure to the pond (or vice versa). This makes dynamic interactions between agricultural subsystems difficult.

In addition, IAA is widely regarded as ‘knowledge-intensive’ since successful application largely requires technical knowledge of multiple production systems (Little and Edwards, 2003; Tran *et al.*, 2013; Limbu *et al.*, 2017). This is particularly true for those who do not already have an aquaculture pond. Furthermore, introducing fish culture to traditionally crop-based homegardens can potentially increase workloads for certain family members (Little and Edwards, 2003). It is often women, in many contexts, who bear a disproportionate burden of on-farm labour, particularly where more labour is required for tasks that are predominantly conceived as roles for women such as sowing, harvesting, and fertiliser application (Setboonsarg, 2002; Halbrendt *et al.*, 2014).

Furthermore, socio-cultural challenges to some of the reportedly beneficial ‘synergistic’ practices often associated with integrated agri-food systems exist. In Bangladesh, as key informants suggested, the practice of recycling kitchen waste, garden waste, and manure, for instance, is commonly perceived as ‘backwards’, and discouraged by aquaculture extension officers. Instead, pond owners, regardless of the scale of their aquaculture operations, are encouraged by government and the majority of programmatic extension officers to purchase commercial feed. This feed, whilst it is undeniably more efficient in terms of fish growth rates, is expensive. In Bangladesh, feed can account for as much as 70% of the cost of production (Mamun-Ur-Rashid *et al.*, 2013). The increasing popularity of commercial feed in Bangladesh is also influenced by the persuasiveness of the feed sector. Many feed dealers allow pond owners to purchase feed on credit which, whilst perhaps well intended and beneficial for some, could easily ‘lock’ others into an agreement, possibly with unfavourable *de facto* terms and conditions, that may not be optimal in the long term. This practice of fish feed on credit in Bangladesh is recorded by Mamun-Ur-Rashid *et al.* (2013) and is reported to occur in other countries like Egypt according to El-Sayed, Dickson and El-Naggar (2015).

Initial evidence suggests that opportunities exist to use RTB crop residues as aquafeed at the commercial scale to lower the cost of compound fish feed. The use of cassava peel, a relatively abundant agricultural by-product in Nigeria, is particularly promising and, if found feasible, could contribute to regional economic growth and create new livelihood opportunities. Additional job opportunities for commercially converting waste into feed could benefit women, who constitute the backbone of cassava processing in Nigeria (Okike *et al.*, 2014; Amole, 2016). But such developments should be carefully managed to ensure that working conditions are safe and that women are offered an equitable salary for their time and labour. Furthermore, again, there is a risk that most of this work associated with the additional processing steps, in on-farm operations that rely on un-paid familial labour especially, would fall disproportionately on women. Though more information is needed regarding the role of women in the aquafeed production and supply chain.

However, it is important to recognise that RTB crop processing activities are, especially in sub-Saharan Africa, limited by the subsistence nature and seasonality of production. Cassava farming is mostly done by smallholders; who, in the case of Nigeria, are responsible for around 80% of the cassava production (Onyenwoke and Simonyan, 2014; Mcnulty and Adewale, 2015). In southern Nigeria, cassava is sown between March and October and harvested in most cases a year later. Accordingly, peak cassava processing periods correspond with these seasons, resulting in a lull in supply between November and February. Mcnulty and Adewale (2015) caution that this inconsistency in the supply of raw material limits the scale of cassava processing in Nigeria. As a result, selected medium to large scale processing sites only operate seasonally (Mcnulty and Adewale, 2015). Consequently, the production of by-products is similarly inconsistent. Government initiatives, such as The Cassava Master Plan, a Nigerian presidential initiative to improve cassava production, and non-governmental initiatives, such as International Institute of Tropical Agriculture's (IITA) efforts to develop early maturing and high-yielding cassava varieties, could help smooth the supply of cassava (International Institute of Tropical Agriculture, no date; UNIDO, 2006). Equally, poor road and storage infrastructure could hinder future developments. As stated by Agboola, Yossa and Verreth (2019), logistics around the collection of relevant cassava by-products need to be organised and should be considered a crucial research area. Though, a major challenge for this system lies with unifying producers from economic sectors that have traditionally been isolated from one another (Davis et al. 2016). A valuable initiative to address this challenge is the ongoing work led by IITA for developing the 'Cassava Peel Tracker', an app to facilitate locating and geo-referencing available peels at cassava processing sites, and hence linking peel suppliers with plants manufacturing cassava-based feed.

Environmental outcomes

In addition to the economic and livelihood opportunities associated with the utilisation of agricultural by-products, specifically cassava peel, there are potentially beneficial environmental outcomes. Utilising agricultural 'wastes' instead of primary products can somewhat reduce existing and increasing pressures on natural resources, but also mitigate some of the environmental impacts associated with the poor handling of the vast quantities of 'waste' produced in food supply chains.

The rapid expansion of intensive feed-driven fish production systems has raised serious environmental concerns with regard to sustainable resource use (Folke and Kautsky, 1992). The use of fishmeal and fish oil, as a valuable source of protein, in the production of some species in particular, and its effects on wild fish stocks is a well-known issue (see Allsopp, Johnston and Santillo, 2008). But meeting rising demands for terrestrially-sourced aquafeed ingredients, including cereal crops used as a primary source of energy, poses a concurrent challenge in terms of environmental sustainability given the global scarcity of, and increased pressure placed on, natural resources such as land and water (Wadhwa, Bakshi and Makkar, 2016). The production of crop-based feed ingredients has been associated with high nutrient and chemical input use and loss, land clearing in sensitive environments and greenhouse gas emissions (Klinger and Naylor, 2012). The efficiency of feed-use and the sourcing of feed inputs for aquaculture are among the most important factors determining the environmental impacts of fish farming (Klinger and Naylor, 2012). Efficient use of available resources, such as agricultural by-products and wastes of agro-processing industries, can thus contribute to the sustainable development of aquaculture (Hasan, 2001; Wadhwa, Bakshi and Makkar, 2016). Whilst these residues are viewed as undesirable 'waste' in one particular stage of the product value chain, they may be valuable resources to other processes inside or outside the supply chain where they were originally generated (Batista, Saes and Fouto, 2015). Absorbing wastes back into the agri-food system, and re-purposing unwanted residues with innovative technologies, can also increase their value

(Toop *et al.*, 2017). Such synergies already exist in the animal feed sector. For instance, the commercial feed sector in Bangladesh effectively utilises locally available agricultural by-products, including broken rice, rice bran, wheat bran, and oil cake (Mamun-Ur-Rashid *et al.*, 2013). Rice bran, which comprises five percent of the total rice yield and is available all year round, is mainly used as feed for cattle and buffalo (Barman and Karim 2007). Broken rice, also produced in rice mills, is most commonly used as feed for poultry. But both broken rice and rice bran at a 20-50% inclusion level, are also an ingredient in fish feed (Mamun-Ur-Rashid *et al.*, 2013).

In Nigeria, cassava is processed into a variety of primary, and secondary products. Substantial quantities of cassava peels are produced by the growing number of processing enterprises in Nigeria (Lukuyu *et al.*, 2014). Cassava is processed to produce *garri, fufu,* ethanol, flour, and starch, which is used in food products like bread and biscuits, and non-food products including adhesives and pharmaceutical products (Onyenwoke and Simonyan, 2014). To produce *garri,* a popular convenience food, cassava roots need to be peeled, grated, fermented and roasted. As part of this process, the cassava peels, an estimated 15% of the whole root, are discarded (Agboola, Yossa and Verreth, 2019). Evidence suggests that as much as six million tonnes of cassava peel, leaves, and pulp is discarded by the starch and *garri* processing sectors per year (FAO, 2007; Lukuyu *et al.*, 2014). The true figure is likely much higher due to government efforts to develop the cassava sector and reduce reliance on imported food (see UNIDO, 2006). More recent research suggests that more than 7.5 million tonnes of cassava peel are produced annually just in South West Nigeria (Naziri and Bennett, 2013). At present, large amounts of these cassava peels are carelessly disposed of into the environment, where they are left to rot away or burnt. These waste heaps emit carbon dioxide, produce a foul smell, and may cause surface water pollution (Lukuyu *et al.*, 2014). Traditionally wastes have been treated as externalities, simply diffused into the ambient environment, but the establishment of such cross-industry linkages, including fish farming, to optimise and repurpose waste products can help to ‘close the loop’ in traditionally linear production systems and mitigate the environmental impact of food supply chains. This requires substantial financial investment and new governance arrangements to facilitate improved institutional arrangements, integrative management and technological innovation (Davis et al. 2016).

Conclusion

The co-production, and dynamic integration, of fish and roots, tubers, and bananas show synergistic promise at both the small and large scales, but more research is needed on contextually appropriate solutions that enhance livelihood, food and nutrition security, and environmental outcomes. Further field-based research is warranted to explore in more detail the outcomes from the integration of RTB crops and fish into both homestead farming systems and diets, likely focussing on countries with high dependency on RTB crops and fish and potential for productivity and nutritional gains.

Whilst the literature search did not find compelling examples of commercially produced complementary foods that combined fish and RTB crops, evidence suggests that traditional rice-based porridge used as a complementary food for infants in Bangladesh can be nutritionally enhanced with the addition of micronutrient-rich small fish and vitamin A-rich orange-fleshed sweetpotato. Efforts to identify alternative micronutrient-rich combinations of fish and RTB products as a complementary food product for infants should be expanded to other geographical regions suffering from severe micronutrient deficiencies.

There is some initial data suggesting that replacing conventional fish feed ingredients such as maize, fishmeal, and soybean meal, with RTB crop residues could reduce the cost of fish production and lead to higher net profits. However, the evidence base is limited. Further research needs to be conducted in this area before generalisations can be made. Efficient use of available resources, such as agricultural by-products and wastes of agro-processing industries which are widely available in most parts of the world, can contribute to the sustainable development of aquaculture. For instance, leveraging cassava peels for use in aquafeed, in Nigeria, could help to mitigate the environmental impact of waste in the cassava value chain, as well as create additional job opportunities for converting waste into feed.

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Table 1. Search term combinations

Integration	Roots, tubers and bananas	Other
integrated agriculture aquaculture	sweetpotato	crops, vegetables, dietary diversity, nutrition, consumption, food security
	cassava	
	yams	
	cocoyam	
	banana, musa, plantain	
pond dike system	sweetpotato	crops, vegetables, integrated, fish, dietary diversity, nutrition, consumption, food security
	cassava	
	yams	
	cocoyam	
	banana, musa, plantain	
fish feed	sweetpotato	aquaculture, waste, by-products
	cassava	
	yams	
	cocoyam	
	banana, musa, plantain	
Fish consumption	sweetpotato, orange-fleshed sweetpotato	nutrition, diet, health, dishes, food, value addition, product, complementary, pregnant, lactating
	cassava, yellow cassava	
	yams	
	cocoyam	
	banana, musa, plantain	

Table 2. Key informant interviews and assigned reference codes

Livelihood/Professional Association	Location	Reference code
Fingerling producer	Nilphamari district, Rangpur	RFING01
Farmer practicing fish polyculture	Nilphamari district, Rangpur	RPOLY02
Fingerling producer and fish feed dealer	Nilphamari district, Rangpur	RFNGFD03
Potato seed farmer	Nilphamari district, Rangpur	RPOTSD04
Research Scientist at BARI sub-station in Rangpur	Rangpur	RBARI05
Feed producer – SMS Feeds Ltd.	Gazipur, Mymensingh	MFEED06
WorldFish project household – Fingerling production in *hapa*	Mymensingh	MHAPA07
Rice mill and pond owner	Mymensingh	MRICE08
Fish market 'Trisal'	Mymensingh	MFSHM09
Professor at the Bangladesh Agricultural University – Horticulture Department.	Mymensingh	MBAU10
Professor at the Bangladesh Agricultural University – Faculty of Fisheries.	Rangpur	MBAU11
Professor at the Bangladesh Fisheries Research Institute	Rangpur	MBFRI12
Scientist at BARI – Sylhet sub-station	Sylhet	SBARI13
Professor at the Sylhet Agricultural University	Sylhet	SSAU14
Suchana Project Household	Sadar sub-district, Sylhet	SSUCH15
Suchana Project Household	Sadar sub-district, Sylhet	SSUCH16
Suchana Project Household	Sadar sub-district, Sylhet	SSUCH17
Suchana Project Household	Golapgonj sub-district, Sylhet	SSUCH18
BARI OFSP contract farmer	Sylhet	SOFSP19
Taro farmer	Sylhet	STARO20
WorldFish Senior Scientist, Bangladesh	Dhaka	WF21
WorldFish Fish Feed Specialist, Bangladesh	Dhaka	WF22
Scientist, International Potato Center, Bangladesh	Interview conducted via Skype	CIP23

Table 3. Features of identified production systems that integrate fish and RTB crops.

Name of IAA system	Country	Crops	RTB crops	Fish and other aquatic animals stocked in ponds	Livestock	Other	Author(s)
Crop-snailery-poultry-livestock-fish production system	Nigeria	Pineapple, papaya, maize, pumpkin, and waterleaf	Plantain	Catfish (spp.), Tilapia (spp.), Snakehead fish, and African Knifefish (*Gymnarchus* niloticus).	Poultry and pigs	Snails (*Archachatina* marginata) and *Achatina* achatina)	(Oribhabor and Ansa, 2006)
Undefined	Nigeria	Rice, fruit trees, and vegetable crops	Banana and plantain	Catfish (spp.), Tilapia (spp.)	Poultry, pigs, rabbits, sheep, goats, and cattle	N/A	(Miller *et al.*, 2006)
Undefined	Malawi	Maize, groundnut, indigenous vegetables, and guava	Banana *	Tilapia (spp.)	N/A	N/A	(Nagoli *et al.*, 2009)
Undefined	Thailand	Papaya, mango, tamarind, yard-long bean, tomato, chillies, cucumber, and onion.	Banana *	Catfish (sp.)	Chicken, ducks, and cows.	N/A	(Setboonsarg, 2002)
Undefined	Global	Aquatic plants, duck weeds, sugar cane, corn, sorghum, maize, and mulberry	Banana *	Carp (sp.)	Chicken, cattle, and ducks	Silkworms	(Al Mamun, Nusrat and Debi, 2011)
Sewage-duckweed-fish-banana integrated biosystem	Bangladesh	Duckweed	Banana	Carp (sp.)	N/A	Community waste water	(Warburton, Pillai-McGarry and Ramage, 2002)
Vuon-Ao-Chuong (Garden-pond-livestock pens)	Vietnam	Rice, corn, citrus, black bean, coconut, jackfruit, orange, bamboo, pineapple, jackfruit, guava, lime, lychee, langon, pomelo etc.	Banana, cassava, sweetpotato, and yam	Carp (*spp.*), Tilapia (*spp.*), Snakehead fish, Catfish (*spp.*) soft shell turtle and frogs	Buffalos, cows, pigs, chickens, and ducks		(Mohri *et al.*, 2013)
Pekarangan (Javanese homegardens)	Indonesia	Rice, maize, coconuts, spinach, leafy vegetables, orange, mango, jackfruit, guava, papaya, coffee, clove, etc.	Banana, cassava, sweetpotato, cocoyam, and yam	Unspecified	Chickens, cows, goats, and sheep		(Mohri *et al.*, 2013)
Pulses or potato-fish seasonal crop-fish system	Bangladesh	N/A	Potato	Unspecified	N/A	N/A	(Dey *et al.*, 2012)
Undefined	Thailand	Morning glory, rice, sugarcane, fruit, and vegetables	Cassava and banana	Catfish (sp.)	Buffalos, cattle, pigs,	Termites	(Pant, Demaine and

					ducks, and chickens		Edwards, 2004)

* Bananas commonly grown but not necessarily.

Table 4. Feeding trials incorporating RTB crop residues into fish feed published 2000 – 2019.

RTB crop	Crop part utilised	Fish species trialled	Author(s)
Cassava	Peel	Tilapia	(Mzengereza *et al.*, 2016) (Ubalua and Ezeronye, 2008) (Ojukannaiye, Mogali and Asuwaju, 2013) (Tachia, Ataguba and Abuh, 2016) (Dada, Adeparu and Malomo, 2015)
		Catfish	(Solomon and Abdulrasheed, 2018)
	Meal/flour	Tilapia	(Sine *et al.*, 2017)
		Catfish	(Abu *et al.*, 2010b) (Abu *et al.*, 2010a)
	Leaf	Tilapia	(Mzengereza *et al.*, 2016) (Tram *et al.*, 2011) (Chhay *et al.*, 2010) (Sine *et al.*, 2017)
		Catfish	(Da *et al.*, 2016) (Bichi and Ahmad, 2010) (Sutriana, 2007) (Tram *et al.*, 2011)
Sweetpotato	Peel	Tilapia	(Mzengereza *et al.*, 2016)
		Catfish	(Solomon, Okomoda, Oloche, 2015) (Olukunle, 2006)
	Meal/flour	Tilapia	(Mzengereza *et al.*, 2016) (Sine *et al.*, 2017)
	Leaf	Tilapia	(Adewolu, 2008) (Mzengereza *et al.*, 2016)
		Catfish	(Da *et al.*, 2016)
Yam	Peel	Catfish	(Lawal *et al.*, 2012) (Solomon and Abdulrasheed, 2018)

Cocoyam	Meal/flour	Catfish	(Aderolu, Lawal and Oladipupo, 2009)
	Leaf	Tilapia	(Mzengereza *et al.*, 2016)
Plantain	Peel	Catfish	(Lawal *et al.*, 2014) (Solomon and Abdulrasheed, 2018)
	Leaf	Tilapia	(Mzengereza *et al.*, 2016)

Note: In the table, Catfish and Tilapia species have been aggregated