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Integrating fish, roots, tubers and bananas in food systems: Opportunities and constraints

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RESEARCH PROGRAM ON Roots, Tubers and Bananas

CIP INTERNATIONAL POTATO CENTER

Integrating fish, roots, tubers and bananas in food systems: Opportunities and constraints

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List of abbreviations and terms

BARI	Bangladesh Agricultural Research Institute
BAU	Bangladesh Agricultural University
BFRI	Bangladesh Fisheries Research Institute
CIP	International Potato Center
CRP	CGIAR Research Program
DFID	Department for International Development
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FISH	CGIAR Research Program on Fish Agri-Food Systems
HKI	Helen Keller International
IAA	Integrated Aquaculture-Agriculture
IDE	International Development Enterprises
IITA	International Institute of Tropical Agriculture
OFSP	Orange-fleshed Sweetpotato
RAE	Retinol Activity Equivalents
RDA	Recommended Dietary Allowance
RTB	CGIAR Research Program on Roots, Tubers and Bananas
SBCC	Social and Behavior Change Communication
SDG	Sustainable Development Goal
WHO	World Health Organization

Executive summary

Introduction

Until recently, nutrition and health outcomes were not considered in the vast majority of agricultural policies, with micronutrient deficiencies receiving limited attention. Despite agricultural growth, undernutrition still persists and has now become a major threat to health in low- and middle-income countries. Nutrition-sensitive agricultural policies are essential in the pursuit of globally agreed nutrition targets. They aim to address the underlying determinants of micronutrient deficiencies by ensuring access to and adequate consumption of a variety of nutritious and safe foods. "Food-based approaches" are widely considered economically and ecologically sustainable approaches to agricultural development that could simultaneously alleviate food insecurity, malnutrition and poverty. Such food-based approaches require effective collaboration and co-ordination between sectors across the food systems.

This working paper is a collaboration between two CGIAR Research Programs (CRPs): Fish Agri-Food Systems (FISH) and Roots, Tubers and Bananas (RTB). This working paper documents linkages between fish, roots, tubers and bananas (RTB crops) within food systems; identifies opportunities for strengthened integration in production systems, animal feed and nutritional products; and identifies constraints and research gaps, and provides policy recommendations that support nutrition-sensitive food systems. This working paper looks into integrated aquaculture—agriculture (IAA) food systems globally, before focusing on two specific countries: Bangladesh and Nigeria. The research is mostly based on peer-reviewed publications, though it is complemented with illustrative accounts from academic professionals, farmers and consumers.

Findings

Integrated aquaculture-agriculture systems: Aquatic foods and roots, tubers and bananas

Bananas and plantain are the most commonly recorded group of RTB crops grown in IAA systems globally. Fish with cassava, sweetpotato, potato, yam and cocoyam are also documented, though to a lesser extent. A large proportion of the IAA systems identified in this working paper are geographically concentrated in South and Southeast Asia. However, in numerous cases, in which fish-crop farming is featured, authors have failed to specify which crops or vegetables they refer to. As a result, it is difficult to uncover the nature of and extent to which RTB crops are cultivated under such systems.

Fish feed: A focal area of integration

A relatively large and growing body of literature explores the viability of using selected RTB crops and their by-products as fish feed. Much of this research has been conducted in Nigeria, but there is growing interest happening in other geographical regions. Research that explores the use of non-conventional fish feed ingredients is commonly rationalized by the high costs of producing fish feed.

The majority of the 27 studies on fish feeds identified were "production-centric"—designed to investigate the effects of replacing a proportion of the conventional energy and protein sources with RTB crop derivatives, and the effects on fish growth performance and feed use. When comparing the trial diet to the conventional control diet, replacement was effective in terms of growth performance up to a certain replacement level (10%–75%). Additional and high quality research needs to be conducted to adequately determine the effects of replacement on fish growth performance and feed use.

Only a few studies identified in this working paper explore the economic implications of replacing conventional feed commodities with RTB crop residues and leaves. In addition, there is a definite lack of literature that attempts to position this topic within a food systems context and assess the dynamics (i.e. the scale of domestic production, spatial, temporal and technological considerations) that would determine whether these RTB crop derivatives could be effectively integrated as fish feed beyond laboratory trials.

Integration at consumption: The role of fish in complementary feeding

Evidence suggests that traditional cereal-based complementary foods for infants in many low-income countries can be nutritionally enhanced with the addition of micronutrient-rich small fish and vitamin A-rich orange-fleshed sweetpotato[1] (OFSP). For instance, a fish-based complementary food product, developed in Bangladesh, 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 old. Future projects should develop social and behavior change communication (SBCC) materials that educate caretakers on the nutritional benefits of feeding children these foods in combination.

Conclusion

The co-production and dynamic integration of fish and RTB crops show great synergistic promise at multiple scales. Efficient use of available resources, such as agricultural by-products and wastes of agro-processing industries which are widely available in many 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 to feed. As women make up the majority of the workforce in cassava processing units in Nigeria (85%), they could also benefit from the income-earning opportunities associated with these innovative cross-sector links.

Further field-based research is recommended to explore contextually appropriate solutions that enhance livelihood, environmental, and food and nutrition security outcomes.

Research and development priorities:

- Further research on incorporating RTB by-products into commercial fish feed should prioritize the following:
  - the effects of replacement on fish growth performance and feed use
  - economic implications
  - practical issues associated with the seasonality of RTB by-products, as medium- to large-scale cassava processing sites only operate seasonally.
- More information regarding the fish feeding practices of smallholder farmers is required to identify best practices for the use of RTB agricultural by-products as fish feed in homestead ponds.
- Efforts to identify contextually appropriate micronutrient-rich combinations of fish and RTB products, such as small indigenous fish and OFSP, should be expanded further to low-income countries, as well as to micronutrient-deficient populations, in which cereal-based complementary foods are commonly fed to young children.

Introduction

The contribution of agriculture to food and nutrition security

As the basis for food production, agriculture obviously makes a contribution to nutrition and is assumed to be a critical determinant of stunting and micronutrient deficiency (Turner et al. 2013; McDermott et al. 2015). Yet, despite agricultural growth, undernutrition still persists and is a major threat to health in low- and middle-income countries (Turner et al. 2013). A historical emphasis on supply-side production of staple commodities in agricultural and food policies is partly to blame (Tontisirin et al. 2002; McDermott et al. 2015). Tontisirin et al. (2002) proclaim that micronutrient outcomes were not considered in the vast majority of these past agricultural policies. Instead, these policies focused on the provision of macronutrients, such as carbohydrates as the energy source and protein provided by staple foods, particularly grains, such as rice, wheat and maize (Babu et al. 2017). The Green Revolution, for example, contributed to rapid growth in food production, poverty reduction and increased household energy consumption. This mostly took place between the 1940s and 1960s and intended to address the challenges of insufficient food faced by many developing countries at the time. But since efforts were mainly focused on increasing the production of staple foods, the Green Revolution often led to a monoculture of rice, wheat and maize. These displaced other nutrient-rich crops and reduced crop diversity in a number of developing countries, with considerable consequences in terms of nutrition outcomes (Headey and Hoddinott 2016; Babu et al. 2017).

Today, agricultural policies and programs increasingly seek to address malnutrition through both nutrition-specific interventions and nutrition-sensitive approaches to agriculture (Fiorella et al. 2016), especially targeting women and children in the first 1000 days of life, from conception to 2 years of age. The first 1000 days are a critical period to promote optimal growth and development of infants and young children and to prevent growth faltering, micronutrient deficiencies and childhood illness (Cusick and Georgieff n.d.; Prado and Dewey 2014).

Nutrition-specific interventions directly target immediate causes of undernutrition, such as inadequate dietary intake and ill health, through iron or folic acid supplementation to pregnant women, fortification of staple foods with micronutrients and nutrition education (Fiorella et al. 2016; Ruel et al. 2018; Transform Nutrition 2019). Supplementation and fortification are commonly deployed strategies for micronutrient deficiencies because they are cost-effective and, to some extent, relatively easy to deliver (Allen 2003). Much of the progress achieved over the last century in curbing malnutrition is attributed to be through nutrition-specific interventions (Fiorella et al. 2016).

On the other hand, nutrition-sensitive agriculture is defined as

> “*An approach that seeks to ensure the production of a variety of affordable, nutritious, culturally appropriate and safe foods in adequate quantity and quality to meet the dietary requirements of populations in a sustainable manner (FAO 2017, viii)*”

Nutrition-sensitive interventions are referred to as “food-based” approaches that aim to address the underlying determinants of micronutrient deficiencies—meaning access to and adequate consumption of a variety of nutritious and safe foods (Tontisirin et al. 2002; FAO 2017; Ruel et al. 2018).

More recently, collaboration and co-ordination between agricultural sectors and across food systems are increasingly considered instrumental as the international agricultural community, among others, works toward global nutrition targets. Thus, research that seeks to accomplish the following is highly relevant and increasingly important to (1) identify how and to what extent integration, rather than specialization of agricultural subsectors, could relieve the ecological, sociopolitical and economic pressures that farming households face, and (2) help tackle the multiple burdens of malnutrition. Integrated aquaculture-agriculture (IAA) systems such as fish-rice farming and fish-livestock farming are widely considered economically and ecologically sustainable approaches to agriculture development that could simultaneously alleviate food insecurity, malnutrition and poverty (Little and Edwards 2003; Ahmed and Garnett 2011; Ahmed et al. 2014). Since the late 1990s, these systems specifically have received considerable attention in the literature.

Integration between fish and roots, tubers and bananas (RTB crops) is described and discussed in this working paper as one area for potential collaboration which has received minimal attention. This working paper has been conducted in the framework of a collaboration between two CGIAR Research Programs (CRPs): FISH, led by WorldFish, and RTB, led by the International Potato Center (CIP).

RTB crops, including but not limited to cassava (*Manihot esculenta*), sweetpotato (*Ipomea batatas*), potato (*Solanum tuberosum*), yam (*Dioscorea* spp.), cocoyam (*Colocasia* spp. and *Xanthosoma* spp.), banana and plantain (*Musa* spp.), have cultural, dietary and economic importance worldwide (CIP FOODSTART+ 2018). Globally, more than a billion people eat potato as a staple, and cassava is considered to be the third-most important food crop in the tropics, after rice and maize (CIP FOODSTART+ 2018; CIP 2018a). Just 100 g of boiled orange-fleshed sweetpotato (OFSP) root contains enough beta-carotene to provide 100% of the recommended dietary allowance (RDA) of vitamin A for children (Low et al. 2017). Thus, because of their popularity and nutritional quality, many RTB crops have great potential to reduce the global prevalence of hunger and malnutrition. As a result of their resilience, these crops can also help farmers adapt to climate change and related extreme weather events (CIP 2018a, Prain and Naziri 2020).

Fish and other aquatic animal products are also of key nutritional significance. Fish, especially small fish, are an important source of micronutrients including calcium, iron, zinc, vitamin A and vitamin B12, as well as essential fatty acids and protein (Longley et al. 2014; Fiorella et al. in press). Data suggests that at least one billion people globally depend on fish as their main animal-source food (Genschick et al. 2015). In 2015, fish provided about 3.2 billion people with about 20% of their average per capita intake of animal protein (FAO 2018). Yet, while there is much discussion around the impact of agriculture on nutrition, fisheries are scarcely acknowledged within relevant agriculture-nutrition global policy arenas and the Sustainable Development Goals (SDGs). The importance of fisheries in local and global food systems, and their contribution to nutrition and health, is overlooked and undervalued (Thilsted et al. 2016).

The purpose of this working paper is to document links among fish and RTB crops within agri-food systems and identify opportunities for strengthened integration in production systems, animal feed and nutrient-rich food products. This report identifies constraints and research gaps and provides policy recommendations that support nutrition-sensitive IAA food systems. The research is mostly based on publications, though it is complemented with illustrative accounts from researchers, development practitioners, farmers and consumers.

This working paper provides a global overview before directing its focus on two countries, Bangladesh and Nigeria, because there is some evidence that IAA food systems already exist or that work exploring potential collaboration between these two food systems is underway. For instance, cassava has been explored for its potential in livestock and aquaculture feeding projects in Nigeria (Lukuyu et al. 2014). OFSP has been included with small fish in complementary food products for young children in Bangladesh (Bogard et al. 2015), and cultivating fish and OFSP in home gardens has been promoted to improve dietary diversity and the nutritional status of household members in northern Bangladesh (Save the Children n.d.). However, the extent of, potential and challenges associated with IAA food systems in these two countries are unclear and poorly documented.

Background: Key concepts and framework for analysis

Integrated aquaculture-agriculture

Integrated agriculture is a specific typology of agriculture, whereby agricultural production is diversified from the landscape level to smallholder plots. The term broadly includes farm management practices such as crop rotation and intercropping, and encompasses the integration of agricultural subsystems, including aquaculture, fruit and vegetable production, and livestock husbandry, which are thought to improve both the use of space and resource management (Hendrickson et al. 2008). The term is used broadly, however, and the concept interpreted variously.

Integrated aquaculture-agriculture (IAA) is commonly equated with two-component agricultural systems: fish-rice or fish-livestock (Edwards 1998). Synergistic recycling and reuse of farm-produced organic residues and by-products are commonly cited characteristics of integrated agriculture as well as IAA (Little and Edwards 2003). For many scholars (Edwards 1998; Karim and Little 2018) dynamic interactions like the recycling of outputs from one subsystem, which otherwise might have been wasted, into an input of another subsystem is a defining feature of IAA. For example, using livestock manure directly in fish culture increases the production of phytoplankton, which is a natural source of fish food. In turn, harnessing nutrients from what might be considered agricultural "waste" is expected to reduce the need for commercial fertilizers, which are commonly applied to ponds to serve the same phytoplankton-producing function (Edwards 1998). To some extent, the system mimics the way natural ecosystems function. In that regard, IAA also satisfies environmental aims (Hendrickson et al. 2008). Additionally, Edwards (1998) asserts that integrated systems should also function to improve people's livelihoods and their welfare, rather than being solely concerned with production objectives. In light of this, integrated agriculture has also been referred to as "multiple-goal agriculture" (Pearson and Ison 1992).

A more holistic conceptualization of IAA extends the focus from relatively simple two-component systems to multicomponent systems that include sequential, in addition to concurrent, links between subsystems, (1) the dynamic use of off-farm resources and agricultural by-products, which can be produced at separate locations and by different people, yet be integrated, and (2) links between agricultural and human activities, for example, the reuse of human excreta or sewage in agricultural production, or the culture of fish in heated effluents of power plants (Prein 2002; Little and Edwards 2003; Ahmed et al. 2014).

Moreover, integrated systems can operate over a variety of scales, ranging from small- to large-scale systems that are fully market orientated (Prein 2002). For instance, large quantities of homogenous wastes produced during the rice milling process, such as rice husk and rice bran, are reused as fish feed (Esa et al. 2013).

Thus, IAA can be comprehensively defined as the following:

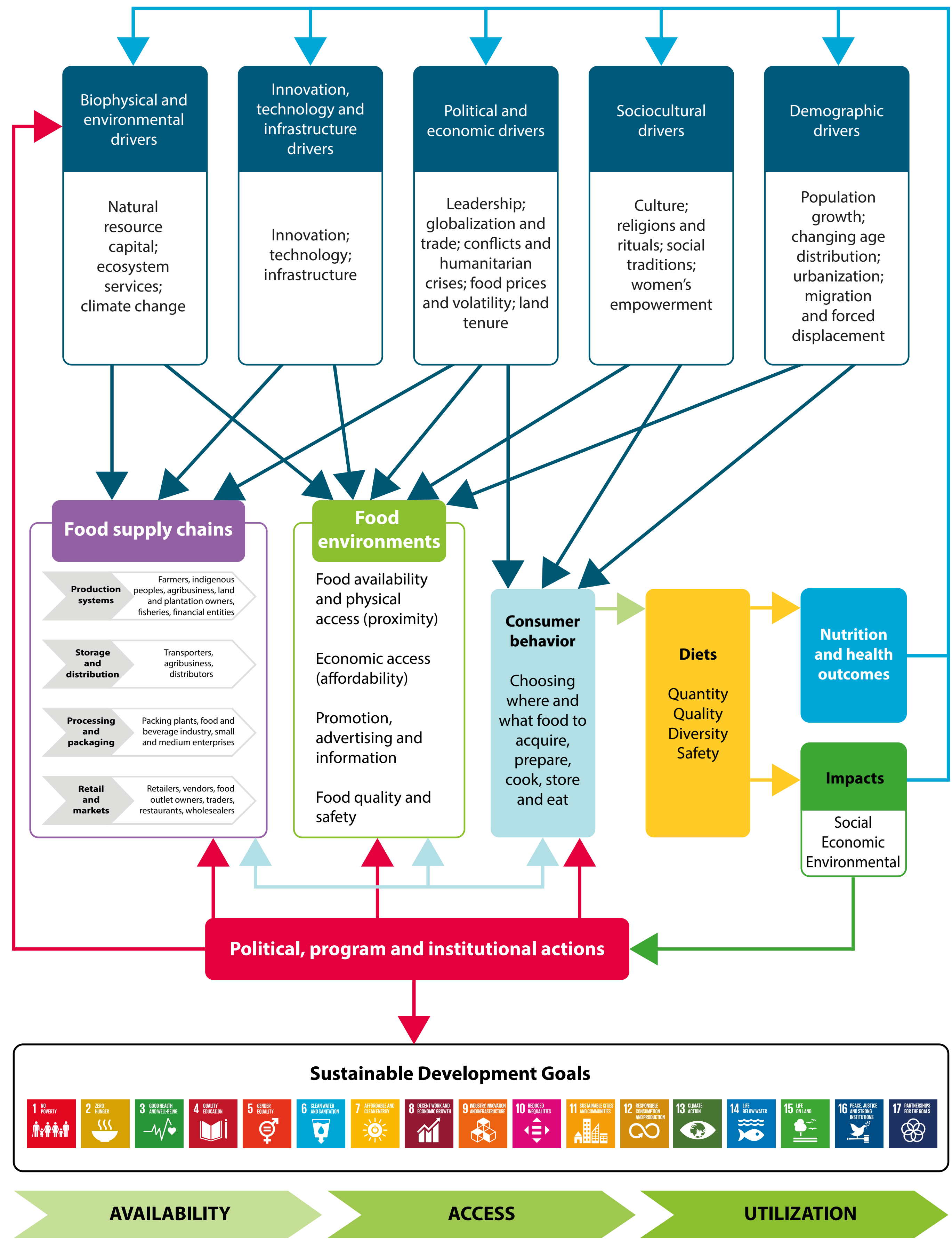
> *Concurrent or sequential linkages between two or more human activity systems (one or more of which is aquaculture), directly on-site, or indirectly through off-site needs and opportunities, or both.*
>
> ***— Edwards 1998, 5***

Approaches to understanding integrated aquaculture-agriculture: A food systems perspective

A systems approach recognizes that IAA comprises a range of complex systems involving various interrelated factors (Hendrickson et al. 2008). To sufficiently comprehend IAA systems and how they function, it is necessary to study the wider political, social, cultural, economic and environmental context (Edwards 1998), especially as food systems today are increasingly globalized and thus influenced by broader political and economic processes that extend beyond national borders (Ericksen et al. 2010). These processes are not static, as food systems react to trends and change drivers across national and international boundaries (Grant 2015). Therefore, looking beyond the specific focus area or focus sector is crucial to truly understand the food systems context and, in turn, design effective nutrition-sensitive interventions that simultaneously avoid adverse effects to planetary health.

This report takes analytical guidance from the conceptual framework of food systems for diet and nutrition (Figure 1) from the High Level Panel of Experts on Food Security and Nutrition (2017). As Figure 1 illustrates, a food systems perspective incorporates the various stages of the food supply chain: production, processing, marketing and consumption.

Parvin and her family having a meal with small indigenous fish and orange-fleshed sweetpotato leaves, Kadirpara village, Jessore District, Bangladesh.



Source: High Level Panel of Experts on Food Security and Nutrition 2017.

Figure 1. Conceptual framework of food systems for diet and nutrition.

Methodology

Literature review: Search strategy

Publications were sourced using the webpages of pertinent government organizations, development practitioners and research institutions, such as WorldFish and CIP, as well as various 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 combinations, such as "fish feed" and "sweetpotato." However, the most appropriate publications were commonly found by consulting the reference lists of key "springboard" publications. Reviewed literature was also identified through the "cited by" function on many of the databases. This provided more recent publications, which is useful when reviewing knowledge progression.

Integration	Roots, tubers and bananas	Other
Integrated aquaculture-agriculture	Sweetpotato	Crops, vegetables, dietary diversity, nutrition, consumption, food security
	Cassava	
	Yam	
	Cocoyam	
	Banana, plantain	
Pond dike system	Sweetpotato	Crops, vegetables, integrated, fish, dietary diversity, nutrition, consumption, food security
	Cassava	
	Yam	
	Cocoyam	
	Banana, plantain	
Fish feed	Sweetpotato	Aquaculture, waste, by-products
	Cassava	
	Yam	
	Cocoyam	
	Banana, plantain	
Consumption, fish	Sweetpotato, OFSP	Nutrition, diet, health, dishes, food, value addition, product, complementary, pregnant, lactating
	Cassava, yellow cassava	
	Yam	
	Cocoyam	
	Banana, plantain	

Table 1. Search term combination.

Eligibility criteria

Papers were considered eligible and valid for inclusion if the text

- contained evidence of synergy between fish and at least one RTB crop;
- was published after the year 2000;
- was produced in English;
- was evaluated to be of good quality considering the following aspects: (a) the quality of the journal the text was published in (according to Scimago Journal & Country Rank (www.scimagojr.com)); (b) the reputation of the publishing institution; (c) whether or not the author's arguments were objective and balanced, such as considering contrary positions and data; and (d) if the author's arguments were supported by primary evidence.

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 crops, as well as on-the-ground evidence of such links, through a food systems lens while paying particular attention to food and nutrition security.

Papers were reviewed exhaustively until the publications did not contribute to new insights to the topic, or within the demarcated timeframe (since 2000). Available literature on this topic was scarce before the year 2000.

This literature review made use of the qualitative coding software NVivo (version 12.2.0) to (1) categorize papers, such as according to publication date, research methodology, location of study, and (2) code extracts of texts into topics, themes for analysis.

Primary data collection

Semi-structured interviews were conducted with academic professionals, fish feed manufacturers, fish feed dealers, fish farmers, farmers growing RTB crops, and households in four divisions of Bangladesh: Dhaka, Mymensingh, Rangpur and Sylhet. Primary qualitative data collection was considered a worthwhile contribution to the literature review findings. It was evident that there was (1) a lack of information on the potential use of RTB crops in fish feed in Bangladesh in comparison to Nigeria (2) a general lack of detail about the crops grown in integrated aquaculture-agriculture home gardens, and (3) few publications that evidenced the consumption of fish with RTB crops in traditional dishes, snacks and complementary feeding. Primary data collection was expected to reveal such instances, if any, yet also help to explain why this topic receives comparatively little attention.

A total of 22 semi-structured interviews were carried out. All but one were conducted face-to-face during a 2-week field visit to Bangladesh, while the remaining one was conducted via Skype. Market prices for various fish species were also observed and noted during a visit to the Trisal fish market in Mymensingh. Basic details of the interviewees are in Appendix 1, along with the associated reference codes which are used as citations in the text that follows.

Each interview was guided by a list of pre-identified, open-ended questions (Appendix 2). Key informants from WorldFish, CIP, the Bangladesh Agricultural University (BAU) and the Bangladesh Fisheries Research Institute (BFRI), for example, were identified using expert sampling strategy, a subtype of purposive sampling, and selected for their topical knowledge (Bryman 2012). Fingerling producers, fish farmers, RTB farmers and project beneficiaries were also purposively sampled, using the critical case sampling method.

These respondents were selected because they were known to (1) have integrated fish and RTB crop production; (2) potentially use alternative aquafeed ingredients, including RTB by-products; and/or (3) could provide contextual insight into the fish and RTB food systems in Bangladesh.

Findings and discussion

An overview

The various search methodologies produced 46 eligible documents, of which 33 are peer-reviewed journal articles and the remaining 13 documents consist of books or book sections (3), institutional reports and working papers (7), conference proceedings (2) and a MSc thesis (Appendix 3). None of the texts was uncovered to be published in so-called predatory journals, and 15 of the 33 journals incorporated were listed in the Scimago Journal and Country Rank database.

IAA production systems are not short of literary attention. There is a substantially large body of literature that investigates and mostly promotes this approach to agriculture. Fish-rice farming and, to a lesser extent, fish-livestock farming are notably discussed and presented in peer-reviewed and grey literature (such as in Ahmed and Garnett 2011, and Ahmed et al. 2011).

However, fish-crop farming, excluding rice, is given comparatively less attention. In addition, in cases in which fish-crop farming is featured, authors have failed to specify which crops or vegetables they refer to (such as Karim and Little 2018). This reduces the contextually diverse array of agricultural products grown under these circumstances to an umbrella heading. As a result, it is difficult to uncover the nature of and extent to which RTB crops are cultivated under such systems. Specific mention was made to RTB crops in 10 documents identified in this review (Appendix 3). However, half of these documents only superficially listed RTB crops as one of the crops grown in the featured integrated production system.

On the other hand, if IAA systems are conceptualized more holistically to include sequential, as well as concurrent interactions, which can occur on or off-site, specific interactions between fish and RTB crops become more evident.

A relatively large and growing body of literature explores the viability of using selected RTB crops as fish feed. Cassava, sweetpotato, cocoyam and yam, among other crops, are generally regarded by fish nutritionists as highly nutritious, cheap and locally accessible fish feed ingredients. Accordingly, 26 of the papers reviewed explore laboratory-based feeding trials or review other literature on productivity-related outcomes of incorporating cassava peels into farm-produced and commercially pelleted feeds.

In addition, 11 documents (eight peer-reviewed journal articles, one conference proceeding, a book chapter and a report) detailing integration between fish and a RTB at the point of consumption were also identified. Four described local dishes that included both fish and one RTB crop (Karuri et al. 2001; Ezeh et al. 2011; Sharma et al. 2016; Talsma et al. 2018). The remaining seven peer-reviewed publications (one review paper and six research papers) broadly detailed the development of "value-added" complementary food products (Nandutu and Howell 2009; Bogard et al. 2015) and the nutritional enhancement of traditional snacks, using fish and one RTB crop (Cliffe and Okereke 2010; Neiva et al. 2011; Akonor et al. 2017; Rochimiwati et al. 2017).

The content of these texts will be described and discussed in more detail in the sections that follow.

Integrated aquaculture-agriculture systems: Fish, roots, tubers and bananas

Globally, "traditional" IAA systems tend to share the same basic structure—a pond, garden and livestock. However, the composition is contextually specific. The particularities between and within regions depend on many factors, including the financial resources available to the individual, climatic conditions, ecological attributes, individual and cultural consumptive preferences, market orientation, accessible market opportunities, availability of labor, land tenure, management objectives and agricultural knowledge (Mohri et al. 2013).

As Table 2 illustrates, in the documents identified using the search terms featured in Table 1, banana and plantain are the most commonly recorded group of RTB crops grown in IAA systems globally.

Name of IAA system	Country	Crops	RTB crops	Fish and other aquatic animals stocked in ponds	Livestock	Other	Author(s)
Fish-snailery-crop poultry-livestock-production system	Nigeria	Pineapple, papaya, maize, pumpkin, waterleaf	Plantain	Catfish, tilapia , snakehead fish, African knifefish (*Gymnarchus* niloticus)	Poultry, pig	Snails (*Archachatina marginata*) and *Achatina achatina*)	Oribhabor and Ansa 2006
N/A *Overview of various integrated aquaculture systems, which does not include all of these components	Nigeria	Rice, fruit trees, vegetable crops	Banana and plantain	Catfish, tilapia	Poultry, pig, rabbit, sheep, goat, cattle	N/A	Miller et al. 2006
N/A *Bananas grown on some farms	Malawi	Maize, groundnut, indigenous vegetable, guava	Banana	Tilapia	N/A	N/A	Nagoli et al. 2009
N/A *Bananas commonly grown though not necessarily	Thailand	Papaya, mango, tamarind, yard-long bean, tomato, chilli, cucumber, onion	Banana	Catfish	Poultry, cattle	N/A	Setboonsarg 2002
N/A *Bananas commonly grown though not necessarily	Global	Aquatic plants, duckweed, sugar cane, corn, sorghum, maize, mulberry	Banana	Carp	Poultry , cattle	Silkworms	Mamun et al. 2011
Sewage-duckweed-fish-banana integrated biosystem	Bangladesh	Duckweed	Banana	Carp	N/A	Community waste water	Warburton et al. 2002
N/A	India	N/A	Banana	Carp spp.	N/A	N/A	Biswas 2004
Vuon-Ao-Chuong (Garden-pond-livestock pens)	Vietnam	Rice, corn, citrus, black bean, coconut, jackfruit, orange, bamboo, pineapple, jackfruit, guava, lime, lychee, longan, pomelo, etc.	Banana, cassava, sweetpotato, yam	Carp, tilapia, snakehead fish, catfish, soft shell turtle, frog	Buffalo, cattle, pig, chicken, duck		Mohri et al. 2013
Pekarangan (Javanese home gardens)	Indonesia	Rice, maize, coconut, spinach, leafy vegetables, oranges, mango, jackfruit, guava, papaya, coffee, clove, etc.	Banana, cassava, sweetpotato, cocoyam, yam	Unspecified	Chicken, cattle, goat, sheep		Mohri et al. 2013
Pulses or fish-potato Seasonal Fish-crop system	Bangladesh	N/A	Potato	Unspecified	N/A	N/A	Dey et al. 2012
N/A	Thailand	Morning glory, rice, sugarcane, fruits, vegetables	Cassava, banana	Catfish	Buffalo, cattle, pig, poultry	Termite	Pant et al. 2004

Table 2. Features of identified integrated aquaculture-agriculture systems.

Eight out of the 10 selected documents note, and in some cases describe, situations in which mostly bananas, and sometimes plantains, are integrated with fish in the same production system. Cases including cassava, sweetpotato, potato, yam and cocoyam with fish are also documented, though to a lesser extent.

In addition, among even the small number of documents identified in this review, a pattern of geographical predominance has emerged in which a larger proportion of the cases of IAA systems featuring fish and RTB crops is from South and Southeast Asia.

Bananas and plantains are grown as major cash and/or food crops within IAA systems in Bangladesh (Warburton et al. 2002), Indonesia (Mohri et al. 2013), Thailand (Setboonsarg 2002), Vietnam (Mohri et al. 2013), Malawi (Nagoli et al. 2009) and Nigeria (Miller et al. 2006; Oribhabor and Ansa 2006) (Table 2). In addition, root and tuber crops are also commonly found in IAA systems in Indonesia, Vietnam (Mohri et al. 2013) and Thailand (Pant et al. 2004).

In Bangladesh, over 1000 ha of land were used for pulses or fish-potato cultivation in 2011 (Dey et al. 2012). Potato or pulses are grown during the dry season, followed by fish culture in the wet season. (Their cultivation does not have to be simultaneous for the system to be considered as "integrated.") This practice more commonly occurs in the Khulna and Rangpur administrative divisions (Dey et al. 2012).

On the other hand, in traditional Javanese home gardens, locally known as *pekarangan*, crops, fish and livestock 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 chicken, cattle, goat and sheep, are also an important feature of Javanese home gardens (Mohri et al. 2013). According to Mohri et al. (2013), 20% of the total area of West Java is occupied by home gardens. These vary in size from a few square meters to several hectares (about 0.4–0.6 ha on average). Figure 2 illustrates a typical Javanese home garden or *pekarangan* system.

Recorded interactions between aquaculture and RTB production

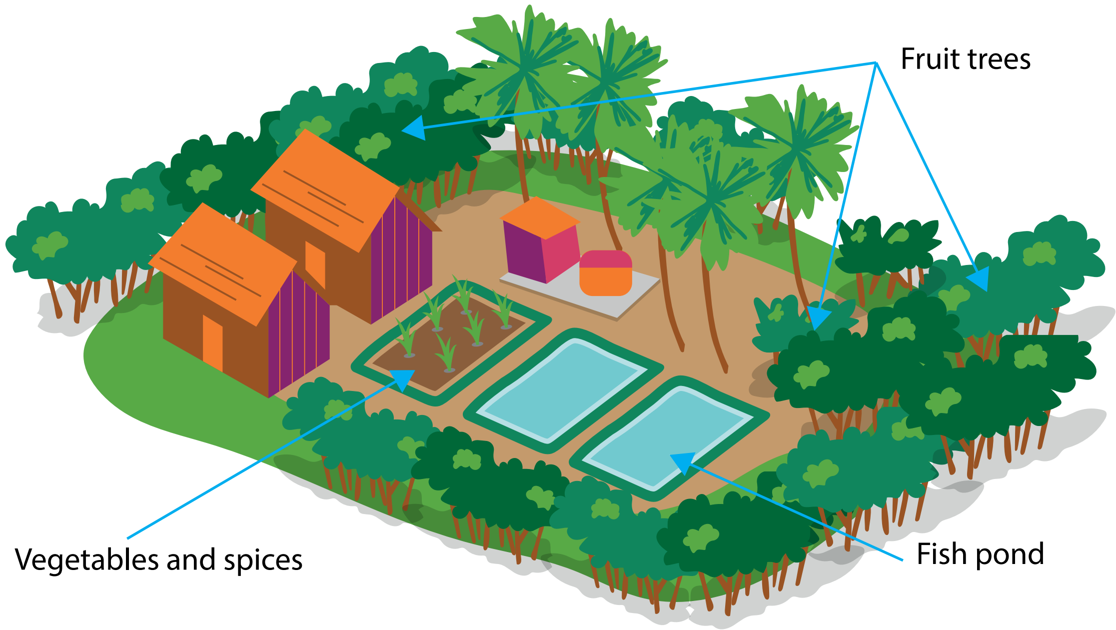
According to the literature, IAA farmers similarly benefit from reclaiming, recycling and reusing nutrients and organic "waste." For instance, water from the pond is used to irrigate the various crops (Miller et al. 2006; Nagoli et al. 2009; Mohri et al. 2013). Oribhabor and Ansa (2006) report that interviewed farmers in the Niger Delta 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 et al. 2004; Mamun et al. 2011). In addition, farmers often use excess pond silt as a fertilizer and apply it directly to boost crop production (Oribhabor and Ansa 2006; Mamun et al. 2011).

Furthermore, vegetable waste is, in some cases, reclaimed to assist fish production (Mamun et al. 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 et al. 2004). Research from Pant et al. (2004) in northeast Thailand reported that over 50% of the 234 IAA practicing households interviewed applied crop by-products to their ponds. Similarly, in both Javanese *pekarangan* and Vietnamese IAA systems, vegetables from the garden are used as feed for fish and livestock in addition to being sold and consumed by humans (Mohri et al. 2013).

Beneficial outcomes of integrated aquaculture-agriculture systems

The identified literature suggests that IAA systems, when compared to commercially oriented monocropping, are generally beneficial for soil conservation, biodiversity, livelihoods, household food and nutrition security.

The identified articles discuss these benefits, though they refer broadly about the system-based benefits rather than distinguishing the advantages of integrating fish with RTB crops in particular. Just a few of the identified documents outline the suspected nutritional benefits of IAA systems compared to the monocropping of rice. However,



Source: Adapted from Mohri et al. 2013.

Figure 2. Javanese home garden or *pekarangan* system.

since this was not a topic of research it is not evidence-based. The following section also draws upon a wider set of published literature to discuss the potential benefits and challenges of integrated fish-RTB systems, though it is limited to discussing the benefits for livelihoods and nutrition at the homestead level.

A resource management strategy for increased and more stable agricultural incomes

Mamun et al. (2011) position IAA as a "resource management strategy" as, according to them, diversifying land use through the integration of aquaculture, crops and often livestock optimizes 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 15 times higher than rice farming.

Increases in income are also likely influenced by reductions in the volume and cost of off-farm inputs—a reduction enabled by the reuse of farm wastes and crop by-products (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. They state that this allowed small-scale farmers to increase cropping intensity and enabled farmers to grow higher value crops. For these reasons, IAA is positioned as particularly appropriate for small-scale, poor farmers (Nhan et al. 2007; Ahmed et al. 2014).

IAA also ensures a steady food supply and cash income through potentially year-round or "off-season" agricultural production (FAO 2000; Nagoli et al. 2009). IAA farmers may be able to exploit seasonally high market prices of agricultural products by selling produce in lean periods. For poor farmers, especially, diversifying production is said to reduce the risk from diseases, water quality, price fluctuations and low profit margins that are often associated with stand-alone fish farms (FAO 2000; Prein 2002; Little and Edwards 2003; Sibhatu et al. 2015). However, there is a lack of large-scale, quantitative data to triangulate these accounts.

Nutritional outcomes

In home gardens, IAA is expected to increase the availability of high-value animal protein, improve food security by somewhat addressing seasonal "lean" periods in food supply, contribute to dietary diversity, and thus improve the nutritional status of people in farming households.

Numerous studies have recorded greater fish consumption associated with the adoption of aquaculture into agricultural systems at the homestead level. Jahan and Pemsl (2011) studied the impact of long-term IAA training in Bangladesh and found that the average per capita consumption of fish, vegetables and potato increased significantly during the project period and that increases in the consumption of these foods were not matched in control households. Similarly, Brummett and Jamu (2011) detail a 208% increase in fresh fish consumption and a 21% increase in dried fish consumption as an outcome of IAA adoption in Malawi. Moreover, Ahmed and Garnett (2011), outlined the dietary benefits of shifting from rice monoculture to integrated rice-fish farming in Bangladesh, and claimed that integrated rice fields contributed to a greater balance in household diets and consumption of fish (Ahmed and Garnett 2011). In addition, Mohri et al. (2013) expressed the importance of the food produced in home gardens during "lean" periods when there is a general decrease in the amount of food and financial resources available.

Although these studies record an increase in fish consumption, they do not specify important parameters such as the size or species of the fish being consumed. As the nutritional value of a fish depends on the size, species and the way it is prepared, cooked and consumed, the nutritional benefits associated with increased fish consumption are varied.

Dietary diversity

Agricultural diversification is believed to contribute to dietary diversity through both subsistence-based and income-generating pathways (Jones 2017). Dietary diversity is defined as "the number of different foods or food groups consumed over a given reference period" (Ruel 2003). Adequate dietary diversity is a key component of healthy diets and is associated with nutrient adequacy as the consumption of a variety of foods is necessary to meet essential nutrient requirements (Ruel 2002). Dietary diversity has been shown to be positively associated with (1) the micronutrient adequacy of the diet of both breastfed and non-breastfed children, adolescents and adults; (2) the nutritional status of children under 5 years old and women (United Nations Standing Committee on Nutrition: Task Force on Assessment n.d.); and (3) child growth in a number of studies in developing countries (Ruel 2002).

A lack of diversity in diets is an issue among poor populations, particularly in low-income countries (Arimond and Ruel 2004). For most poor people in low-income countries, their diet consists predominantly of starchy staples, generally few or no animal-source foods and few or only seasonal fruits and vegetables (Arimond and Ruel 2004). Such a diet tends to be low in a number of micronutrients, and in plant-based diets specifically, the micronutrients present are often in forms that are not easily absorbed (Ruel 2003). As such, various health and nutrition-focused international development organizations, including Helen Keller International (HKI), have designed nutrition-sensitive agricultural programs to encourage homestead production diversity with the goal to improve the consumption of a greater variety of fruits, vegetables and animal-source foods (Helen Keller International n.d.; Olney et al. 2009).

IAA systems, specifically diversified production, on smallholder farms are widely perceived as a useful approach to improve dietary diversity, both directly and indirectly (Prein and Ahmed 2000; Sibhatu 2015). In brief, it is hypothesized that a smallholder that produces a greater variety of agricultural products is more likely to "directly" consume a greater variety of these products grown on-farm, based on the assumption that households set aside at least a proportion of their agricultural produce for their own consumption. The various food crops, fruits, vegetables and animal-source foods produced in Javanese home gardens, for example, provide households with a diverse source of carbohydrates, protein, vitamins and minerals (Mohri et al. 2013). 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 2015).

According to Prein and Ahmed (2000), studies to assess the contribution of IAA systems to improved food and nutrition security were initiated about two decades ago, and a number of studies have been conducted since. However, as reported by Sibhatu et al. (2015), empirical evidence on the relationship between production diversity and consumption diversity specifically remains relatively scarce. According to Sibhatu et al. (2015), on-farm production diversity is positively associated with dietary diversity in some situations, and the direction and strength of the relationship is situation-specific. In a relatively recent published review paper, Jones (2017) found that 90% of the

21 identified studies examining the association between agricultural biodiversity and nutritional outcomes observed a positive association between agricultural biodiversity and dietary diversity. However, they note that the magnitude of this association is small—just a one unit increase in crop species richness was associated with a 0.01 to 0.25 unit increase in the number of food groups consumed by households (Jones 2017).

Challenges

Production diversity versus market diversity

Sibhatu et al. (2015) suggest that additional factors, such as market access, also have positive effects on dietary diversity—perhaps even a larger effect than on-farm production diversity. They also argue the idea that on-farm production diversity will inevitably lead to increased dietary diversity is too simplistic, because it assumes that the farm provides all, or at least a greater, supply of household food than the market. They also claim that households with higher incomes have more diverse diets than subsistence farms, on average, as they have greater financial access to a diverse range of foods from the market, and the market is believed to provide more diverse foods than any individual household can produce. As a result, Sibhatu et al. (2015) propose that the commercialized production of cash crops and cash earnings from off-farm activities contribute to dietary diversity and that this diversity acquired from the market cannot be fully substituted through diverse subsistence production. In their opinion, increasing the nutritional status of poor households, in low-income countries, more likely requires interventions that facilitate market access rather than promoting further production diversification. However, the role of production diversity versus market diversity is widely debated (Bellon et al. 2016).

Knowledge and time requirements

The adoption of IAA is not without challenges. IAA is widely regarded as "knowledge-intensive" as successful application largely requires technical knowledge of the production system (Little and Edwards 2003; Tran et al. 2013; Limbu et al. 2017). This is particularly true for those who do not already have a pond. In addition, introducing fish culture to traditionally crop-based home gardens can potentially increase workloads for certain family members (Little and Edwards 2003). In many situations, women bear a disproportionate burden of on-farm labor, particularly where more labor is required for tasks that are predominantly considered as roles for women, such as sowing, harvesting and fertilizer application, though these vary in different societal contexts (Setboonsarg 2002; Halbrendt et al. 2014). As a result, interventions must consider the potentially uneven labor-related impacts of IAA for women and men.

Temporal and spatial mismatches

Residues from crop harvests, which can be used as pond inputs, might only be available at specific times of the year, although they are required for the duration of fish production. In addition, the period when the crop residues are available may not appropriately synchronize with fish production cycles or seasons (Prein 2002).

As Prein (2002) explains, small-scale rural farms are often fragmented. Homesteads, fish ponds and crop plots 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.

Case study: Suchana project, northeast Bangladesh

The following section presents a case study of integrated homestead production of fish and RTB crops in northeast Bangladesh.

Locational and programmatic context

Suchana: Ending the Cycle of Undernutrition in Bangladesh is a multisectoral, 6-year project led by Save the Children. It is funded by the Department for International Development (DFID) and the European Union (WorldFish n.d.) and supported through a consortium of partners, including WorldFish, HKI and International Development Enterprises, among others. The project aims to address regionally high rates of malnutrition in the Sylhet and Moulvibazar districts in the northeast of the country through nutrition-sensitive and nutrition-specific interventions (Suchana n.d.).

There are nearly 10 million people living in Sylhet Division, and 68% live below the international poverty line of USD 1.25 a day (WorldFish 2017a). The scale of poverty in this area is just one of the factors believed to contribute to the prevalence of chronic undernutrition and exceptionally high rates of infant and under-5 mortality—55 and 67 per 1000 children, respectively, in 2014 (NIPORT et al. 2016). The limited availability and affordability of land and food also contribute to the poor nutritional status of households in the region (WorldFish 2017a). Even though nutritious foods are available locally, they are not necessarily affordable, especially for the poorest households (Ferdous et al. 2016; WorldFish 2017a). While subsistence-based food production can provide a direct and low-cost source of nutritious foods, there is reportedly little homestead vegetable, fish and poultry production in the division, so households tend to rely heavily on the staple food, rice. As a result, diets are visibly low in diversity and often lack nutritional quality (WorldFish 2017a). However, traditional food habits also restrict diets (Thilsted and Wahab 2014). According to Ferdous et al. (2016), average consumption of vegetables and fruits in Bangladesh, assessed at 126 g/capita/day, is far below the minimum recommended daily consumption of 400 g/capita/day.

Under the Suchana project, consortium partners are promoting the homestead production and consumption of micronutrient-rich small fish and vitamin A-rich OFSP.

Fish and vegetable cultivation on homesteads in Bangladesh is of particular significance, with about 62% of farmers characterized as landless (Ferdousy et al. 2018). The size of home gardens in Bangladesh ranges from 0.004 to 0.08 ha. Although relatively small, they can be highly productive and contribute significantly to household food security (Ferdousy et al. 2018). Moreover, as women are the main caretakers of home gardens in Bangladesh, homestead-based interventions are said to have "empowering" impacts for rural women, given that they are at least gender-sensitive[2] (Ferdousy et al. 2018).

In 2017, during Phase 1, a total of 12,166 households received support on nutrition-sensitive fish production and vegetable gardening (WorldFish 2018). The support included skills training, providing inputs such as fingerlings, feed, seeds and fertilizer, facilitating supply chain interactions and market engagements (WorldFish n.d.).

Integrated production of fish and RTB crops

In an interview with a project participant, in the Sadar subdistrict of Sylhet, consumption of fish was reported as six times a week (SSUCH17). Mola carplet (*Amblypharyngodon mola*) cultured in the homestead pond, along with tilapia and various species of carp, are regularly harvested by women for household consumption using a gill net. Mola carplet, when eaten whole, has great potential to reduce micronutrient deficiencies (Keus et al. 2017). However, the market price of micronutrient-rich, small indigenous fish species, such as mola carplet, is generally high, in comparison to larger and more commonly cultured species, such as pangas (*Pangasius* spp.) (MFSHM09). This somewhat highlights the value of nutrition-sensitive homestead fish production as a direct and relatively cheap source of micronutrients.

Before the implementation of the Suchana project, households in the region mostly produced and consumed a local white variety of sweetpotato (SSUCH15). Through the Suchana project, consortium partners introduced the nutritionally superior OFSP varieties to project households. Planted from October and harvested before the end of April, OFSP mostly grows in sandy soil on riverside embankments locally known as *chor* land (SBARI13; SSAU14). OFSP, in addition to its nutritional quality, is a relatively low-cost, low-maintenance and resilient crop (SBARI13; RBARI05; CIP23). That makes it suitable for the home gardens of micronutrient-deficient, poor households.

OFSP grown by project households is mostly kept for family consumption, though some of the harvest is gifted to neighbors and relatives (SSUCH15). The OFSP root is commonly consumed boiled, fried, steamed or cooked under hot coals (SSUCH15). The leaves of the plant, which are rich in vitamin, minerals, essential fatty acids and protein, are also consumed. The leaves can be harvested for consumption throughout the growing period (SSUCH16).

A wild variety of taro was also observed growing on the dike of ponds among Suchana households, along with some bananas.

(SSUCH15; SSUCH17). In fact, this is something that was observed on pond dikes more widely in Rangpur and Sylhet divisions (Plate 1).

The stolon, leaves, rhizome and stem of the taro plant are all edible (Kawochar et al. 2014), though the stolon and leaves are more commonly consumed by households and can be harvested starting from about two months after planting (SSUCH15; SSUCH17; SSUCH18; CIP23). One household reported consumption of the stolon and leaves on a weekly basis (SSUCH17), though the plant is consumed less frequently by other households, roughly once a month (SSUCH15).

However, papaya trees and winter vegetables, such as gourd, are more commonly grown on pond dikes than RTB crops (MBFRI12). According to a representative from the BFRI and a professor from the BAU, the concept of pond dike cropping is more popular in the Khulna region. In part, this is because a large proportion of the land in this region is saline and unsuitable for agricultural production and that pond dikes provide an elevated growing area unaffected by increasingly saline soil conditions (MBAU10). As a result, most new ponds being constructed, regardless of their size and market orientation, are built with wider dikes to plant crops (MBAU10).

Nevertheless, an annual assessment report of the Suchana interventions rolled out in 2017, and conducted by WorldFish (2018), revealed significant increases in the (a) sale of fish from ponds; (b) proportion of vegetables produced used for family consumption; (c) women's participation in household decision-making related to production, harvesting and use of aquacultural and agricultural products; and (d) dietary diversity in women of reproductive age, and young children (6–23 months old).

Dynamic interactions between fish production and RTB crops

When considering IAA as a "synergistic" farm system (characterized by by-product recycling and reuse, for instance), the application of this label to all home garden systems in Bangladesh is somewhat problematic. While some households reported recycling cattle dung and kitchen waste for agricultural production, there were less obvious interactions between aquaculture ponds and other farm subsystems.

Cattle dung is applied to the land when it is being prepared for planting (SSUCH15). As the quality of pond sediment is deemed inferior, it not used

Plate 1. Fish pond with wild varieties of taro and banana growing on a pond dike in Rangpur Division, Bangladesh.

in the same manner. Kitchen waste, including vegetable peels and cooked rice, is in some cases also used as compost and applied to homestead vegetable gardens (SSUCH17). Alternatively, kitchen waste is fed to cattle, along with excess sweetpotato and banana leaves gathered from plants growing on pond dikes (MRICE08; SOFSP19; SSUCH15; RFING01). In one household, banana leaves were laid over the top of the roots (Plate 2) to protect gourd seedlings and plant roots from heavy rainfall, pests and poultry (SSUCH17). Banana leaves play an additional role as feed in grass carp production. According to one fish farmer in Mymensingh, banana leaves are applied to the pond, with grass cuttings, every 10 to 15 days (MRICE08).

Similarly, though not evident through publications, key informants interviewed in Bangladesh reported that farmers occasionally feed potato to fish (RBARI05; CIP23). More specifically, farmers are known to boil old potato, harvested in the previous year and not consumed before the new harvest period and then feed them to fish, poultry and cattle (RBARI05; CIP23). In addition, semi-automated fish feed producers, who produce on a small-scale with basic technologies (mostly for personal use) are said to include potato in the same manner in their fish feed when the market price for potato is low (prices are generally low during the harvesting period in February when the market is saturated (WFMAM22)). Nevertheless, broken rice and rice bran are more commonly included as a source of carbohydrates in the composition of homemade fish feed as they are cheap and can be bought directly from rice mills (WFMAM22).

Broadly, it was reported that these "synergistic" practices are not as popular as they were 20 years ago (WFBEN21; WFMAM22). People are thought to have acquired better management practices and use improved and more efficient technology and inputs to increase production (WFMAM22). Seemingly, the practice of recycling kitchen waste, garden waste and manure, for instance, is perceived as "backward," a thing of the past, and is actually discouraged by most aquaculture extension officers (WFBEN21; WFMAM22; MBFRI12).

The application of kitchen waste, garden waste and manure to homestead ponds is not only discouraged because of their production-related inferiority to compound feed and chemical fertilizers, but also because households are said to use pond water as a drinking water source. There is

Plate 2. Banana leaves laid to protect roots and gourd saplings from pests and heavy rainfall, Rangpur Division, Bangladesh.

little information regarding the magnitude of this practice, though Benneyworth et al. (2016) in their study in coastal, southwest Bangladesh found that fish or shrimp pond water was a source of drinking water for 20% of the 200 households interviewed. The application of cattle dung in this case is particularly worrisome as zoonotic pathogens may spread in the treated water, and drinking or bathing with this water may cause illness such as diarrhea (Penakalapati et al. 2017).

Semi-automated feed producers are feasibly more likely to include excess homestead produce in their feed because they produce on a much smaller scale than commercial enterprises. However, they receive very little financial and programmatic support to improve the quality of their feed (WFMAM22). 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. Although more efficient in terms of fish growth rates, etc., this feed 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. According to one key informant, the commercial fish feed sector in Bangladesh is quite domineering and arguably uses its relatively powerful position to influence pond owners to purchase commercial compound feed (MBFRI12). In addition, many feed dealers allow pond owners to purchase feed on credit, which, while perhaps well-intended and beneficial for some, could easily "lock" others into an agreement, possibly with unfavorable *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, such as Egypt (El-Sayed et al. 2015, Kleih et al. 2013).

Section summary

RTB crops are grown in IAA systems globally, but it is difficult to uncover the nature of and extent to which RTB crops are cultivated under such systems. In numerous cases in which fish-crop farming is featured, authors have failed to specify which crops or vegetables they refer to. Nevertheless, the featured literature suggests that IAA systems, when compared to commercially oriented monocropping, are generally beneficial for soil conservation, biodiversity, livelihoods, household food and nutrition security. However, these publications talk broadly about IAA systems benefits, rather than distinguishing the advantages of integrating fish with RTB crops. Further research is required to discern the value of this integration at the homestead level.

The literature suggests that synergistic relationships between agricultural systems at the homestead level is common, especially in South and Southeast Asia. In Bangladesh, preliminary evidence suggests that while fish are often cultivated in homestead gardens alongside banana and cocoyam, the characteristic reuse and recycling of agricultural by-products are rare. It is perceived as "backward" and actually discouraged by agricultural extension service providers. More rigorous research is needed on the suitability and acceptance of this practice in different contexts.

Fish feed: A focal area of integration

Nutritional requirements, composition and sustainability

Like other animals, fish require adequate levels of energy, carbohydrates, protein, fiber, fat, vitamins and minerals for metabolism, growth and development (NRC 1993 and 2011). Under semi-intensive and intensive culture conditions, naturally occurring food sources such as phytoplankton provide fish, especially those stocked at high densities, with insufficient nutrients. For an aquaculture venture to be viable, it is necessary to feed cultured fish with formulated or compound feeds (NRC 2011). Feeding regimes vary according to the nutritional requirements of the species under culture, the size and age of the fish, and the level of intensity of the production (Lall and Dumas 2015). It is recommended that tilapia feeding regimes follow a feeding rate of 2%–8% bodyweight, depending on the stage of growth (Kenya Bureau of Standards 2015). On the other hand, African catfish cultivated under intensive conditions can be fed up to six times per day (FAO 2007b).

Compound feeds allow farmers to increase stocking density, increase yield, shorten cultivation periods by promoting faster growth (Nwokocha and Nwokocha 2013; Li and Robinson 2015; Solomon et al. 2015), so the importance of compound feeds depends on the desired intensity of aquaculture practice.

To function effectively, compound feeds must contain all essential nutrients. According to Lawal et al. (2014, 221), "The dietary requirements of cultured fish are probably the most important factor influencing the success of any fish farming enterprise."

Fish diets generally contain variable amounts of carbohydrates, which act as the most inexpensive source of energy (Arthur and Phillips 1972; Lall and Dumas 2015), though carbohydrates are also used for their binding properties (Lall and Dumas 2015). Nevertheless, the amount of carbohydrates included in the diet depends on the fish species and their ability to digest carbohydrates.

Digestibility is also significantly affected by the size and age of the fish, even within the same species (Lall and Dumas 2015). Commonly used energy sources in feed formulation include maize, potato, rice bran, wheat, soybean, sorghum, corn and cassava (Boyd 2015).

Maize is popularly included in fish feed as it is readily available and easily digested by most commercial fish species (Abu et al. 2010b). In sub-Saharan Africa, maize constitutes about 10%–40% by weight of most commercial aquaculture feeds (Lukuyu et al. 2014). It is widely used, but is problematic because both humans and animals (including livestock) consume these energy sources. This results in competition, which is exacerbated by growing human populations and the increased scope and intensity of the aquaculture industry (Lawal et al. 2014). In several regions of the world, there is a shortage of cereals (Lukuyu et al. 2014). For example, in Nigeria maize is consumed in traditional dishes such as *ogi* and *tuwo* (Udo and Umanah. 2017). According to Abu et al. (2010), the cost of maize is increasingly prohibitive and the price fluctuates regularly.

Fish require a significant amount of protein and vary according to the species. Carnivorous species such as catfish require higher levels of protein for growth and development (Mertz 1972; Oliva-Teles et al. 2015). Furthermore, the age of a fish affects its protein requirement. Fry and fingerlings require higher levels of protein for optimum development, whereas, "growers" and "broodfish" require less (Kenya Bureau of Standards 2015). Subsequently, the crude protein content of pelleted aquaculture feed ranges from 25% to 55% (Boyd 2015).

Currently, protein for global commercial feed production is primarily obtained from animal sources, mostly fish (Boyd 2015). FAO (2007) reports that the Vietnamese aquaculture industry uses about 62,500 t of fishmeal per year. In most sub- Saharan African countries, aquafeed formulations commonly rely on imported fishmeal to provide the majority of the necessary dietary protein (FAO 2007b). Fishmeal is often composed of fish from marine trawlers or fish processing enterprises and commonly contains small, pelagic, oceanic fish, such as herring, anchovy and sardine (Nwokocha and Nwokocha 2013; Boyd 2015).

According to Gatlin et al. (2007) and Oliva-Teles et al. (2015) fishmeal is popularly used because of its high protein quality (amino acid profile) and palatability. As a result, the demand for fishmeal has increased. The use of fishmeal in increasingly intensive aquaculture production systems has also increased and placed additional pressure on already overexploited wild fishstocks, a global concern, and elevated competition with human wild caught fish consumption (Ibiyo and Olowosegun 2005; Boyd 2015). The favorability and increased scarcity of fishmeal have affected its price. In fact, the high costs of fishmeal (up to USD 1210/t, in 2008 (Rana et al. 2009)) is in part responsible for the high costs of fish feed (Lukuyu et al. 2014). Lawal et al. (2012) reported that in Africa, fish feed accounts for about 60% of the total cost of fish production. Moreover, commercial feeds are too expensive for many small-scale aquaculture farmers, which reportedly limits their ability to intensify aquaculture production (Aya 2017).

Fats and oils form another major component of aquafeed and affects the quality and palatability of the feed. Fats and oils complement carbohydrates and proteins as an energy source, while providing essential fatty acids for optimal growth and development of the fish (Lee and Sinnhuber 1972).

Vitamins are also required, though in smaller quantities for optimum growth, health (disease prevention) and reproduction (Halver 1972). Minerals, also in comparatively small quantities, are necessary for metabolism and skeletal development (NRC 1993).

Non-conventional fish feed ingredients

Since the mid-1980s, fish nutritionists have explored the effectiveness of incorporating "non-conventional" protein and energy sources into fish feed for use in aquaculture. According to Oliva-Teles et al. (2015), reducing aquafeed dependency on fishmeal and fish oil is important. This research is commonly rationalized by the high costs of fish feed, especially the cost of conventional animal protein such as fishmeal, and commonly used energy sources such as maize, which is an issue seemingly experienced in numerous countries. In aquaculture, feed accounts for 50%–70% of the production cost (Rana et al. 2009; Tshinyama et al. 2018). The price of most common feed ingredients is a function of global availability and exchange rates (FAO 2007b; El-Sayed et al. 2015). As such, according to FAO (2007) the global market price of soybean meal increased dramatically from USD 92/t in 2000 to USD 221/t in just 3 years. The prices of feed commodities are expected to increase even further, in part from climate-induced erratic supplies. Nevertheless, the prices of feed commodities are highly variable among countries and vary seasonally within countries (FAO 2007b).

Dependencies on imported feed ingredients and/or commercially produced feed also influence the prohibitive prices of fish feed. According to FAO (2007), Bangladesh, China, India, Indonesia, the Philippines, Thailand, Vietnam, Ghana, Kenya, Malawi, Nigeria, Uganda and Zambia were all, at this time, net importers of fishmeal and/or fish oil. In 2000, over 80% of the fishmeal available for use in Nigeria was imported, mainly from Denmark and Norway (Fagbenro and Adebayo 2005), whereas in Egypt, between 50% and 90% of aquaculture feed ingredients are imported (El-Sayed 2015). This shows the importance of finding cheap, optimum performing, regionally available alternatives (Tshinyama et al. 2018).

Some non-conventional plant and animal protein sources explored in the literature include groundnut meal (Tram et al. 2011), papaya leaves (Olusola and Olaifa 2018), earthworm and garden snail (Sogbesan and Ugwumba 2008), grasshopper meal (Okoye and Nnanji 2004 in Gabriel et al. 2007), cassava peel (Ubalua and Ezeronye 2008), cassava leaves (Sutriana 2007) and sweetpotato leaves (Adewolu 2008). Several non-conventional energy sources were identified to replace maize, and they include sweetpotato meal (Olukunle 2006), cassava root meal (Abu et al. 2010), banana peel (Lawal et al. 2014), cocoyam meal (Aderolu et al. 2009), yam peel (Lawal et al. 2012), cowpea, waterleaf, sugarcane fiber and palm kernel cake (Nwokocha and Nwokocha 2013). Fish nutritionists have selected these feed ingredients for trials based on a variety of desirable characteristics, including theirnon-competitiveness, nutritional content, low prices and regular availability in the local context.

Roots, tubers and bananas as non-conventional fish feed ingredients

It has been suggested that many RTB crop residues, by-products and wastes can be appropriately developed as components of aquaculture feeds (Lukuyu et al. 2014), particularly by-products, such as peels and leaves, because they are non-competitive, regularly available and easily accessed at low prices (Lukuyu et al. 2014).

Abu et al. (2010b) reported that cassava root meal is of comparable quality as an energy source and also cheaper and more readily available than maize in Nigeria. Furthermore, Solomon et al. (2015) reported that sweetpotato peel contains important micronutrients, such as vitamins B and C as well as iron. In addition, plant leaves such as cassava and sweetpotato leaves, are high in protein, fiber, vitamins and minerals (Olusola and Olaifa 2018). Plant leaves are also said to be the cheapest potential source of protein (Olusola and Olaifa 2018). Sweetpotato leaf meal is reported to have a high protein content, high amino acid score and contains vitamins A, B2, C and E (Adewolu 2008). It can also be harvested many times throughout the year, though it is generally unavailable in large commercial quantities (Gabriel et al. 2007; Adewolu 2008). Moreover, root and tuber crops, such as cassava, are highly resilient. Many can be grown in poor soil conditions and survive long periods of water deficit, which are invaluable characteristics in the face of a changing climate (Mzengereza et al. 2014, Prain and Naziri 2020). The "hardiness" of these crops is likely to stabilize their price and market supply, making them more attractive to rely upon than conventional crops, such as maize.

Literature review findings: Roots, tubers and bananas as fish feed

Research on the integration of RTB crops in fish feed over the past decade and half has been dominated by quantitative laboratory-based feed trials (16 out of the 27 reviewed papers). The majority of these trials explored the incorporation of cassava or sweetpotato in feed fed to tilapia or catfish (Table 3). These studies were designed to investigate the effects of replacing a percentage of conventional protein or energy sources with RTB crops on primarily growth performance and feed use. The results of the feeding trials are not easily summarized, since most of the studies varied according to the crop, crop part, fish species, age of the fish, or the processing techniques applied to the feed ingredients. In general, however, it seems that maize or fishmeal can, to a degree, be replaced effectively by the trialled RTB crop residues and leaves. In fact, only one study (Lawal et al. 2012) concluded that it was not favorable to replace maize in the diet of catfish fingerlings. However, multiple studies found that replacement was only effective in terms of growth performance, when comparing the trial diet to the conventional control diet, up to a certain replacement level (10%–75%). Adewolu (2008) reported that sweetpotato leaf meal can effectively replace conventional protein sources (such as groundnut cake, soybean and fishmeal) up to 15%, without

RTB crop	Crop part use	Fish species trialled	Author(s)
Cassava	Peel	Tilapia	Mzengereza et al. 2016; Ubalua and Ezeronye 2008
	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 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
Banana	Peel	Catfish	Lawal et al. 2014
	Leaf	Tilapia	Mzengereza et al. 2016
Cocoyam	Meal/flour	Catfish	Aderolu et al. 2009
	Leaf	Tilapia	Mzengereza et al. 2016
Yam	Peel	Catfish	Lawal et al. 2012

Note: Catfish species and tilapia have been aggregated.

Table 3. Outlines of feeding trials (conducted globally and published after 2000) on fish feeds containing RTB crops.

compromising growth. On the other hand, Bichi and Ahmad (2010) found that the optimum replacement level of maize with cassava leaves was about 65%, in juvenile African catfish.

It is widely believed that antinutritional factors (including tannins, hydrocyanic acids, oxalates, saponins, phenolic acids, glycosides and flavonoids) commonly found in RTB crops, especially in their leaves, can have serious implications on the performance and health status of fish. As such, levels of antinutritional compounds, alongside prohibitively high levels of fiber, are mostly hypothesized as the reason why growth performance, accompanied by low feed use, declines with increased levels of RTB crops, specifically leaf meal. According to Mzengereza et al. (2014), high crude fiber levels can impede digestibility and thereby limit the rate of nutrient absorption. Similarly, high levels of antinutritional factors such as saponins can reduce nutrient absorption and protein digestibility (Olusola and Olaifa 2018).

Fish nutritionists such as Aderolu et al. (2009) and Chhay et al. (2010) have designed and conducted feeding trials to compare the growth performance, feed use and carcass traits of fish fed feed containing variously processed cocoyam. This study was developed because it is commonly understood that processing root meal, peel and leaves may inhibit the antinutritional compounds in these ingredients. Aderolu et al. (2009) found that juvenile African catfish fed feed containing boiled cocoyam had a better mean weight gain, feed conversion ratio and protein efficiency ratio than those fed feed containing raw and fermented cocoyam. On the other hand, Chhay et al. (2010) found that there were no apparent benefits, in terms of growth response, from sun-drying cassava leaves used in tilapia feed as opposed to including them in the fresh form.

It is important to recognize that different fish species are likely to respond variably to compound feeds because of their individual capabilities to digest plant-based energy, protein and fiber. Mzengereza et al. (2016) explain that tilapia, for example, as herbivorous fish are physiologically adapted to use high fiber feeds. As a result, they can arguably be fed exclusively plant-based diets, unlike African catfish. Tram et al. (2011) somewhat explores this concept and compares how different species (Nile tilapia and hybrid catfish) perform and use plant protein compared to animal protein in feeding trials. The study indicated that both species have a similar capacity to digest animal and plant protein, though to validate this, additional studies should be conducted.

In addition to the aforementioned feeding trials that focused on growth performance and feed use, a few studies identified in this review explored the economic implications of replacing conventional feed commodities with RTB crop residues and leaves. Sine et al. (2017) detailed 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) went one step further and conducted a cost-benefit analysis of replacing conventional energy sources with non-conventional whole cassava root meal. They concluded that whole cassava root meal can replace maize in the diet of hybrid catfish effectively, with higher net profits, up to 100%. But the highest profit was achieved by selling fish fed a diet with a replacement level of just 66%. Therefore, while RTB-based replacements in general may not perform as well as conventional feed ingredients, such as maize or fishmeal, they might still make business sense to replace these conventional feedstuffs, in the case of hybrid catfish, according to Abu et al. (2010b). However, the study they carried out was specific to the hybrid catfish species and also specific to conditions in Nigeria. Since commodity prices vary regionally, largely because of the regional availability of a crop, these findings are not universally representative. Further research needs to be conducted in this area before generalizations can be made.

Focus on Nigeria

Researchers based in Nigeria conducted a large proportion of the identified feeding trials (10 out of 16) (Table 4). The following section attempts to broaden the discussion to understand the motivations for this research by situating this regional focus on non-conventional fish feed ingredients within the Nigerian agri-food systems context.

In 2015, a total of 1,027,058 t of fish were produced in Nigeria, of which the aquaculture sector produced 316,727 t (National Bureau of Statistics 2017). Although fish production has increased significantly since 2000, domestic production does not meet domestic demand. As a result, Nigeria depends on imports to close this deficit. Since 2001, Nigeria has imported over 600,000 t fish per year, though today the figure is closer to 750,000 t per year (FAO 2007a; Igoni-Egweke 2018). As the country's population and per capita income continue to increase, the fish supply-demand gap is projected to widen even further. Developments to the aquaculture sector are regarded as pivotal to bridge this gap (FAO 2007a; Federal Ministry of Agriculture and Rural Development 2008; Abdullah 2011; Igoni-Egweke 2018).

Currently, catfish (*Clarias* spp.) dominate the aquaculture sector, followed by tilapia (*Hemichromis* spp. and *Oreochromis* spp.), and are cultivated on small- to medium-scale[3] farms. The majority of these operations are in the South, South West and North Central regions of the country (FAO 2007a), though there are a few, and a growing number of large-scale intensively managed fish farms (Miller and Atanda 2011).

Nigeria is the largest aquaculture producer in sub-Saharan Africa (FAO 2018). Yet, the scale of production today is still considered low in relation to its potential. According to Igoni- Egweke (2018), less than 1% of the freshwater and just 0.05% of the brackish water identified as suitable for fish cultivation are currently being used for aquaculture. Growth in the sector is still inhibited by the high cost of inputs (feed and fingerlings), lack of affordable credit for fish farmers, poor management skills and ineffective aquaculture extension services (Igoni-Egweke 2018).

In Nigeria, the aquaculture industry used an estimated 35,570 t of feed in 2000 (Udo and Umanah 2017). However, poor feed quality, scarcity and the high cost of compound feeds remain major obstacles to aquaculture development (Nwokocha and Nwokocha 2013).

High cost of compound feeds

Globally, average feed costs often account for over 50% of the variable costs of an aquaculture enterprise (NRC 2011). In Nigeria, feed costs are reported to vary from 61% to 80% of total production costs, depending on the location and type of production system (Adeoye et al. 2012; Omobepade et al. 2015; Igoni-Egweke 2018).

Feed is reported to be an especially costly input in intensive catfish culture because catfish requires a diet high in protein, and conventional sources of protein, particularly fishmeal, are generally expensive (Nwokocha and Nwokocha 2013). The high reported costs of compound feeds are ascribed to the cost of raw materials, which in some instances are imported (Nwokocha and Nwokocha 2013). Consequently, fish feed

Cambodia	Chhay et al. 2010
Indonesia	Sutriana 2007
Malawi	Mzengereza et al. 2016
Nigeria	Solomon 2015; Adewolu 2008; Abu et al. 2010b; Lawal et al. 2012; Aderolu 2009; Lawal et al. 2014; Abu et al. 2010a; Bichi and Ahmad 2010; Olukunle 2006; Ubalua and Ezeronye 2008
Papua New Guinea	Sine et al. 2017
Vietnam	Da et al. 2016; Tram et al. 2011

Table 4. Geographic distribution of feeding trials on cassava peel, published after 2000.

prices often depend on fluctuating international commodity markets (FAO 2007b).

Soybean and fishmeal are major sources of protein in commercial feed in Nigeria, and both are mostly imported since national production fails to meet demand. In 2000, over 55,000 t of fishmeal were imported, mostly from Denmark and Norway (Fagbenro and Adebayo 2005 cited in FAO 2007b). In 2004, 550,000 t of soybean meal were imported to meet consumer demand (FAO 2007b). In the same period, Nigeria also imported fishmeal at the cost of USD 870–1350/t (FAO 2007b). The high costs of importing feed ingredients are reflected in high fish feed prices. Over the past decade, the cost of raw materials, particularly fishmeal, maize and soybean have also increased. As a result, the price of fish feed has risen drastically, as much as 80% in Lagos State, according to Udo and Umanah (2017).

Commercial feeds are also imported in large volumes. Evidence suggests that over 53% of fish farmers in Nigeria use imported feeds, either in combination with locally pelleted feeds or exclusively (Udo and Umanah 2017). An estimated 75% of the sector's total fish feed requirement is imported (Udo and Umanah 2017).

Domestic fish feed production

The fish feed industry and technology are still poorly developed in Nigeria, as across most of the African continent (Gabriel et al. 2007). The feed industry is mostly set up for poultry feed production. In 2001, only a few of the 620 feed mills in Nigeria produced compound feed for fish (FAO 2007b). FAO (2007b) reported that there were just 10 feed production plants dedicated to manufacturing fish feed at the time of their study. Many of these plants were located in the southwest of Nigeria, such as Lagos, Ibadan and Ilorin. However, the number of fish feed manufacturers has undoubtedly risen in response to the boom in commercial fish farming (Udo and Umanah 2017), as evidenced by the increased quantity of fish feed produced. An estimated 636,000 t of compound fish feed were produced in Nigeria in 2015 as compared to 35,750 t produced in the 2000–2001 fiscal year (FAO 2007b; Udo and Umanah 2017). More and more domestic animal feed millers are producing fish feeds, and some even offer compounding services to farmers who are prepared to self-formulate their feeds (Udo and Umanah 2017). However, the scale of domestic feed production fails to meet the demand from the rapidly growing aquaculture industry.

Because of their prevalence in the Nigerian food systems, RTB crop products and residues, such as cassava peel and sweetpotato, have been identified as priority non-conventional fish feed ingredients for future development.

Roots, tubers and bananas in Nigeria

Domestic production: An overview

Major root and tuber crops grown in Nigeria include cassava, sweetpotato, yams and cocoyams (Iyagba 2010). Table 5 shows that considerable quantities of cassava and yams are produced

Crop	Production (t/year)*
Cassava	59,500,000
Yam	48,000,000
Maize	10,400,000
Rice (paddy)	9,900,000
Oil palm fruit	7,800,000
Sorghum	6,900,000
Sweetpotato	4,000,000
Cowpea (dry)	3,400,000
Taro (cocoyam)	3,300,000
Plantain and others	3,200,000
Groundnut (with shell)	2,400,000
Millet	1,500,000
Potato	1,300,000
Soybean	700,000
Sesame seed	600,000
Seed cotton	300,000
Carrot and turnip	200,000
Cashew nut (with shell)	100,000
Wheat	70,000

**Figures rounded to the nearest 100,000 t.*

Source: FAOSTAT 2017.

Table 5. Crop production in Nigeria (2017).

annually. In fact, Nigeria is the world's leading producer of cassava and third-largest producer of sweetpotato (based on quantity). It is also the fourth-largest producer of banana and plantain in sub-Saharan Africa (International Institute of Tropical Agriculture, n.d.; Ahmad et al. 2014; Onyenwoke and Simonyan 2014).

Table 5 further suggests that cassava and yam products are more available than other ingredients commonly incorporated into domestic fish feed, such as maize and soybean. Based on annual production, cassava and yams present greater opportunities for integration in fish feed than other identified non-conventional feed ingredients, such as groundnut and seed cotton. It is worth noting, however, that the availability of the crop is also influenced by postharvest losses, levels of consumption and their use in other markets.

Cassava processing and by-products

In Nigeria, cassava is processed into a variety of primary and secondary products. Substantial quantities of cassava peels and leaves are rejected as by-products from the growing primary production enterprises in Nigeria (Lukuyu et al. 2014).

In Nigeria, cassava is processed to produce *garri*[6], *fufu*, ethanol, flour and starch, which are used in food products such as bread and biscuit as well as non-food products, including adhesives and pharmaceutical products (Onyenwoke and Simonyan 2014). *Garri* is a quick and easy to cook convenience food in Nigeria, and competes with rice and staple cereals such as maize, because of its low price, convenience and storability (Mcnulty and Adewale 2015). To produce *garri*, cassava roots are peeled, grated, fermented and roasted. As part of this process, the cassava peels, an estimated 15% of the whole root, are discarded (Agboola 2019) (Plate 3).

Similarly, waste products are produced during the stages of ethanol, flour and starch production. In 2015, there were three large-scale processors in Nigeria and over 100 high quality cassava flour (HQCF) processors. The two largest plants are capable of processing more than 45 t of HQCF per day (Mcnulty and Adewale 2015). Presumably large quantities of by-products are also available at these locations.

As much as 6 million t/year of cassava peels, leaves and pulp are discarded by the starch and *garri* processing sectors (FAO 2007b; Lukuyu et al. 2014). There is no more recent nationally representative data on the quantity of cassava by-products generated. This figure is likely to have increased following government efforts to develop the cassava sector and reduce reliance on imported foods (UNIDO 2006).

Plate 3. Discarded cassava peels at a *garri* processing village in Oyo State, Nigeria.

Other RTB crops and by-products

Sweetpotato is still considered a minor crop in Nigeria despite its reputation as the third- largest producer in the world (Ahmad et al. 2014). It is extensively cultivated in the tropical North Central and South West regions (Sanusi et al. 2016). However, the level of production remains relatively low as compared to cassava (Udemezue et al. 2018). According to Adewumi and Adebayo (2008), there is a lack of awareness of the commercial value and nutrition security benefits of sweetpotato, so the crop has not been exploited to its full potential. Unlike cassava, sweetpotato is consumed in limited forms—50% of sweetpotato produced in Nigeria is either boiled or fried for consumption (Odebode et al. 2008). Processing sweetpotato is generally performed by processors at a small-scale level, such as household producers and consumers, so the scale of sweetpotato by-products is very small compared to that of cassava. However, recent efforts to promote the sweetpotato industry have resulted in the development of sweetpotato *garri*, also known as *sparri* (Yusuf et al. 2017). If this product is widely embraced, its production could result in a more centralized and perhaps greater availability of sweetpotato peels and rejected roots.

In 2017, Nigeria produced over 47 million t of yam and about 3 million t of cocoyam. Like sweetpotato, yam is also predominantly produced in the Southern and the North Central regions of the country (Agboola et al. 2019). Despite the seemingly large volume of yams produced per year, production has not increased with population growth, so demand exceeds supply (Ibok et al. 2015). The culture system for yam is also highly labor intensive, and rural labor is generally scarce and expensive. These two factors have resulted in high market prices, rendering yam a luxury food rather than a staple, especially in urban areas (Toba 2014). Yam production is also reportedly hindered by diseases, limited storage infrastructure, a lack of affordable credit forfarmers and insufficient market information (Toba 2014).

Similar to cassava, yam is also processed into chips, flour and flakes. Processing the yam tuber into chips is generally done by peeling, washing, chipping and then drying. This increases the shelf life, storability and marketing potential of the crop (Omohimi et al. 2018). Yam chips and flour are commonly sold in markets in the South West zone (Omohimi et al. 2018), though according to Omohimi et al. (2018) yam flakes are mostly found in markets within close proximity to the place of production. Yam flour, which can be purchased directly or produced from the chips, is commonly used to make *amala,* a porridge-like food mothers in the South West zone use to feed infants (Omohimi et al. 2018). However, processing is mostly undertaken at small-scale level only, so the by-products, such as leaves and peels, that could be used in aquafeed (if households themselves have not already used them) are dispersed among scattered rural yam producers (Omohimi et al. 2018).

Banana and plantain production in Nigeria is concentrated in the south (Akinyemi et al. 2017). Plantain in the South West zone are processed into products such as plantain chips, plantain flour, plantain balls and biscuits. Large amounts of peel are likely discarded by the reportedly small-scale processing enterprises, though information on available quantity is unavailable (Adeoye et al. 2013).

The current role of RTB crops in livestock feed in Nigeria

Available literature suggests that smallholders somewhat use RTB crops or by-products to feed their livestock. Small-scale farmers use cassava, yam, plantain, banana and sweetpotato by-products—peels, leaves and other residues (often when blended with other ingredients)—to feed sheep, goats and poultry (UNIDO 2006; Agboola et al. 2019). As Adewumi and Adebayo (2008) reported, sweetpotato leaves, fresh or in the form of silage, are sometimes fed to livestock. In addition to by-products, livestock keepers and small-scale feed millers also find use for RTB primary products, such as sweetpotato roots, in their operations (Adewumi and Adebayo 2008). These are sometimes cleaned, shredded or sliced and dried before they are fed whole or ground to livestock (Adewumi and Adebayo 2008). Furthermore, Onyenwoke and Simonyan (2014) found that small feed millers use dried cassava chips, which are a primary cassava product, when they are locally available at low prices.

Nevertheless, a substantial quantity of cassava peel is discarded because it is considered a low-value feed ingredient for ruminants (Agboola et al. 2019). Although smallholders use RTB crop derivatives to feed livestock, Onyenwoke and Simonyan (2014) report that, at the time of writing, "no major livestock feed mill uses cassava as a raw material."

Agboola et al. (2019) suggest that cassava peels sourced locally are also used in aquafeed production, though cassava flour, a primary product, is more commonly used as a source of energy and binding ingredient in farm-made feeds. However, there is a lack of detailed accounts of the inclusion, particularly the scale of inclusion, of cassava primary and by-products in aquafeed.

On the other hand, Agboola et al. (2019) report that other RTB by-products, such as cassava leaves, yam peel, cocoyam peel and leaves, are not currently used in aquafeed production. Nevertheless, the current use of RTB by-products in livestock feed is indicative of the potential for the aquafeed sector to make use of these products.

An opportunity to improve food and nutrition security

Like many low-income food deficit countries,[4] Nigeria has a high prevalence of food and nutrition insecurity (Matemilola and Elegbede 2017). An estimated 58% of households suffer from chronic or transitory food insecurity (Ogundari 2017). In addition, an average of 21.5 million people were classified as undernourished between 2015 and 2017, and 43.6% of children under 5 years of age were classified as stunted in 2016 (FAOSTAT 2017). Nutrient deficiencies can be detrimental to an individual's growth and development, productivity, immune strength, cognitive function and quality of life.

Fish is an important animal-source food for many people in Nigeria, because it is often the cheapest and most accessible animal-source food (Bradley et al. in press). Fish consumption is estimated at 13.3 kg/capita/year. This is higher than the regional average for Africa, which is estimated at 9.9 kg/capita/year, though still considerably lower than the global average of 20.3 kg/capita/year (FAO 2018), so there is space to promote fish consumption to address the aforementioned micronutrient deficiencies. If harnessed, fish can effectively play a key role in attaining food and nutrition security in Nigeria because of its richness in vitamin A, zinc, iron and calcium, essential fatty acids and animal protein (WorldFish 2017b; Bradley et al. in press). However, as is outlined in the previous sections, fish demand currently exceeds supply, and fish production from both capture fisheries and aquaculture is limited by various circumstances, including high cost of production due, in part, to the high costs of fish feed and a reliance on imported fish feed in the aquaculture sector (Miller and Atanda 2011; Omobepade et al. 2015; Igoni-Egweke 2018).

Using RTB by-products that are potentially cheap and locally available as aquafeed ingredients could reduce the cost of feed and, therefore, contribute to increasing the accessibility and affordability of fish for human consumption. As the papers reviewed in this report suggest, replacing conventional feed ingredients, such as maize, soybean and fishmeal, with locally available, cheap and comparably nutritious feedstuffs, such as cassava peels could result in greater net profits.

In addition, the economic potential and returns might attract additional people to take up fish farming and maybe even prompt the injection of capital, which is another challenge the sector currently faces. A reduction in the cost of fish feed might also allow fish farmers who currently limit their use of high quality commercial feed to the initial stages of cultivation because of financial limitations to extend this period (FAO 2007b). In addition, surplus farm profits could be re-invested to expand operations and ultimately increase fish yield.

Protein-rich plant-based feed ingredients, such as sweetpotato and cassava leaves, provide an opportunity to reduce or completely replace the need for fish in fish feed. According to FAO (2007b), approximately 10%–20% of the artisanal and industrial marine and inland fisheries catch is processed into fishmeal along with the waste from the shrimp processing industry (shrimp head and tail). In Nigeria, about 75% of the fishmeal produced domestically is used in aquaculture (Udo and Umanah 2017). For instance, the Clupieds, a small indigenous fish from Lake Kainji, are reportedly sun-dried, pulverised and packaged as fishmeal for commercial use in aquaculture nationwide (FAO 2007a; Akintola and Fakoya 2017). Yet these are one of the most common small fish that people in

Nigeria eat, and they are rich in essential nutrients. When eaten whole, they are perhaps more nutritious than the larger fish, such as tilapia, which is popularly stocked in aquaculture ponds. From a nutritional perspective, then, it is better for people to redirect these small fish for consumption rather than for use in the aquaculture industry. Promoting the replacement of fishmeal with protein-rich RTB by-products that do not compete with human consumption would assist with this redirection.

It is worth noting, however, that while these changes to the aquaculture sector could theoretically increase the physical availability of fish, this does not necessarily lead to increased consumption. Access to fish for consumption is also influenced by income, geographical location, socioeconomic status and the adequacy of postharvest infrastructure and markets (Bradley et al. in press). Fish consumption is also influenced by complex sociocultural and behavioral factors, including food culture, consumer preferences and perceptions (Onuorah and Ayo 2006). Therefore, a linear, causal relationship between increased production or the physical availability and consumption of fish is difficult to establish. Increased production is just one of a multitude of factors that influence consumption.

In addition to the potential improvements to food and nutrition security, exploiting currently under-used cassava peel from the cassava processing sector in Nigeria would also have beneficial environmental impacts. Currently, large amounts of cassava peel are carelessly disposed of into the environment, where they are left to rot. These waste heaps emit carbon dioxide, produce a foul smell and may cause surface water pollution (Lukuyu et al. 2014).

Challenges

Scale and seasonality

RTB processing activities are limited by the subsistence nature and seasonality of production. Smallholders grow about 80% of Nigeria's annual cassava yield, and they do so with few technological resources and a heavy reliance on familial labor (Onyenwoke and Simonyan 2014; Mcnulty and Adewale 2015). In southern regions, cassava is sown between March and October and usually harvested a year later. Peak cassava processing periods correspond with these seasons, resulting in a lull in supply between November and February. Mcnulty and Adewale (2015) claim that this inconsistency in the supply of fresh roots limits the scale of cassava processing in Nigeria. This means that most of the medium- to large-scale processing sites only operate seasonally (Mcnulty and Adewale 2015), so the production of by-products is likely inconsistent. Government and nongovernmental initiatives could help smooth the supply of cassava (International Institute of Tropical Agriculture n.d.; UNIDO 2006). Among these is the presidential initiative called the Cassava Master Plan, which attempts to improve production technologies, and the efforts of the International Institute of Tropical Agriculture (IITA) to develop early maturing and high-yielding cassava varieties. However, further information is needed on the volume of cassava leaves and peels available within the country.

Logistical/spatial considerations

Various logistical questions have so far gone unanswered. Currently, poor road and storage infrastructure hinders the distribution of RTB crops from farm to consumer (Onyenwoke and Simonyan 2014; Mcnulty and Adewale 2015). It is unlikely, that the distribution of cassava peel from *garri* processing sites or cassava leaves from various production areas to feed mills will function without similar challenges. As stated by Agboola (2019), logistics around the collection of relevant cassava by-products need to be organized and should be considered a crucial research action.

Conveniently, a large proportion of cassava is grown and processed in the South and North Central zones of the country, which are also where a significant number of fish farms, feed mills and manufacturers is located. This is a favorable circumstance if commercial cassava processors are to be vertically integrated with commercial feed mills or fish feed manufacturers.

Additional processing requirements and associated workload

As suggested by many authors (FAO 2007; Ogugua and Eyo 2007; Nwokocha and Nwokocha 2013), it is beneficial to process RTB derivatives, especially leaves, before they are incorporated into fish feed to decrease the fiber content and antinutritional factors. This might require additional or differential technical knowledge, skills, equipment, energy, labor and time resources that are not necessarily locally developed or available. However, manufacturers may consider the additional efforts not worth the savings gained.

Additional job opportunities for commercially converting waste to feed could feasibly benefit women who constitute the majority of the workforce in cassava processing units in Nigeria (85% women) (Amole 2016; Okike et al. 2014). Yet such developments should be carefully managed to ensure that working conditions are safe and that women get an equitable compensation for their time and labor.

There is also a risk that most of this work associated with the additional processing steps would fall disproportionately on women, especially on-farm operations that rely on unpaid familial labor. More information is needed regarding the role of women in the aquafeed production and supply chain.

Space for incorporation of RTB crops in aquafeeds in Bangladesh

A brief introduction to aquaculture in Bangladesh

Bangladesh is one of the world's major producers of fish, contributing to the livelihoods and employment of millions of Bangladeshis (Belton et al. 2011). With 4.3 million ha of perennial and seasonal inland waters, 2.5 million ha of coastal lands and a 480 km coastline, Bangladesh has abundant water resources (Zaher and Mazid 1992). For the financial year 2016-2017, over 4.1 billion metric tons of fish were produced in Bangladesh (Department of Fisheries 2017). Aquaculture plays a major and increasing role in total fish production (Hossain 2014), contributing about 56% to total production in 2016–2017 (Department of Fisheries 2017). Commonly cultured fish and other aquatic animal species include Indian major carp species, catfish, snakeheads, various non-native large fish species, small indigenous fish species and crustaceans (Table 6).

Changing fish feed requirements

Aquaculture in Bangladesh started as a low intensity semi-subsistence activity. Over the past 20 years, however, the sector has expanded as a result of rapid commercialization, intensification, specialization and development of input businesses and suppliers—fingerlings and feed specifically (Belton et al. 2011; Belton et al. 2014). At the same time, the use and demand for compound fish feed have increased in reaction to this expansion (Zaher and Mazid 1992). In 1992, the demand for compounded supplementary feeds in aquaculture was very low, between 3000 and 4000 t per year (Zaher and Mazid 1992). Demand for compound feed has increased rapidly since. Between 2008 and 2012, the rate of commercial feed production increased at an average of 32% per year (Mamun-Ur-Rashid et al. 2013). With increasing demand and market value for fish, more and more farmers are beginning to replace farm-made and raw, unformulated feeds with commercially produced compound feed to increase production (Zaher and Mazid 1992; Mamun-Ur-Rashid et al. 2013). In 2012, about 100 commercial feed mills in Bangladesh produced a combined total of 1,070,000 t of formulated aquafeed (Agboola et al. 2019).

The intensification of fish production and the subsequent higher demand for compound fish feed have raised a number of issues, including concerns over environmental sustainability, the price of imported feed ingredients, competition between the dominant poultry sector over feed ingredients (particularly maize) and competition between the use of marine fish for human consumption and in aquafeeds (Mamun-Ur-Rashid et al. 2013).

Overview of common feed ingredients

According to Mamun-Ur-Rashid et al. (2013) Bangladesh produces 50%–55% of the ingredients used in commercial fish feed production, whereas the remainder is imported. Imported raw materials contribute more than 50% to the total cost of commercial feed production in Bangladesh. Feed costs account for 70%–75% of farm operating costs (Mamun-Ur-Rashid et al. 2013). The main ingredients used for aquafeed production are rice bran, maize, soybean meal, mustard oil cake, fishmeal, meat and bone meal (Table 7) (Mamun-Ur-Rashid et al. 2013).

Rice is the most important crop cultivated in Bangladesh, and rice bran, derived from rice milling, is extensively used for feeding fish because it is cheap and largely available year-round (Zaher and Mazid 1992). Three types of rice bran are used: de-oiled rice bran (a by-product of rice bran oil production), grade A rice bran (which has a high ratio of bran to husk) and grade B rice bran (having a lower ratio of bran to husk than grade A) (Mamun-Ur-Rashid et al. 2013). Rice bran is derived from the three rice production systems: *aus*, *boro and amon* which take place at different times of the year, thereby enabling a continual production of rice and a year-round supply of rice bran (Agboola et al. 2019).

Opportunities for incorporating RTB products into aquafeed

The Bangladeshi aquafeed sector has access to large amounts of locally available carbohydrate-high agricultural by-products, which have been successfully incorporated into fish feed. Competition from the poultry and cattle sectors is the only significant threat to the use of rice-based and wheat-based feed ingredients (Agboola et al. 2019).

	Common name	Scientific name
Carp	Catla	*Catla catla*
	Rohu	*Labeo rohita*
	Mrigal	*Cirrhinus mrigala*
	Labeo	*Labeo calbasu*
	Grass carp	*Ctenopharyngodon idellus*
	Common carp	*Cyprinus carpio*
	Silver carp	*Hypophthalmichthys molitrix*
Catfish	Walking catfish	*Clarias batrachus*
	African catfish	*Clarias gariepinus*
	Pangas	*Pangasianodon hypophthalmus*
	Stinging catfish	*Heteropneustes fossilis*
Snakehead	Striped snakehead	*Channa striata*
	Spotted snakehead	*Channa punctatus*
Non-native large fish species	Tilapia	*Orechromis niloticus*
	Silver barb	*Puntius gonionotus*
Small indigenous fish species	Mola carplet	*Amblypharyngodon mola*
	Climbing perch	*Anabas testudineus*
Crustacean	Black tiger shrimp	*Penaeus monodon*
	Freshwater prawn	*Macrobrachium rosenbergii*

Sources: Zaher and Mazid 1992; Shamsuzzaman et al. 2017.

Table 6. Commonly cultured fish and other aquatic animals in Bangladesh.

Ingredient	Rate of inclusion (% composition)	Source (local or imported)	Local production (t per year)*	Availability (peak season)	Price (USD per kg)**
Rice bran	20–50	Local	1,735,500 (2016)***	Nationwide, year-round (harvesting)	0.17–0.24
Broken rice	0–30	Local	347,100–2,429,700 (2016)****	Nationwide, year-round (harvesting)	0.25–0.26
Rice polish	0–50	Local	1,041,300 (2016) *****	Nationwide, year-round (harvesting)	Information not found (INF)
Maize	5–20	Local	2,445,000 (2016)	INF	0.21–0.24
Wheat	0–20	Local and imported	1,248,000 (2016)	INF	INF
Wheat bran	0–20	Local and imported	INF	Nationwide, year-round (harvesting)	INF
Wheat flour	0–15	Local	INF	Nationwide, year-round (harvesting)	0.24–0.26
Soybean meal	10–30	Local and imported	789,000* (2016)	INF	0.43–0.48
Mustard and rape oil cake	10–25	Local and imported	327,000* (2016)	Nationwide, year-round (Jan.–Mar.)	0.31–0.33
Khesari seed		Local	122,000 (2016)	INF	INF
Fishmeal	5–20	Local and imported	37,500 (trash fish)	INF	0.50–0.95
Fish oil	0.1–0.2	Local and imported	INF	INF	2.14
Meat and bone meal	10–30	Local and imported	INF	INF	0.23–0.30

** Rounded to the nearest thousand.*
*** Based on exchange rate of BDT 1 to USD 0.012.*
**** Based on the knowledge that rice bran is about 5% of the total rice yield, which in 2016 was 34,710,000 (Agboola et al. 2019).*
***** Based on the knowledge that broken rice is between 1% and 7% of the total rice yield.*
****** Based on the knowledge that rice polish is about 3% of the total rice yield.*

Sources: Agboola et al. 2019; Mamun-Ur-Rashid et al. 2013; Zaher and Mazid 1992; Belton et al. 2011; MRICE08; MFEED06.

Table 7. Major commercial aquafeed ingredients in Bangladesh.

With regard to potentially including RTB crops in fish feed formulations in Bangladesh, potato- and banana-derived by-products present the most practical opportunities, based on the scale of production (Table 8) and associated waste residues. As an energy source, however, they are perhaps not as urgently required in the Bangladeshi context or in comparison to Nigeria.

Potato and potato peel

In 2016, Bangladesh produced 9.5 million metric tons of potatoes (Agboola et al. 2019). The crop is extensively cultivated and consumed almost daily by the majority of the population (Sultana et al. 2016). Nevertheless, several metric tons of potatoes are wasted every year because of inadequate storage facilities and oversupply (Sultana et al. 2016; Agboola et al. 2019), and potato peels are often discarded as well.

According to Agboola et al. (2019) potato peels contain considerable amounts of nutrients—64.6% total carbohydrates, 13% crude protein, 0.9% crude fat, 12.5% crude fiber and 9% ash - so in theory they could be effectively incorporated into the diets of various fish species. Sultana et al. (2016) previously explored this in relation to the use of potato in poultry rations in Bangladesh and found that potato could effectively replace maize meal with no significant differences in the feed conversion ratio, survivability rate, egg production and egg quality. They also claim that since the annual potato yield in Bangladesh is greater than that of maize (potatoes show higher productivity rates and have a shorter harvesting period) potatoes could play a crucial role in the sustainable development of the poultry sector (Sultana et al. 2016). Strategies such as including unused potatoes and discarded potato peels in aquafeeds needs to be examined (Agboola et al. 2019).

Banana peel and leaf

According to Agboola (2019), banana peel and leaf could also be included in aquafeed. Bangladesh produces nearly 1 million metric tons of banana annually (Hossain et al. 2016). Substantial quantities of by-products in the form of peel, which make up about 30% of the total banana production, often accompany the consumption and use of banana (Agboola et al. 2019). Ripe banana peel contains 56.5% total carbohydrates, 16.8% crude fiber, 12.1% ash, 7.8% crude fat and 6.8% crude protein (Hossain et al. 2015). This can be converted into chips or other forms before being included into animal feeds, as can banana leaf (another by-product), which can be dried and processed into banana leaf meal and be included in aquafeed (Agboola 2019).

Commonly used protein sources and associated challenges

Although a substantial amount of the carbohydrate sources in the Bangladeshi aquafeed sector is agricultural by-products and thus do not compete with human consumption, the sector does rely heavily upon fishmeal as the primary source of protein. As such, competition between the use of fish for human consumption and in aquafeeds is likely and problematic, given Bangladesh's human nutrition challenges, but has yet to be explored (Mamun-Ur-Rashid et al. 2013).

Crop	Production (t)
Banana	807,104
Bean, green	137,495
Chick pea	6,237
Cucumber and gherkin	121,254
Maize	3,025,392
Papaya	134,647
Potato	10,215,957
Pulses*	119,000
Pumpkin, squash and gourd	340,908
Rice, paddy	48,980,000
Spinach	66,292
Sweetpotato	262,702
Tomato	388,725
Wheat	1,311,473

**Not elsewhere specified—those not already included in another category.*
Source: FAOSTAT.

Table 8. Selected crop production in Bangladesh (2017).

Most feed producers aim to include at least 5% fishmeal, though some companies include much more, such as in floating catfish feed, which is composed of 40% fish. Domestic demand for fishmeal is greater than local supply, so fishmeal is also imported from China, Malaysia and India (Mamun-Ur-Rashid et al. 2013; Belton et al. 2011).

There is a lack of data available on the quantity of fishmeal produced in Bangladesh and the composition of local fishmeal and its value chain (Agboola et al. 2019). However, local fishmeal is generally said to be manufactured using fish waste, crab and other aquatic animals, though the composition of fishmeal varies greatly, as does the quality (Agboola et al. 2019). According to Mamun-Ur-Rashid et al. (2013) *chewa* (*Pseudapocryptes elongates*), a small mudskipper that is found in Kuakata, southern Bangladesh and the northern Bay of Bengal, is the highest quality, locally available source of fishmeal, with a 44%–52% crude protein content. Belton et al. (2011) reports that 10 companies use this species as a fishmeal source, though demand for this species exceeds supply.

Plant-based feed ingredients, such as mustard oil cake and soybean meal, are commonly incorporated into aquafeed in Bangladesh and are valued for their relatively high protein content as well as total carbohydrate content (Table 9).

In 2016, a total of 327,000 t rape and mustard oil cakes were produced nationally, though Bangladesh imported 136,000 t rapeseed meal from India to supplement its local oil cake production (Agboola et al. 2019). Requirements in other feed sectors, poultry in particular, also influence demand for rape and mustard oil cakes (Agboola et al. 2019). There is intense competition between the poultry and aquaculture feed sectors for the use of soybean meal, a by-product of the extraction of soybean oil (Agboola et al. 2019). Bangladesh also relies on imports of soybean to meet domestic demand for soybean meal, which is currently about 1.3 million metric tons (Agboola et al. 2019).

Alternative plant-based protein sources: Opportunity for RTB

In terms of protein sources, RTB crops do not currently present any significant opportunities for inclusion in aquafeed production in Bangladesh, unlike Nigeria. Cassava and sweetpotato production in Bangladesh is minimal[5] (CIP23), so the supply of protein-rich leaf meal would be insufficient for commercial usage. Efforts to increase sweetpotato production in Bangladesh are underway, which could open up some opportunities for incorporation in the future (CIP23). However, there are better and more contextually relevant plant-based protein sources currently used in the country's aquafeed production that could be promoted further.

In their recent study, Agboola et al. (2019) identified some promising alternative plant-based protein sources that require further investigation: sesame seed cake, groundnut cake and duckweed (see Table 9 for nutrient composition). Sesame seed cake, a by-product generated after removing oil from sesame seeds, is used in domestic aquafeed production, though to a small extent. But Agboola et al. (2019) conclude that because of the nutritional profile of this feedstuff, there is potential for sesame seed meal and sesame oil to become valuable ingredients in aquafeed production.

Section summary

Aquaculture involves raising fish under a controlled environment in which feeding, growth, reproduction and health can be managed. Fish require adequate levels of carbohydrate, protein, fat and oil, fiber, vitamins and minerals for metabolism, growth and development.

In semi-intensive to intensive culture systems, it is necessary to feed cultured fish compound feeds to meet these nutritional requirements. Compound feeds allow farmers to increase stocking density, increase yield and shorten cultivation periods by promoting faster growth (Nwokocha and Nwokocha 2013; Solomon 2015).

Several authors have suggested that to achieve greater and more sustainable growth in the aquaculture sector, it is necessary to develop the domestic aquafeed industry by (1) regulating the industry through setting quality control standards; (2) training fish farmers and feed manufacturers on how to formulate and produce nutritionally balanced high quality fish feed; (3) increasing the affordability of machineries through provision of subsidies; (4) identifying locally available feed ingredients; and (5) using waste products in fish feed to replace imported feedstuff. There is

Ingredient	Crude protein	Crude lipid	Ash	Crude fiber	Total carbohydrates
Maize	9.7	5.0	7.3	2.5	75.6
Wheat	10.2	2.2	11.6	3.0	73.0
Wheat bran	16.4	5.7	4.9	Unknown	Unknown
Wheat flour	14.7	2.9	2.3	1.4	78.7
Rice	8.4	2.1	2.2	1.6	85.7
Rice polish	13.8	10.8	9.7	11.5	54.2
Rice bran	8.4	10.2	15.0	16.3	50.0
Broken rice	10.6	2.1	2.2	3.1	82.0
Soybean meal	40.0	7.2	5.2	3.9	43.7
Mustard oil cake	32.5	12.0	11.6	9.4	34.5
Potato	2.8	0.2	1.4	4.9	90.7
Potato peel	13.0	0.9	9.0	12.5	64.6
Green banana peel	7.0	6.0	8.8	24.1	54.1
Ripe banana peel	6.8	7.8	12.1	16.8	56.5
Banana blossom	13.8	3.9	10.2	27.4	44.7
Cassava leaf meal	12.6	6.7	8.9	13.4	71.8
Cassava peel	2.9	0.6	1.8	1.8	92.9
Sweetpotato leaf meal	24.7	3.2	11.4	4.6	11.7
Sweetpotato peel	6.3	0.2	6.0	11.5	12.5
Sesame seed oil cake	32.8	8.1	13.9	5.2	39.9
Duckweed	29.5	4.3	31.5	10.9	23.8
Groundnut seed cake	46.2	6.9	5.2	7.5	34.2

Sources: Agboola et al. 2019; Olusola and Olaifa 2018; Nwokocha and Nwokocha 2013.

Table 9. Proximate percentage composition of selected aquafeed ingredients in Bangladesh.

the evident interest in comparably nutritious, affordable and locally available non-conventional fish feed ingredients (FAO 2007b; Gabriel et al. 2007; Fayose and Ogunlowo 2012).

To a degree, it seems that the trialled RTB crop residues and leaves can replace maize or fishmeal more effectively. A few studies also indicate this could result in positive economic implications for farmers (Abu et al. 2010b; Sine et al. 2017)

Although we have identified some RTB crop by-products that could be harnessed as local and cheap carbohydrate sources in aquafeed, more up-to-date information on the cassava peel value chain in Nigeria is needed, and greater effort needs to be directed to identifying and promoting contextually relevant, effective and non-competitive protein sources in both Bangladesh and Nigeria. Reducing the pressure on fish for fishmeal has both nutritional and environmental implications.

Integration at consumption

Evidence of fish being eaten with roots, tubers or bananas

In a report exploring the market opportunities of cassava-based products, Karuri et al. (2001) identified fish being incorporated in two cassava-based dishes commonly eaten by various people in Kenya. Similarly, in their book chapter on cassava-based products, Sharma et al. (2016) give a detailed account of various, yet quite similar, cassava-based food products eaten by populations in mostly West African countries. As well as describing the processes involved in making these products, Sharma et al. (2016) name the foods that traditionally complement these cassava-based food products. Fish is a common accompaniment in Côte d'Ivoire, Ghana, Kenya and Nigeria.

In Côte d'Ivoire, *attoukpou* is commonly served with sauce, vegetables and fish or meat. It is also one of a number of foods formed using *garri*. In this case, *attoukpou* is made by molding *garri* into flattened shapes before steam cooking (Sharma et al. 2016).

Konkonte, a traditional Ghanaian dish is also made with cassava flour ground from sun-dried cassava chips that is then added to boiling water and stirred until it forms a smooth, thick paste. This is served with ground pepper and fish or meat and is considered a customary dish for lactating mothers, particularly among the Krobo people in eastern Ghana (Sharma et al. 2016). In southern parts of Ghana, however, it is considered a "poor man's food," which limits its consumption (Sharma et al. 2016).

Cassava fish stew, eaten by people in the coastal provinces of Kenya, is prepared by peeling, slicing and cooking cassava root along with tomato and onion. Fresh fish is either added to the mixture with coconut milk or fried in oil and then added afterward to the boiling cassava with groundnut flour instead of coconut milk (Karuri et al. 2001). In western Kenya, cassava-based *ugali* is made by peeling, washing, slicing and sun-drying cassava root. The sun-dried chips are mixed with dried maize, sorghum or millet, and then the mixture is milled into a fine flour. Finally, the flour is added to boiling water and stirred into a semi-solid porridge. The dish is commonly served with smoked fish (Karuri et al. 2001).

Somewhat similar to *ugali*, *kpokpo garri*, which is a variation of regular *garri*, is often eaten with dried or smoked fish, groundnut and/or coconut kernel in midwestern Nigeria (Sharma et al. 2016). Unlike standard *garri*, the fermented and dried grated cassava is not sieved before roasting, which results in the creation of shapeless cakes. *Kpokpo garri* is also traditionally served with roasted maggots and palm wine (Sharma et al. 2016).

The nutritional value of cassava-based dishes

Across much of Africa, especially in Ghana and Nigeria, cassava is an important root crop and is consumed as a staple food (FAO and IFAD 2005). Cassava or cassava products, such as *garri*, are consumed almost daily by Nigerians (Onyenwoke and Simonyan 2014). In Nigeria, both rural and urban populations consume cassava root as an inexpensive source of carbohydrates (Mcnulty and Adewale 2015). *Garri* is popular because it is easy to prepare and has a long shelf life (Mcnulty and Adewale 2015). In its raw state, cassava has a relatively high calcium content when compared to other staple crops and a high vitamin C content.

However, much of the nutritional value of cassava root is contained in the peel, so when the root is peeled and discarded, as it often is, a substantial amount of minerals and other nutrients, such as calcium and iron, are lost (Table 10). Processing also has a significant effect on the nutritional value of cassava, as shown in Table 10. Vitamin C is sensitive to heat and most processing procedures employed result in a drastic loss of this vitamin. This means that the nutritional value of cassava root is greatly reduced when it is eaten as *garri* or cassava flour. Mcnulty and Adewale (2015) suggest that people with a predominantly cassava root-based diet are at risk of micronutrient malnutrition, which can cause night blindness, stunting and increased susceptibility to disease.

Attempts to increase the nutritional value of staple foods through biofortification

Biofortification of staple crops is one of the approaches agroindustry, international development organizations and governments have taken to address micronutrient deficiencies. Biofortification is the processes through which the nutritional quality of a food crop is deliberately improved through conventional plant breeding or modern biotechnology (Oparinde et al. 2014). Evidence suggests this approach is technically realistic and does not compromise agronomic activity (Nestel et al. 2006). As it targets staple food crops (e.g. rice, cassava, wheat, maize and sweetpotato) that low-income households frequently consume, biofortification is said to capitalize on the regular daily intake of a consistent and large amount of food staples by all family members to ensure impact (Nestel et al. 2006).

Biofortification examples: Vitamin A-rich yellow cassava

HarvestPlus and partners have developed and deployed biofortified vitamin A-rich yellow cassava varieties to address vitamin A deficiency in Nigeria (Mcnulty and Adewale 2015). According to Oparinde et al. (2014), vitamin A deficiency is a major public health problem in Nigeria, about 30% of children under 5 years old are deficient. Vitamin A deficiency limits growth, weakens immunity, affects sight and increases the risk of mortality (National Population Commission [Nigeria] and ICF International 2014). As part of this initiative, HarvestPlus has investigated the consumer acceptance of *garri* made with vitamin A-enriched yellow cassava.[6] Oparinde et al. (2014) found that established regional color preferences influenced consumers' willingness to pay premium prices for the biofortified cassava. In Oyo State, South West Nigeria, *garri* is commonly produced by mixing grated or ground cassava with palm oil, creating a distinctively yellow variety of *garri*. Thus, in this region, even in the absence of nutrition information campaigns, consumers were willing to pay higher prices for the biofortified variety (Oparinde et al. 2014). In addition, Tahirou et al. (2015) showed that farmers in Oyo State had the highest reported adoption rate of biofortified cassava.

While this initial evidence highlights a promising point of market entry for yellow cassava, the regionally high prices suggest that this

	Whole root (raw)	Peeled root (raw)	Boiled root	*Garri*	Flour (retting and no peel)
Protein (g)	1.0	0.48	0.38	0.37	0.16–0.22
Fat (g)	0.1	0.1	0.04	0.2	0.04–0.06
Carbohydrate (g)	37.9	31.0	27.4	28.8	20.9–25.1
Calcium (mg)	26	13	12	10	6.0–8.0
Iron (mg)	3.5	0.4	0.4	1.5	0.2–0.7
Zinc (mg)	0.34	/	/	/	/
Potassium (mg)	271	/	/	/	/
Vitamin C (mg)	33	20	1	2	0

Source: Adapted from Montagnac, Davis and Tanumihardjo 2009.

Table 10. Nutritional value after processing 100 g of cassava root.

intervention may not reach the intended population—low-income, micronutrient-deficient populations. Perhaps such issues will be discussed as a result of the large-scale efficacy trial, which according to Bouis and Saltzman (2017) is underway.

Vitamin A-rich orange-fleshed sweetpotato

In Bangladesh, the Bangladesh Agricultural Research Institute (BARI) has introduced vitamin A-rich OFSP varieties in collaboration with CIP and promoted at the household level by various international development organizations, including HKI, through the Suchana project. One small boiled root, roughly 100 g, of most OFSP varieties is said to provide 100% of the RDA of vitamin A for children, or at 400 Retinol Activity Equivalents (RAE) (Low et al. 2017). Moreover, over 80% of the beta-carotene content in OFSP is retained when boiled, a retention level superior to most other crops (Low et al. 2017). However, unlike cassava in Nigeria, sweetpotato is not a staple crop in Bangladesh, where only a relatively small amount of local white varieties is available. Personal communication with project households, implementing partners and regional academic professionals indicates that organizations working on the introduction of OFSP in Bangladesh have faced some issues regarding consumer acceptance, specifically taste preferences. Although the introduction of OFSP has been accompanied with nutrition information campaigns, the households interviewed prefer the taste and texture of the local white, nutritionally inferior sweetpotato varieties (SOFSP19; SSUCH16; SSAU14; RBARI05; CIP23). Consumers described the texture of cooked OFSP as "sluggy" and undesirable, which can be ascribed to its higher moisture content. Steaming the root instead of boiling it was said to reduce the unpleasant "sluggishness" (SOFSP19). But the orange varieties are also considered unappealingly less sweet than the white varieties. Consumers are also apprehensive about its orange color (CIP23).

Nevertheless, OFSP has received some market traction, particularly in Dhaka's supermarket chains, including Shwapno and Agora (CIP23), that service the urban better-off population. Representatives from CIP in Bangladesh communicated that market-savvy farmers have been selling OFSP to supermarkets in Dhaka for BDT 30 (USD 0.36) per kg. The supermarkets then sell these to relatively wealthy, urban dwellers for BDT 60–75 (USD 0.71-0.89) per kilogram (CIP23). This is 10 times the price of OFSP sold in rural, "local" markets, which is about BDT 6–7 (0.07–0.08 USD) per kilogram (CIP23).

The potential of OFSP was recognized in 1995, and today the agricultural community perceives biofortified OFSP as a "superfood," a largely successful example of the role biofortification can play in nutrition-sensitive agricultural production (Bouis and Saltzman 2017; Low et al. 2017). It has been used instrumentally in over 14 sub-Saharan African countries to address widespread vitamin A deficiency (International Potato Center 2018b).

White sweetpotato is an important staple in countries such as Burundi, Malawi, Rwanda, and Uganda, with over 80 kg per capita per year consumed (Low et al. 2017).

In Uganda, an average of 1,841,667 t of sweetpotato was produced per year, from 2012 to 2014 (Low et al. 2017). Sweetpotato in sub-Saharan Africa is generally considered a crop of the poor, and production in Eastern, Central and Southern Africa is dominated by women (Low et al. 2017). According to Low et al. (2017) the use of OFSP to address vitamin A-deficiency is logical as farmers already know how to cultivate sweetpotato and because those most at risk are children in poor households in which women are the dominant food preparers and caregivers.

The primary evidence for the effectiveness of biofortification comes from the consumption of OFSP in sub-Saharan Africa (Bouis and Saltzman 2017). From 2006 to 2009, OFSP interventions, led by HarvestPlus, reached over 24,000 households in Uganda and Mozambique. In rural Uganda, this resulted in increased vitamin A intakes among children and women and improved vitamin A status among children (Bouis and Saltzman 2017). In Mozambique, Bouis and Saltzman (2017) reported that consumption of biofortified OFSP reduced the prevalence and duration of diarrhea in children under 5 years of age.

Although there is relatively sufficient evidence of the appropriateness and efficacy of OFSP-based integrated agriculture-nutrition programs in sub-Saharan Africa, its suitability in the Bangladeshi context is less pronounced. In 2017, Bangladesh produced 262,702 t of sweetpotato (FAOSTAT), though this figure is almost consistently lower than it has been in the past (see Figure 3). The production of sweetpotato in Bangladesh is seasonal (Hossain et al. 2018), generally planted in October and harvested before the end of April (SBARI13; SSAU14). Farmers in Bangladesh consider this cultivation period too long (roughly 4 months). Nationally, the ideal cultivation period is 90–100 days, which is met by most other crops commonly grown in Bangladesh (CIP23). Perhaps this is one reason why the popularity of sweetpotato has seemingly decreased over the past 50 years. During a visit to Suchana project households' homestead gardens in mid-February, one woman mentioned how she had decided to harvest her sweetpotato crop early so that she could plant lady fingers (okra) before the raining season (SSUCH16) (Plate 4). Therefore, CIP is collaborating with BARI to increase the dry matter content and developing early maturing varieties of OFSP (Naziri, personal communication, 2019).

Figure 3. Sweetpotato production in Bangladesh.

Plate 4. Sweetpotatoes harvested from a SUCHANA project household's homestead garden, Sylhet, Bangladesh.

Although there is a breadth of research on the production and consumption of sweetpotato in Bangladesh, relatively less information exists on other micronutrient-rich, locally produced and consumed crops, such as Indian spinach (*Basella alba*) (Hossain et al. 2018) and taro.

Other vitamin A-rich crops

Indian spinach is a low cost, green leafy vegetable available year-round in Bangladesh (Hossain et al. 2018). In their study on the effects of sweetpotato and Indian spinach consumption on total body vitamin A stores in Bangladeshi men, Hossain et al. (2018) concluded that daily consumption of Indian spinach has a positive effect on vitamin A status.

While the vitamin A content of OFSP is superior to taro leaves (Table 11), the consumption of taro leaves (100 g) contributes 30% of the recommended daily vitamin A requirement for women (over 13 years old, based on a RDA of 700 µg per day) and 53% for children (based on a RDA of 400 µg per day). Taro leaves contain relatively higher amounts of calcium, potassium, ascorbic acid and folate in comparison to boiled OFSP root and leaf (Table 11). They are eaten on a weekly to monthly basis in Bangladesh (SSUCH15; SSUCH17) and generally consumed with small prawns or dried fish (SSUCH15; SSUCH16; SSUCH17; SSUCH18). Occasionally, the leaves are consumed with large fish (SSUCH18) or jackfruit seed (SSUCH17). However, these accounts are only exemplary. To the authors' knowledge, there is no data regarding the scale and geographical distribution of taro produced or consumed nationally and research on this potentially nutritionally valuable crop is missing.

Adding fish in dishes and meals

As the literature suggests, fish often accompanies staple cassava products in traditional dishes from Côte d'Ivoire, Ghana, Kenya and Nigeria. Fish are a good source of readily absorbable and bioavailable micronutrients, including calcium, iron, zinc and vitamin A and are rich in high quality and readily digested protein as well as energy (Neumann et al. 2014).

In eastern Kenya, Talsma et al. (2018) trialled yellow cassava for its potential contribution to the dietary nutrient adequacy of primary school children. Biofortified yellow cassava was introduced into school lunch to increase vitamin A intake, though yellow cassava is known to be generally poor in other nutrients, including iron and zinc. An assessment of the potential effect of introducing a yellow cassava-based school lunch, combined with additional food-based recommendations on overall nutrient adequacy, was conducted. Talsma et al. (2018) reported that the addition of

	Taro, cooked, without salt (per 100 g)	Taro leaf, steamed, without salt (per 100 g)	Taro shoots, cooked, without salt (per 100 g)	OFSP root, boiled, without skin (per 100 g)	Sweetpotato leaf, steamed without salt (per 100 g)
Calcium (mg)	18	86	14	27	33
Iron (mg)	0.72	1.18	0.41	0.72	0.63
Potassium (mg)	484	460	344	230	312
Zinc (mg)	0.27	0.21	0.54	0.20	0.26
Vitamin C, total ascorbic acid (mg)	5.0	35.5	18.9	12.8	1.5
Vitamin B6 (mg)	0.331	0.072	0.112	0.165	0.160
Folate, DFE (µg)	19	48	3	6	49
Vitamin A, RAE (µg)	4	212	3	787	147

Table 11. Selected vitamin and mineral content in taro and sweetpotato.

dried small fish, two servings a week, to the yellow cassava school lunch best optimized the overall nutrient adequacy of the diet of primary school children.

Although all species of fish contain considerable amounts of protein, some have exceptionally high levels of micronutrients and essentially fatty acids (Longley et al. 2014). Small fish species such as darkina *(Esomus danricus)* and mola, derived from inland capture fisheries in Bangladesh, contain superior amounts of micronutrients and lipids as compared to farmed large freshwater fish such as silver carp (Table 12) especially when eaten whole with heads and bones included (Roos et al. 2007; Belton and Thilsted 2014). While fish unquestionably adds nutritional value to the featured traditional dishes eaten in Côte d'Ivoire, Ghana, Kenya and Nigeria, the degree of value added is undetermined as the species that commonly accompany these dishes are unrecorded. It is also unclear which parts of the fish are consumed.

Moreover, the documents identified provide little insight into the commonness or universality of these cassava-based dishes consumed with fish. It is more than likely that socioeconomic status influences the amount and frequency of fish and meat consumed with these cassava-based dishes. In Nigeria, evidence suggests that variation in the frequency of fish consumption based on socioeconomic status is probable.

According to a study conducted by IPSOS (2017), 74% of people of high socioeconomic status surveyed consumed fish or seafood twice a week compared to 40% from the lowest socioeconomic group. The species of fish eaten is also likely affected by relative wealth, as the market value of fish varies according to the species. Additionally, the availability, preference and species of fish consumed are often regionally unique and seasonal (Bradley et al. in press).

The enhancing factor of fish

In addition to its intrinsic nutrient content, fish, like other animal-sourced food, further contributes to food and nutrition security by facilitating the uptake of nutrients from dietary components of vegetable origin (Belton and Thilsted 2014). Fish, specifically, enhances the bioavailability[7] of non-heme iron and zinc from plant sources (Tontisirin et al. 2002). Even relatively small amounts of meat (about 50 g for adults) have been demonstrated to enhance non-heme iron absorption from a basic meal with low iron bioavailability (Bæch et al. 2003), though the exact mechanism through which meat has an enhancing effect on iron absorption has not yet been explained in detail (see Michaelsen et al. 2009). Similarly, Sandstrom et al. (1989) found in their study that small amounts of animal-source food significantly improved the value of a legume-based meal as a source of zinc. They concluded that relatively small amounts of animal-source foods can significantly improve the value of a legume-based meal as a source of zinc.

	Common name	Scientific name	Vitamin A RAE	Calcium (g)	Calcium (g)*	Iron (mg)	Zinc (mg)
Small indigenous fish species	Darkina	*Esomus danricus*	890 ± 380 (3)	0.9 ± 0.4 (3)	0.8 ± 0.3 (3)	12.0 ± 9.1 (3)	4.0 ± 1.0 (3)
	Mola	*Amblypharyngodon mola*	2680 ± 390 (7)	0.9 ± 0.1 (3)	0.8 ± 0.0 (3)	5.7 ± 3.7 (3)	3.2 ± 0.5 (3)
	Puti	*Puntius sophore*	60 ± 20 (3)	1.2 ± 0.2 (4)	0.8 ± 0.1 (4)	3.0 ± 0.9 (4)	3.1 ± 0.5 (4)
Commonly cultured large fish species: carp	Mrigal	*Cirrhinus cirrhosus*	< 30 (1)	1.0 ± 0.1 (3)	0.0 ± 0.0 (3)	2.5 ± 1.3 (3)	Not measured
	Silver carp	*Hypophthamichyths molitrix*	< 30 (3)	0.9 ± 0.4 (3)	0.0 ± 0.0 (3)	4.4 ± 1.8 (3)	Not measured

**After correcting for calcium in the plate waste (mainly bones).*

Source: Adapted from Roos et al. 2007.

Table 12. Vitamin A, calcium, iron and zinc contents in selected, commonly consumed fish species in Bangladesh (per 100 g, raw, cleaned parts).

Ascorbic acid (vitamin C) is also an important bioavailability enhancer of non-heme iron (Davidsson 2003), especially in low-income countries, where meat intake is low (Tontisirin et al. 2002). According to Michaelsen et al. (2009), orange, apple and pear can have a similar effect, as meat and fish do, on the absorption of non-heme iron.

Unlike plant-source foods, fish and other animal-source foods do not contain iron, zinc and calcium absorption inhibitors, such as phytic acid, polyphenols and oxalic acid (Michaelsen et al. 2009; Gibson et al. 2010; Longley et al. 2014). Cereals, legumes and oleaginous seeds have especially high levels of phytic acid, so on their own they have a low bioavailability of iron (Davidsson 2003; Gibson et al. 2010). Roots and tubers, most leafy vegetables and fruits contain much lower amounts of phytic acid (Gibson et al. 2010). However, green leafy vegetables contain high levels of polyphenols, which can seriously inhibit the absorption of non-heme iron (Michaelsen et al. 2009).

In summary, the combination of foods eaten in a meal strongly influences the absorption of micronutrients, but absorption is also influenced by food processing techniques (Tontisirin et al. 2002). For example, fermentation, germination and malting of cereals, legumes and oily seeds increase the absorption of iron by lowering the phytic acid and polyphenol content (Tontisirin et al. 2002). Similarly, the absorption of non-heme iron and zinc in tubers has been shown to be enhanced by mild heat treatment (Tontisirin et al. 2002).

Improving the nutritional value of traditional cassava/potato snacks with fish

Consumption of street foods and affordable snack foods is an important component of the diet of adults and children in developing countries, especially for the urban poor (Steyn et al. 2013). In sub-Saharan Africa, school children are reported to eat a large amount of street foods (FAO and Sokoine University 2006). Steyn et al. (2013) reported that 13%–40% of children's daily energy intake comes from street foods.

In low-income countries, traditional snack foods are generally carbohydrate-based. Although they are a good source of energy and perhaps protein (Steyn et al. 2013), the micronutrient contribution of street foods is unknown. However, it is thought to be insignificant (Cliffe and Okereke 2010). Therefore nutritionists have been exploring avenues for enhancing the nutritional value of traditional snack foods. Four articles have been identified here that, primarily with the addition of fish, hoped to develop a "value added," mostly cassava-based snack (Table 13) (Cliffe and Okereke 2010; Neiva et al. 2011; Akonor et al. 2017; Rochimiwati et al. 2017).

Three of these studies featured a form of fish cracker (Neiva et al. 2011; Akonor et al. 2017; Rochimiwati et al. 2017). Neiva et al. (2011), for example, aimed to develop sensory acceptable, nutritionally valuable fish crackers using minced low market value species, in this case Southern King Croaker and Sand Drum. This research was driven by a desire to increase fish consumption and the dietary intake of essential amino acids including lysine (Neiva et al. 2011). Rochimiwati et al. (2017) focused on modifying a similar product but with flying fish.

Fish crackers, already popular in Asian countries, are traditionally made with cassava-derived starch and are slowly becoming a popular snack in Ghana (Akonor et al. 2017). Unlike the two studies mentioned above, Akonor et al. (2017) explored the sensory acceptability, based on taste, crispiness and puffiness, of replacing cassava starch with HQCF. However, this study was rationalized by a desire to explore commercial market opportunities for HQCF in Ghana rather than by nutritional objectives. As a result, the authors did not compare the nutritional composition of fish crackers made with cassava starch versus HQCF.

On the other hand, Cliffe and Okereke (2010) developed a recipe for fish yam/sweetpotato balls. By using contextually undervalued pelagic fish species, cockles and oysters, they intended to produce a cheap, "value added" protein enhanced snack product suitable for the Nigerian market. In their recipe, yam or sweetpotato cubes are boiled and mashed into a paste and then mixed with minced fish. The mixture is then rolled into balls, rolled in egg and bread crumbs then deep-fried (Cliffe and Okereke 2010). Unfortunately, they do not include the nutritional composition of these "value added" snack balls and do not rationalize their use of yam or sweetpotato. The sweetpotato balls scored well in the consumer preference survey, based on texture, aroma, taste, color and overall appearance (Cliffe and Okereke 2010), though there were only five panelists.

Complementary food products for infants and young children

Complementary feeding refers to the timely introduction of safe and nutritious foods in addition to breastfeeding. It occurs when the infant is about 6 months of age (World Health Organization 2008). In low-income countries, most infants are given cereal-based complementary foods (Francis Kweku Amagloh et al. 2012).

The most effective complementary foods are micronutrient-dense, prepared using a variety of foods and include an animal-source food. Improving complementary feeding practices is considered a "food-based" effort to improve the nutrient intake of children during the first 1000 days of life (Bogard et al. 2015). Fortification is the addition of micronutrients at the processing phase, and fortifying plant-based, commercially produced complementary foods to achieve desired nutrition densities is one approach. But not all mothers have the means to buy these products (Bogard et al. 2015). Home-based approaches are a valuable alternative. They include encouraging the addition of local, culturally acceptable, nutrient-rich ingredients, as well as animal-source foods, in complementary feeding practices through educational campaigns.

Bogard et al. (2015) developed a fish-based complementary food product, targeting improved nutrition in the first 1000 days. The complementary food is based on the traditional rice-based porridge used in Bangladesh. To enhance its nutritional quality, 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, a small indigenous fish species, was selected for its high iron, calcium and zinc content (Bogard et al. 2015).

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 aged 12 to 23 months (Bogard et al. 2015). The fish-based complementary food contributed substantially to essential fatty acid requirements so the potential nutritional contribution of this complementary food may be even greater than the laboratory analyses indicate because of the aforementioned "meat factor" associated with the consumption of fish and other animal-source foods (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 and then compared these products to commercial infant foods (Nandutu and Howell 2009). However, the focus of the research was to compare the digestibility and consistency of the sweetpotato-based complementary food as well as assess the effects of introducing antioxidants to increase the shelf life of the product (Nandutu and Howell 2009), so the micronutrient composition of the OFSP-based complementary food product is not reported in the paper.

Section summary

The literature search did not find compelling examples of commercially produced complementary foods that combined fish and RTB crops, but there is the natural tendency for cultures to combine fish with starch-based products. Fish is a common accompaniment to cassava-based food products in Côte d'Ivoire, Ghana, Kenya, and Nigeria (Karuri et al. 2001; Sharma et al. 2016), and the addition of fish to these traditional dishes unquestionably adds to their nutritional value. 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 OFSP (Bogard et al. 2015).

Name of product	Fish species incorporated	Bones	Head	RTB incorporated	Targeted population	Research focus				Study rationale	Study location	Author(s)
						Consumer acceptability	Commercial viability	Nutritional value enhancement	Storage and packaging			
Fish crackers	Minced Southern King Croaker (*Menticirrhus americanus*) and Sand Drum (*Umbrina coroides*)	Excluded	Excluded	Cassava starch*	Adults (19–65 years old)	X		X	X	- Improve nutritional value of a traditional snack - Increase intake of lysine (essential amino acid) through increased fish consumption	Brazil (location of author)	Neiva et al. 2011
Cireng (a traditional Indonesian snack)	Flying fish (*Exocoetidae* spp.)	Excluded	Not detailed	Cassava flour and tapioca flour **	Children (of school age)			X		- Improve the nutritional value of a traditional snack	Indonesia	(Rochimiwatiet al. 2017)
Prawn crackers	Powdered black tiger prawn	N/A	Excluded	HQCF and cassava starch	Unspecified	X				- Improve the nutritional value of a cracker snack by replacing tapioca starch with HQCF	Ghana	Akonor et al. 2017
Fish-yam balls/ fish-sweetpotato balls	Minced small pelagic fish (species not specified)	Not detailed	Excluded	Yam/sweetpotato (cut into cubes, boiled until soft and mashed into paste and mixed with minced fish)	Unspecified	X				- Improve the nutritional value of snacks	Nigeria	Cliffe and Okereke 2010
Porridge	Oven-dried and powdered darkina	Included	Included	OFSP flour (peeled, blanched, oven-dried and ground into flour)	Infants and children, especially in the first 1000 days of life	X	X	X		- Improve the nutritional value of traditional rice-based porridge using animal-source foods, specifically underused small indigenous fish	Bangladesh	Bogard et al. 2015
Porridge	Tilapia (skinned fillets)	Not detailed	Not detailed	OFSP root (sliced, freeze-dried, blended, ground)	Infants			X	X	- Improve the nutritional value of cereal-based porridge	Uganda	Nandutu and Howell 2009

* Cassava starch here is not a value addition, but part of the original recipe.
** Cassava flour made from the whole root is less processed, so it contains more vitamin C (tapioca is the bleached and extracted starch of the cassava root) is more processed and contains less fewer vitamins.

Table 13. Overview of identified research papers on fish-RTB food products.

Conclusion

In this working paper, the current and potential role of fish and RTB crops in food systems in Bangladesh and Nigeria are outlined and discussed, focusing on livelihood and food and nutrition security outcomes. Our research has uncovered multiple potential synergies for the co-production and dynamic integration of fish and RTB crops.

Firstly, co-production of fish and vegetables is common among smallholders in South and Southeast Asia. Most literature records the co-production of fish with banana. In IAA systems, there are scattered references to co-production of fish with cassava, sweetpotato, potato, yam and cocoyam. It is difficult to uncover the true extent to which RTB crops are cultivated in IAA systems because most authors fail to report the types of crops planted. Sweetpotato and cocoyam were seen growing on pond dikes in Bangladesh, and they are commonly eaten with fish. Yet, very little published literature exists regarding their co-production and consumption.

The literature suggests that IAA systems, when compared to market-oriented monocropping, are generally beneficial for soil conservation, biodiversity, livelihoods and household food and nutrition security. IAA is positioned as particularly appropriate for small-scale, poor farmers and suitable for areas with low availability of agricultural land (Nhan et al. 2007; Ahmed et al. 2014). However, there is a lack of large-scale quantitative evidence to confirm this.

The literature suggests that IAA smallholders in South and Southeast Asia benefit from recycling and reusing organic "waste" produced on-farm. Examples included the use of RTB by-products as fish feed and the use of excess pond silt as crop fertilizer. However, field work in Bangladesh showed that the use of agricultural by-products by smallholders is rare and perceived as "backward." Farmers noted that Bangladeshi agricultural extension providers discouraged this practice.

The literature search reported that RTB by-products for commercial fish feed is a relatively large and growing body of work. Twenty-seven studies were identified that investigated the effects of replacing a percentage of the conventional protein or energy sources in fish feed with RTB crop derivatives. Many of these studies were conducted in Nigeria and were driven by rising costs of fish feed containing imported ingredients. Cassava peel was identified as a priority RTB fish feed ingredient in Nigeria because of the existence of a cassava processing industry to produce the staple *garri* and therefore the centralization of discarded cassava peel. Leveraging cassava peel for use in aquafeed could help to mitigate the environmental impact of "waste" in the food supply chain, as well as create additional job opportunities for converting waste to feed. Since women make up the majority (85%) of the workforce in cassava processing units in Nigeria, they could also benefit from the income-earning opportunities associated with these innovative cross-sector links (Amole 2016; Okike et al. 2014). A similar opportunity was not identified in Bangladesh because of the abundance of cheap, locally available non-RTB carbohydrate sources (e.g. broken rice, rice bran, wheat bran and oil cake) that are already used in commercial fish feed.

The literature search did not find compelling examples of commercially produced complementary foods that combined fish and RTB crops. However, there is the natural tendency for cultures to combine fish with carbohydrate-based products. Fish is a common accompaniment to cassava-based food products in Côte d'Ivoire, Ghana, Kenya and Nigeria (Karuri et al. 2001; Sharma et al. 2016). The addition of fish to these traditional dishes unquestionably adds to their nutritional value. 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 OFSP (Bogard et al. 2015).

Overall, the co-production and dynamic integration of fish and RTB show great synergistic promise at both the small and large scale. However, more research is needed on contextually appropriate solutions that improve both livelihoods and food and nutrition security.

Research, programmatic, and policy implications

- Using RTB by-products as aquafeed could reduce farmers' use of external inputs and decrease production costs, though evidence is inconclusive. Research is needed to understand how integrated fish-RTB production systems can lead to environmental, social, economical and nutritional benefits.
- Opportunities exist to use RTB by-products as aquafeed at commercial scale, to lower the cost of compound fish feed. These efforts should prioritize areas where fish feed costs represent a high proportion of farmers' production costs, and also, where locally available RTB by-products are underutilized, are cheaper than other carbohydrate sources and are less geographically scattered. Further research on replacing traditional ingredients with RTB by-products should prioritize the following:
    - the effects of replacement on fish growth performance and feed use
    - economic implications of replacing traditional ingredients with RTB crops
    - practical issues associated with the seasonality of RTB by-products, such as medium- to large-scale cassava processing sites, which only operate seasonally.
- Further research is needed on fish feeding practices of smallholder farmers to identify best practices in using RTB by-products as fish feed in homestead ponds.
- Future programs can identify micronutrient-rich combinations of fish and RTB products, such as small indigenous fish and OFSP. SBCC materials and approaches that educate caretakers of the nutritional benefits of feeding young children these foods in combination can be developed and used.

Notes

1 The term orange-fleshed sweetpotato (OFSP) is used throughout this report.

2 Gender-sensitive interventions attempt to redress existing gender inequalities through addressing gender norms, roles and access to resources (UN Women n.d.).

3 "Small-scale" fish farms are those with just one pond of 0.05 ha to farms of several ponds with a total surface area of 1 ha, with a stocking density between 1 and 2 fish/m^2 and annual fish yields from 1 to 2 t per hectare. "Medium-scale" farms have higher stocking densities from 4 to 20 fish/m^2 and produce between 4 and 20 t fish/ha per year (Agboola 2019).

4 FAO considers Nigeria a low-income, food-deficit country, based on its gross national income and net food trade (FAO 2016).

5 To the authors' knowledge, nationally representative production data for cassava and sweetpotato is not available.

6 Odebode et al. (2008) reports that sweetpotato has also been effectively made into *garri*, coined "*sparri*," using the same processes.

7 Bioavailability refers to the proportion of an ingested nutrient in food that is absorbed and used through normal metabolic pathways (Gibson et al. 2010).

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Appendix 1. Overview of interviews conducted, observational data collected and associated reference codes used in discussion

Date	Livelihood/ professional association	Sex	Location	Additional details	Reference code
26.02.19	Fingerling producer	Male	Nilphamari District, Rangpur	• 10 m^2 pond • carp and tilapia • integrated with rice production	RFING01
26.02.19	Farmer practicing fish polyculture	Male	Nilphamari District, Rangpur	• mola and carp • gourds, mangoes, lemons trees, cattle, chickens in homestead garden • pond located away from home • grows eucalyptus on pond dike for • timber production	RPOLY02
27.02.19	Fingerling producer and fish feed dealer	Male	Nilphamari District, Rangpur	• fingerlings produced in concrete tanks • carp • distributes commercial feed	RFNGFD03
27.02.19	Potato seed farmer	Male	Nilphamari District, Rangpur	• contracted by the government to supply potato seeds • potato grown in rotation with rice	RPOTSD04
27.02.19	Research scientist at the BARI substation in Rangpur	Male	Rangpur		RBARI05
02.03.19	Feed producer at SMS Feeds Ltd.	Male	Gazipur, Mymensingh	• produces feed for fish, poultry and cattle • tilapia, carp and catfish • floating and sinking feed • 32,000 t of fish feed in 2018 • 25,000 t of floating feed	MFEED06
02.03.19	WorldFish project household conducting fingerling production in *hapas*	Male	Mymensingh		MHAPA07
02.03.19	Rice mill and pond owner	Male	Mymensingh	• processed 14,000 t of rice in 2018 • pond is 3.5 ha • tilapia and Indian major carp • banana, carrot, radish, winter vegetable, papaya produced on pond dike • produces own feed	MRICE08
03.03.19	Trisal fish market	N/A	Mymensingh	personal observation	MFSHM09
03.03.19	Scientist in the Horticulture Department at the Bangladesh Agricultural University	Male	Mymensingh		MBAU10

Date	Livelihood/ professional association	Sex	Location	Additional details	Reference code
03.03.19	Scientists from the Faculty of Fisheries at the Bangladesh Agricultural University	Male	Rangpur		MBAU11
03.03.19	Scientist from the Bangladesh Fisheries Research Institute	Male	Rangpur		MBFRI12
04.03.19	Scientist at BARI in Sylhet substation	Male	Sylhet		SBARI13
04.03.19	Professors from Sylhet Agricultural University	Male	Sylhet		SSAU14
05.03.19	Suchana project household	Female	Sadar Subdistrict, Sylhet	• OFSP, spinach, aubergine, potato, cabbage, tomato, French beans, sweet gourd • stock tilapia, rohu, catla and puti	SSUCH15
05.03.19	Suchana project household	Female	Sadar Subdistrict, Sylhet	• poultry-based beneficiary—no fish • uses nearby capture fisheries • homestead garden 20 m^2 • banana (over 30 trees), OFSP (two varieties) and local white-fleshed sweetpotato, lady finger, drumstick, aubergine	SSUCH16
05.03.19	Suchana project household	Female	Sadar Subdistrict, Sylhet	• stocks tilapia, rohu and silver carp, and mola. • gourd, long bean, country bean, bitter gourd, sponge gourd, mustard grain, spinach, red amaranth, sweetpotato (local variety) and carrot	SSUCH17
05.03.19	Suchana project household	Female and male	Golapgonj Subdistrict, Sylhet	• poultry-based Suchana beneficiary • taro, gourd	SSUCH18
05.03.19	BARI OFSP contract farmer	Male	Sylhet	• contracted to grow BARI varieties of OFSP on 0.25 ha • primarily sells the seed but also harvests the root at the end of the growing period	SOFSP19
05.03.19	Taro farmer	Male	Sylhet	leases 0.2 ha of land to grow taro	STARO20
24.02.19	Scientist at WorldFish	Male	Dhaka		WFBEN21
24.02.19	Fish feed specialist at WorldFish	Male	Dhaka		WFMAM22
18.03.19	Scientists from CIP in Bangladesh	Male and female	SKYPE		CIP23

Appendix 2. Interview question guide

Interview questions for key informants:

RTB crops

1. What RTB crops are commonly consumed in Bangladesh?
   1.1. How are they consumed? In what dishes? Which parts of the crop are consumed?
2. Are these crops grown nationally, regionally and/or imported?
   2.1. What are the growing seasons?
3. What is the average annual price (per kg) for these crops or the price compared to rice? Please provide examples.
   3.1. Do these prices fluctuate often, seasonally?
   3.2. Do these prices differ regionally?
4. Are there other nonconsumptive markets in Bangladesh for these crops?
5. Are these crops commercially processed to make value-added food products, such as flour, or other nonconsumptive goods in Bangladesh?

Fish feed

1. In general, what do small-scale fish farmers in Bangladesh use to feed their fish: commercially pelleted fish feed, farm-made fish feed, kitchen waste, manure or a combination of these feeds?
   1.1. What do medium- to large-scale fish farmers in Bangladesh use?
2. For those farmers who produce fish feed on site, what ingredients do they commonly use?
   2.1. Where do they source these ingredients?
   2.2. Why do they choose to produce feeds on-farm?
3. What is the average cost of purchasing commercial feed?
   3.1. How much feed is produced nationally versus how much is imported?
   3.2. Is there regional or seasonal variance?
4. What are the major problems farmers face in terms of price, quality and availability of fish feed?
5. To your knowledge, how many large and how many small to medium commercial feed manufacturers operate in Bangladesh?
   5.1. Are they regionally concentrated?
   5.2. What is the production capacity of these industries (metric tons per year). Do they meet farmer demand?
6. Which ingredients do commercial feed manufacturers commonly use? That is, what are the primary protein and energy sources?
   6.1. Are these ingredients sourced regionally?
   6.2. Are they available year-round?
   6.3. Are they prohibitively costly?
   6.4. Do they compete with human consumption?
7. Broadly speaking, what challenges do the aquafeed industry face?
8. Are there manufacturers who experiment with the use of nonconventional feed ingredients? RTB crops specifically?
9. How does the government support the industry? Is it influencing the direction of the industry?
10. What is the role of NGOs/public-private partnerships in shaping industry progression?
11. What is your personal outlook on the potential for incorporating RTB crops, specifically their waste products, as well as associated challenges, etc.?

Integrated production

1. In Bangladesh, what percentage of ponds could be classified as "integrated-production systems"?
    1.1. Are IAA systems regionally concentrated? Or are they associated with a particular typology of farmer, such as small-scale, medium-scale or female farmers?
2. What percentage of IAA systems include integration with crops (excluding rice)?
    2.1. Which crops?
    2.2. Are any of these RTB crops?
    2.3. Please explain some of the existing interactions and their benefits.
3. What potential opportunities and challenges could occur in the future?

Consumption

1. Are there value-added food products that contain fish and RTB crops?
    1.1. Are they regional? Are they seasonally consumed?
2. Do any local dishes contain fish and RTB crops?
    2.1. Are they regional? Are they seasonally consumed?
3. What are some of the opportunities, as well as current research, partnerships and investments for consuming fish and RTB crops?
4. What are the challenges to consuming fish and RTB crops?

Interview questions for farmers

*Note: Location and farm ownership (public/private/cooperative/other)

1. Does the farm include arable land?
    1.1. If yes, how many hectares?
    1.2. What crops are planted?
        1.2.1. Any RTB crops? Now or in the past?
        1.2.2. Do you see any benefit in growing RTB crops?
        1.2.3. Do you think the main food crop (root, tuber or fruit) is marketable or useful to your household?
        1.2.4. Are there ways that "waste" products could be useful to you?
    1.3. What percentage of the crops produced are marketed, gifted and consumed?
    1.4. Where are they sold?
2. What fish species are cultured on your farm?
    2.1. Where do you culture your fish (earthen ponds, concrete tanks, cages, other)?
    2.2. What is the size of your pond: area and depth, number of hatcheries, stocking density?
    2.3. What percentage of the fish harvested are marketed, gifted and consumed?
3. Do you use commercial fish feeds?
    3.1. If yes, which type of feed (extruded, pelleted, both)?
        3.1.1. Where do you buy your feeds from (feed mill, wholesaler, retailer, other)?
        3.1.2. What is the total cost of feed over the culture period?
        3.1.3. Why do you buy commercial feed?
        3.1.4. Have you noticed any changes over time in terms of the price, availability and quality of fish feed?
    3.2. If no, do you make your feed on-farm?
        3.2.1. What ingredients are needed for on-farm feeds? Please list the ingredient, source and price (per metric ton).
        3.2.2. Have there been any changes in the price of ingredients compared to previous years? If yes, can you state the reason for the price change?
        3.2.3 What processing methods do you adopt during feed preparation?
        3.2.4. What is the reason for preparing your fish feeds on the farm?

3.3. Do you supplement naturally occurring feed with other organic and inorganic inputs, such as fertilizer, manure, kitchen waste?
   3.3.1 If yes, then what?
   3.3.2 How often?
   3.3.3 Where do you source these inputs?
   3.3.4 Why don't you buy or manufacture feeds?

4. How do you store your ingredients and/or feed and prevent them from deteriorating?
5. What do you do with organic farm waste, like crop leaves?
   5.1. When you clean the ponds? What do you do with the pond sludge?
   5.2. What do you do with kitchen waste, like potato peels and cooked rice?
   5.3. Do you strategically plant crops next to the fish ponds on pond dikes?
      5.3.1 If yes, what are the benefits of doing so?
6. Do you see any opportunities for RTB crops to benefit your fish farming?

Interview questions for feed manufacturers

* Note location

1. What is the annual capacity of the feed mill?
2. What type of animal feed is produced (poultry, pig, fish, ruminant, other)?
   2.1. What percentage of total annual feed production is fish feed?
      2.1.1. What type of fish feed do you produce (pelleted, extruded, both)?
      2.1.2. What type of fish species do you produce feed for?
3. Please list the conventional fish feed ingredients you use (source, amount in metric tons per year).
   3.1. Do you use any nonconventional (uncommon) fish feed ingredients?
      3.1.1. Do you use RTB crops or their by-products?
   3.2. When buying feed ingredients, what are the major problems you face in terms of price, quality and availability?
   3.3. How have prices of feed ingredients changed compared to previous years?
      3.3.1. What factors are responsible for the price change?
4. In cases where antinutritional factors are present, how do you get rid of them? Which processing techniques do you use? Is this easy? Does it come with any challenges?
5. Do you see any opportunities to use the waste products of RTB crops in your feed production? What is your level of interest?
   5.1. What are the factors you would consider before incorporating RTB crops or RTB by-products?
   5.2. Do you foresee any challenges associated with using feed ingredients, like potato peels for example?
   5.3. Do you know any feed manufacturers who use RTB products?

Appendix 3. Overview of reviewed literature

Author(s)	Title of publication	Date of publication	Publication type	Relevance of study				Study type				Topics discussed/research questions addressed					Geographic focus ***
				Fish-RTB focused? *	RTB crops as fish feed	Integrated agriculture-aquaculture	Integrated consumption	Primary data collection			Literature review	Productivity/ efficiency of production system or specific system intervention/ development of a product	Production value chain	Environment	Socioeconomics	Food and nutrition	
								Quantitative	Qualitative	Mixed							
Pant et al. 2004	Assessment of the aquaculture subsystem in integrated agriculture–aquaculture systems in northeast Thailand	2004	Peer-reviewed journal article			X		X				X					Thailand
Setboonsarg 2002	General division of labour in integrated agriculture of northeast Thailand	2002	Book section			X				X					X		Thailand
Miller et al. 2006	Integrated irrigation-aquaculture opportunities in Nigeria: The special programme for food security and rice-fish farming in Nigeria	2006	Book section			X					X	X*****					Nigeria
Nagoli et al. 2009	Adapting integrated agriculture aquaculture for HIV- and AIDS-affected households: The case of Malawi	2009	Grey literature – end of project report			X				X		X			X		Malawi
Mamun et al. 2011	Integrated farming system: Prospects in Bangladesh	2011	Peer-reviewed journal article			X					X	X			X		Global
Warburton et al. 2002	Integrated biosystems for sustainable development	2002	Conference proceedings			X					X	X					Global (with relevant case study in Bangladesh)
Oribhabor and Ansa 2006	Organic waste reclamation, recycling and re-use in integrated fish farming in the Niger Delta	2006	Peer-reviewed journal article			X			X		X	X		X			Nigeria
Mohri et al. 2013	Assessment of ecosystem services in home garden systems in Indonesia, Sri Lanka and Vietnam	2013	Peer-reviewed journal article			X					X			X	X	X	Indonesia, Sri Lanka and Vietnam
Dey et al. 2012	Change and diversity in smallholder rice-fish systems: Recent evidence from Bangladesh	2012	Grey literature – institutional discussion paper			X		X			X	X*****					Bangladesh
Biswas 2004	Effect of banana pseudo stem juice on water quality and fish growth: A study on the validation of indigenous technical knowledge	2004	MSc Thesis			X		X				X					India
Solomon et al. 2015	Evaluation of sweetpotato (*Ipomea batatas*) peel as a replacement for maize meal in the diet of *Clarias gariepinus* fingerling	2015	Peer-reviewed journal article	X	X			X				X					Nigeria

Author(s)	Title of publication	Date of publication	Publication type	Relevance of study				Study type				Topics discussed/research questions addressed					Geographic focus ***
				Fish-RTB focused? *	RTB crops as fish feed	Integrated agriculture-aquaculture	Integrated consumption	Primary data collection			Literature review	Productivity/ efficiency of production system or specific system intervention/ development of a product	Production value chain	Environment	Socioeconomics	Food and nutrition	
								Quantitative	Qualitative	Mixed							
Gabriel et al. 2007	Locally produced fish feed: Potentials for aquaculture development in sub-Saharan Africa	2007	Peer-reviewed journal article		X						X	X	X		X	X	Sub-Saharan Africa
Da et al. 2016	Growth performance, feed utilisation and biological indices of Tra catfish (*Pangasianodon hypophthalmus*) cultured in net cages in pond fed diets based on locally available feed resources	2016	Peer-reviewed journal article	X	X			X				X					Vietnam
Adewolu 2008	Potentials of sweetpotato (*Ipomoea batatas*) leaf meal as dietary ingredient for tilapia zilli fingerlings	2008	Peer-reviewed journal article	X	X			X				X					Nigeria
Abu et al. 2010b	Economic viability of replacing maize with whole cassava root meal in the diet of hybrid catfish	2010	Peer-reviewed journal article	X	X			X				X			X		Nigeria
Akoetey 2017	Potential use of by-products from cultivation and processing of sweetpotatoes	2017	Peer-reviewed journal article	X	X**						X	X					Global
Lukuyu et al. 2014	Use of cassava in livestock and aquaculture feeding programs	2014	Grey literature – research report	X	X**						X	X					Global
Lawal et al. 2012	Dietary effects of yam peels on the growth and haematology of *Clarias gariepinus* (Burchell, 1822) juveniles	2012	Peer-reviewed journal article	X	X			X				X					Nigeria
Aderolu et al. 2009	Processed cocoyam tuber as carbohydrate source in the diet of juvenile African catfish (*Clarias gariepinus*)	2009	Peer-reviewed journal article	X	X			X				X					Nigeria
Lawal et al. 2014	Dietary effects of ripe and unripe banana peels on the growth and economy of production of juvenile catfish (*Clarias gariepinus* Burchell, 1822)	2014	Peer-reviewed journal article	X	X			X				X					Nigeria
Olusola and Olaifa 2018	Evaluation of some edible leaves as potential feed ingredients in aquatic animal nutrition and health	2018	Peer-reviewed journal article	X	X			X				X					Nigeria
Nwokocha and Nwokocha 2013	Development of aquacultural feeds from locally available feedstuff: A giant step towards food security in Nigeria	2013	Peer-reviewed journal article		X						X		X				Nigeria
Ogugua, and Eyo 2007	Finfish feed technology in Nigeria	2007	Peer-reviewed journal article	X	X						X	X	X				Nigeria

Author(s)	Title of publication	Date of publication	Publication type	Relevance of study				Study type				Topics discussed/research questions addressed					Geographic focus ***
				Fish-RTB focused? *	RTB crops as fish feed	Integrated agriculture-aquaculture	Integrated consumption	Primary data collection			Literature review	Productivity/ efficiency of production system or specific system intervention/ development of a product	Production value chain	Environment	Socioeconomics	Food and nutrition	
								Quantitative	Qualitative	Mixed							
Mzengereza et al. 2014	Nutritional value of locally available plants with potential for diets of *Tilapia rendalli* in pond aquaculture in Nkhata Bay, Malawi	2014	Peer-reviewed journal article		X			X				X					Malawi
FAO 2007b	Study and analysis of feeds and fertilizers for sustainable aquaculture development	2007	Grey literature – report		X						X	X	X	X	X		Global case studies
Mzengereza et al. 2016	Apparent nutrient digestibility of plant based diets by *Tilapia rendalli* (Boulenger, 1896)	2016	Peer-reviewed journal article	X	X			X				X					Malawi
Fayose and Ogunlowo 2012	The search for high quality and affordable fish feed in Nigeria	2012	Grey literature – conference proceedings	X	X			X				X	X				Nigeria
Abu et al. 2010)	Chemical composition and cyanide levels of hybrid catfish fed whole cassava root meal in replacement of maize	2010	Peer-reviewed journal article	X	X			X				X					Nigeria
Bichi and Ahmad 2010	Growth performance and nutrient utilization of African catfish (*Clarias Gariepinus*) fed varying dietary levels of processed cassava leaves	2010	Peer-reviewed journal article	X	X			X				X					Nigeria
Munguti et al. 2012	Nutritive value and availability of commonly used feed ingredients for farmed Nile tilapia (*Oreochromis niloticus* L.) and African catfish (*Clarias gariepinus*, Burchell) in Kenya, Rwanda and Tanzania	2012	Peer-reviewed journal article		X			X				X	X				East Africa
Olukunle 2006	Nutritive potential of sweetpotato meal and root replacement value for maize in diets of African catfish (*Clarias gariepinus*) advanced fry	2006	Peer-reviewed journal article	X	X			X				X					Nigeria
Sutriana 2007	The use of cassava leaves as a dietary component for African catfish fry	2007	Peer-reviewed journal article	X	X			X				X					Indonesia
Tram et al. 2011	A comparative study on the apparent digestibility of selected feedstuffs in hybrid catfish (*Clarias macrocephalus* x *Clarias gariepinus*) and Nile tilapia (*Oreochromis niloticus*)	2011	Peer-reviewed journal article	X	X			X				X					Vietnam
Chhay et al. 2010	Effect of sun-dried and fresh cassava leaves on growth of tilapia (*Oreochromis niloticus*) fish fed basal diets of rice bran or rice bran mixed with cassava root meal	2010	Peer-reviewed journal article	X	X			X				X					Cambodia

Author(s)	Title of publication	Date of publication	Publication type	Relevance of study				Study type				Topics discussed/research questions addressed					Geographic focus ***
				Fish-RTB focused? *	RTB crops as fish feed	Integrated agriculture-aquaculture	Integrated consumption	Primary data collection			Literature review	Productivity/ efficiency of production system or specific system intervention/ development of a product	Production value chain	Environment	Socioeconomics	Food and nutrition	
								Quantitative	Qualitative	Mixed							
Ubalua and Ezeronye 2008	Growth responses and nutritional evaluation of cassava peel based diet on tilapia (*Oreochromis niloticus*) fish fingerlings	2008	Peer-reviewed journal article	X	X			X				X					Nigeria
Sine et al. 2017	Growth performance of juvenile genetically improved farmed tilapia (GIFT) fed a feed concentrate blended with cassava or sweetpotato	2017	Book section	X	X			X				X					Papua New Guinea
Neiva et al. 2011	Fish crackers development from minced fish and starch: An innovative approach to a traditional product	2011	Peer-reviewed journal article	X			X			X		X				X	Brazil
Rochimiwati 2017	Nutrition value of development of snack *cireng* cassava and fish	2017	Peer-reviewed journal article	X			X	X				X				X	Indonesia
Akonor et al. 2017	Sensory optimization of crackers developed from high-quality cassava flour, starch, and prawn powder	2017	Peer-reviewed journal article	X			X	X				X	X			X	Ghana
Karuri et al. 2001	Marketing opportunities for cassava-based products: An assessment of the industrial potential in Kenya	2001	Grey literature - report				X****		X				X				Kenya
Sharma et al. 2016	Tropical roots and tubers: Production, processing and technology	2016	Book				X				X	X					Global
Cliffe and Okereke 2010	Value addition for snacks using fish	2010	Conference proceedings	X			X	X				X	X			X	Nigeria
Bogard et al. 2015	Inclusion of small indigenous fish improves nutritional quality during the first 1000 days	2015	Peer-reviewed journal article				X			X		X	X			X	Bangladesh
Talsma et al. 2018	The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya: The use of linear programming	2018	Peer-reviewed journal article				X	X								X	Kenya
Amagloh et al. 2012	Complementary food blends and malnutrition among infants in Ghana: A review and a proposed solution	2012	Peer-reviewed journal article				X				X					X	Ghana
Nandutu and Howell 2009	Nutritional and rheological properties of sweetpotato based infant food and its preservation using antioxidants	2009	Peer-reviewed journal article	X			X	X				X	X			X	Uganda

*All studies included in this table at the very least refer to the integration of fish and one or more RTB crops. However, the papers that are not indicated as RTB specific are papers where RTB crops are only superficially included.
**Discussion not dedicated solely to uses in aquaculture but also includes the use of sweetpotato by-products, such as biogas or cassava, as livestock feed, for example.
***For lab-based primary research papers, the geographic focus is listed as the country where the research was carried out or author affiliations.
****Does not focus solely on products for human consumption.
*****These documents include a description of a selected IAA system, changes over time and opportunities for development.

RESEARCH PROGRAM ON
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Led by WorldFish

About FISH

The CGIAR Research Program on Fish Agri-Food Systems (FISH) is a multidisciplinary research program. Designed in collaboration with research partners, beneficiaries and stakeholders, FISH develops and implements research innovations that optimize the individual and joint contributions of aquaculture and small-scale fisheries to reducing poverty, improving food and nutrition security and sustaining the underlying natural resources and ecosystems services upon which both depend. The program is led by WorldFish, a member of the CGIAR Consortium. CGIAR is a global research partnership for a food secure future.

For more information, please visit fish.cgiar.org