Assessing the Environmental Impacts and Nutritional Outcomes of Tilapia Farming in Bangladesh

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By

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Abstract

There is an urgent need to transform global food systems into sustainable models which provide affordable, healthy, and micronutrient rich foods for all. This requires data-driven interventions and policies guided by rigorous food system performance assessments. Life Cycle Assessment (LCA) modelling is increasingly being used to evaluate the combined environmental and nutritional performance of food systems, known as nutritional Life Cycle Assessments (n-LCA). This thesis utilises novel n-LCA methodology to assess tilapia aquaculture and integrated agriculture-aquaculture systems in Bangladesh.

The environmental and nutritional performance of fishponds, rice-fish co-culture, and poultry-fish co-culture was assessed by combining a nutrition metric, the Potential Nutrient Adequacy (PNA) metric, with LCA methods. Affordability assessments and food and nutrition security assessments were also performed to evaluate the economic and nutritional performance of the farming systems. Additionally, on-station experimental trials compared the environmental footprint and nutritional quality of four different tilapia strains cultured under intensive and semi-intensive feeding and harvesting regimes. A nutritional composition analysis was performed for tilapia taken from different farming systems across Bangladesh with results showing small tilapia, typically consumed whole, and large tilapia, from which only the flesh is eaten, have different nutrient contents due to the differences in consumption practices. Furthermore, diet, seasonality, and farm type significantly impact the level of nutrients in both small and large tilapias.

Fishponds were found to have an overall better environmental performance compared to the rice-fish and poultry-fish farms. Results show feeds, fertilisers, energy, and chemical inputs have higher environmental impacts compared to other material inputs across all farm types. Result from the affordability assessment identified tilapia and two other fish species (*Cirrhinus mrigala* and *Esomus danricus*) as the most affordable sources of essential micronutrients and has shown these three fish species have a better environmental footprint compared to the other 17 fish species found in the farming systems and considered in this study.

Results from the experimental trial, found the local strain had better productivity compared to the three genetically improved strains, and the intensively managed treatments performed better compared to the semi-intensive treatments in terms of nutritional quality and economic returns. When the nutrition metric was integrated into the LCA, results showed intensive treatments also performed better than semi-intensive treatments for several environmental impact categories.

In conclusion, this thesis provides an important example of how nutrition can be combined with Life Cycle Assessments and offers insight into the impacts nutrition metrics can have on the overall results of performance assessments. Utilising the potential nutrient adequacy metric as a nutritional functional unit provides a more transparent approach to food system LCAs, although further development, testing, and validation of n-LCA methodology is needed to refine the process. This thesis also shows the nutritional quality of tilapia has been undervalued in the literature and that tilapia can provide sustainable, affordable nutrition to populations across Bangladesh.

Declaration

This thesis is composed of the original research which I undertook and contains no material which has already been published or was written by someone else. Where appropriate, the work carried out by others has been fully acknowledged.

Ethical approval was granted by the University of Stirling Ethics Committee for all necessary fieldwork. Approval was sought before the work was carried out.

S.Horn

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Glossary of Abbreviations and Acronyms

ASFs	Animal-source foods
ASPN	Average Share of Priority Nutrients
BDHS	Bangladesh Demographic and Health Survey
BMI	Body Mass Index
BNMSS	Bangladesh National Micronutrient Status Survey
CDDS	Children Dietary Diversity Scores
DRI	Daily Recommended Intake
FAI	Food Affordability Index
FAO	Food and Agriculture Organisation
FCR	Feed Conversion Ratio
FGD	Focus Group Discussion
FO	Fish-only farming households
FSNSP	Food Security and Nutritional Surveillance Project
FU	Functional unit
GAIN	Global Alliance for Improved Nutrition
GHG	Greenhouse Gas Emissions
GIFT	Genetically Improved Farmed Tilapia
GWP LUC	Global Warming Potential from Land Use Change
HDDS	Household Dietary Diversity Scores
HFIAS	Household Food Insecurity Access Scale
ISO	International Standard Organisation
LCA	Life Cycle Assessment
LCI(s)	Life Cycle Inventory / Inventories
LCIA	Life Cycle Impact Assessment
LMICs	Low- and Middle- Income Countries
MoF	Ministry of Fisheries
MT	Metric Tonnes
NC	Nutrient Content
NCDB	Nutritional Composition Databases
NGOs	Non-Government Organisations
NIPORT	National Institute of Population Research and Training
n-LCA	nutritional-LCA
NSTU	Noakhali Science and Technology University
NY	Nutritional Yields
PF	Poultry-Fish
PNA	Potential Nutrient Adequacy
RF	Rice-Fish
RFFSP	Rice-Field Fish Seed Production
RNI	Recommended Nutrient Intakes
RO	Rice-Only
SDGs	Sustainable Development Goals
SIS	Small Indigenous fish Species

SME	Small and Medium commercial Enterprises
TBN	Tilapia Breeding Nucleus
TSP	Triple Super Phosphate
UoS	University of Stirling
USD	United States Dollar
WDDS	Women Dietary Diversity Scores

Chapter 1

General Introduction

1.1 Introduction

Aquaculture systems are some of the most nutritionally important food systems globally, as production grows rapidly to meet the rising demands for seafood from an increasing population. Healthier economies and stagnant capture fisheries production have encouraged aquaculture growth and now, more than ever, researchers are considering aquatic food production as one of the solutions to food and nutrition insecurity (Golden et al., 2021; Naylor et al., 2021). However, the aquaculture sector also faces scrutiny of its environmental footprint and overall sustainability. The sustainability of any food system should be multidimensional, i.e., environmental, societal, and economic (United Nations, 2015). It has been shown that aquaculture development can have positive impacts on income, employment and fish consumption, especially in low- and middle- income countries (LMICs) (Ahmed and Lorica, 2002; Béné et al., 2015a, 2015b; Filipski and Belton, 2018; Irz et al., 2007; Jahan et al., 2010; Toufique and Belton, 2014), but the environmental sustainability of fish farming has long been a topic of discussion (Fry et al., 2018; Naylor et al., 2000; Pounds et al., 2022; Tlusty et al., 2018, 2019).

The aquaculture sector in Bangladesh has been growing at a rate of 4% - 10% annually over the past three decades (DoF, 2022) and many academics, government organisations and other stakeholders believe increases in fish production can improve farmer livelihoods and nutrition security through improvements in availability, affordability, and access to aquatic food sources (Blue Foods (BFA, 2021)). Bangladesh experiences high levels of nutritional insecurity with research showing high rates of morbidity, maternal mortality, and child wasting and stunting linked to high malnutrition rates (ICDDRB, 2020; JPGSPH, 2019; Mahmood et al., 2013). Inadequate access to a nutritionally significant, diverse diet and a poor healthcare system has led to high levels of undernutrition, and more recently obesity, in the country (JPGSPH, 2016). Research has shown aquaculture in Bangladesh can have a positive impact on farmers livelihoods (Karim, 2006) and fish consumption rates (Toufique and Belton, 2014), but questions remain over the impacts of aquaculture on nutrition security (Bogard et al., 2017a), particularly if a limited range of farmed fish is essentially substituting for highly diverse wild aquatic foods. Further research is required to determine the impacts aquaculture has had on the availability, accessibility, and affordability of fish in Bangladesh, and which fish production systems should be prioritised when addressing food and nutrition insecurity.

In 2019, over half of all methane emissions, 78% of all nitrous oxide emissions, and 21% of carbon dioxide emissions were produced by the global agri-food system (FAO, 2021). Additionally, agri-food systems were responsible for three-quarters of global consumptive water-use and occupied 43% of desert-free and ice-free land (Poore and Nemecek, 2018). Meanwhile, the number of people suffering from malnutrition has risen over the past few years, likely worsened by the Covid-19 pandemic, with 768 million people affected by hunger and 3.1 billion people unable to afford a healthy diet in 2021 (Development Initiatives, 2022). Therefore, it is obvious major transformations of the global food system are necessary to overcome nutrition insecurity while producing food within planetary boundaries (Steffen et al., 2015). To achieve sustainable transformations, interdisciplinary approaches should be taken during research and development of food systems as researchers and policymakers require rigorous, reliable data to make informed decisions. The nutritional importance of Blue Foods has often been overlooked, but it is increasingly being recognised within the literature and by policymakers. Recently, it has been acknowledged that freshwater and marine food sources are often reduced to a single category (“fish” or “seafood”) or are excluded altogether in the food systems discourse (Golden et al., 2021; Stetkiewicz et al., 2022). The Blue Food Assessment (BFA, 2021) has been developed to highlight this and bring attention to the heterogeneity and diverse nutritional significance of Blue Foods and encourage researchers to include these important foods, and the systems in which they are produced, when considering global food systems research and/or transformation. Pounds et al. (2022) also highlight the importance, and challenges, of assessing aquatic food production at system level.

Low- and middle-income countries (LMICs) are known to rely more on fish for their nutritional security than better off countries. For this reason, government and non-governmental organisations (NGOs) often attempt to introduce simple but effective technologies to improve the aquaculture and fisheries sectors. Such technological innovations that have been introduced into tilapia ponds in Bangladesh include the use of genetically improved stocks, aeration, excavation/deepening of ponds, and use of cages in ponds. Several breeding programs aimed at improving tilapia production were established after the realisation that there had been a lack of attention given to the potential gains that could be made through the genetic enhancement of farmed fish. The Genetically Improved Farmed Tilapia program (GIFT) (Eknath *et al*., 1993) which began over 3 decades ago, led to further genetic improvement programs such as GET-EXCEL (Tayamen, 2004) and GST (dos Santos *et al*., 2019). It is widely accepted that improved strains have enabled an increase in production of farmed tilapia across Asia and beyond. The GIFT program, initiated by ICLARM (now WorldFish), has received a considerable amount of global attention. The program resulted in the adaptation and development of selective breeding technology which produced a strain of tilapia with superior productivity when compared to unimproved strains in a number of countries across Asia (ADB, 2006; Dey *et al*., 2000). The approach used to develop the improved strain has received global recognition for the potential to address hunger, malnutrition, and poverty. During the selective breeding stage and the subsequent dissemination of GIFT ex-ante studies suggested the new strains had great economic potential for both producers and consumers (Dey, 2000) and it was claimed that investment in GIFT could benefit national economies (Ponzoni *et al*., 2007). Although the main objective of the breeding program was to increase production and consumption of farmed tilapia in response to concerns regarding hunger and malnutrition in LMICs, the genetic material was appropriated by private companies and, rather than advance aquaculture and improve the livelihoods of the poor, it was used for profit (Ponzoni *et al*., 2010). Nevertheless, WorldFish have continued to work with governments and local producers to increase tilapia production to improve farmer livelihoods therefore it is still generally accepted that the poor have benefitted from the development of improved tilapia strains.

Literature on tilapia is plentiful and it is easy to find studies on GIFT biology and genetics, dietary and environmental requirements, diseases, culture trends and the selective breeding techniques (Center, 2010; El-sayed, 2006; McAndrew *et al*., 2016; Thodesen and Ponzoni, 2004; Wang and Lu, 2016; Jauncey, 1998; ICLARM, 1995, ADB, 2006). A considerable number of studies have been published which document the GIFT development process (Eknath *et al*., 1993; Ansah *et al*., 2014; ADB, 2006; Gupta *et al*., 2010; Ponzoni *et al*., 2010), evaluate GIFT performance on a genetic level (Bentsen et al., 2017, 2012; Hamzah et al., 2016; Khaw et al., 2016; Rajaee, 2011), assess production performance under experimental conditions (Dong et al., 2008; Haque et al., 2016; Horn et al., 2021; Kabir et al., 2019; Omasaki et al., 2017a; Ridha, n.d.; Santos et al., 2018; Sultana et al., n.d.) and make recommendations for further development and improvements of GIFT (Dan and Little, 2000; Nguyen and Ponzoni, 2006; Omasaki et al., 2017b; Ponzoni et al., 2008; Uddin et al., 2007). Comparatively, societal and environmental impact assessments of tilapia farming are less abundant within the literature. The small number of impact assessments mainly focus on economic impacts of novel farming technology, thus there is a lack of empirical evidence of the environmental impacts or nutritional outcomes of tilapia farming. It has been suggested the improved strains may be more environmentally friendly since the feed conversion rates are generally lower, meaning higher production levels for the same level of input. However, this has never been researched and local strains may perform better since many tilapia producers are not using high-input - high-output systems.

Many programmes and interventions have been established with the aim of improving food and nutrition security and research institutions have emphasized the importance of capturing evidence of the nutritional impacts from agricultural interventions and innovations (Bird *et al*., 2019; Temple *et al*., 2018). Impact evaluations of these types of projects have provided mixed results however a review of agricultural impact literature has suggested the use of appropriate indicators can make nutritional impact studies more robust (Herforth and Ballard, 2016). The food and nutrition security impacts of tilapia farming in Bangladesh remain relatively unknown so further research is needed which should use appropriate indicators. Guidelines have been published for use of different indicators at national, household, and individual level and offer insight into how indicators should be used (Lele et al., 2016). Rigorous monitoring of impacts of fish production and consumption is a necessary step in transforming global food production into sustainable and equitable systems. As tilapia is a widely cultured and readily available and affordable species, identifying the nutritional benefits of tilapia is essential in developing nutrition-sensitive policies and interventions and educating people about cultured fish in relation to their dietary needs.

In the early 1990s CARE and DFID worked with 40 rice farmers in Northwest Bangladesh introducing fish into paddies as a biological pest control which also provided an extra cash crop (Barman and Little, 2006; Haque, 2007). Fingerlings and fry produced in conventional hatcheries and nurseries were often transported to the Northwest by train from Jessore and Rajshahi, an extended supply chain that resulted in delivery of inconsistent quality of seed. The rice-field fish seed production (RFFSP) in irrigated rice fields was explored as a solution to the strong emergent demand for quality fish seed. Common carp hatchlings were first introduced in 1991 into the irrigated rice fields of the 40 participating farmers resulting in the availability of large, quality fingerlings for sale at the beginning of the wet season. Fingerling farmers then began collecting carp eggs from fish farms and introducing them into their rice-fields, which further reduced dependency on hatcheries. Further development of RFFSP followed as farmers diversified production to include many other species including tilapia.

An early strain of WorldFish Genetically Improved Farmed Tilapia (GIFT) was introduced into irrigated rice fields in 1999 as part of a pilot study looking at the impacts of GIFT in rice-fish systems (Barman and Little, 2006). GIFT had significantly positive effects on the livelihoods of both poor and better-off producers and quickly became common in RFFSP systems (Haque et al., 2014; Little et al., 2007). Subsequent impact evaluations have shown the spread of tilapia in RFFSP systems occurred organically and was facilitated by wealthier farmers and fish traders (Little et al., 2007). Wealthy farmers retained and produced tilapia broodstock year-round as they owned perennial waters and fish traders promoted tilapia fingerling production. A follow-up project in 2008 aimed to enhance the benefits of RRFSP by scaling up production in the Northwest region through the dissemination of tilapia and carp fry/broodfish to small-scale fish producers (Barman et al., 2011). Mixed sex GIFT fry was introduced to the area from a commercial hatchery based in Mymensingh. Again, fingerling traders were key in scaling fingerling production in rice fields as they promoted production, developed markets, and helped create new fish fingerling markets. As a result, the benefits of trading fingerlings were well-recognised, and the number of traders grew rapidly (Barman et al., 2011).

The rice-fish farming systems in Bangladesh, wherein a wide range of fish are now produced, are considered to have positive impacts on the consumption of fish, especially among impoverished communities (Haque et al., 2014). Rice farmers that adopted RFFSP had higher incomes and consumed more fish than non-adopters (Haque et al., 2010). Tilapia fingerlings (produced in rice-fields) contributed greatly to the food security of poorer people as they were consumed during '*monga* months' (periods of food shortage characterised by low income) (Haque et al., 2010; Zug, 2006). Recent visits to the area suggest several of the initial recipients of GIFT broodstock 20 years ago were still producing mixed sex tilapia without having replaced their broodstock, as they allow the fish to free-breed and crop off larger fish for sale. It was hypothesized that free-breeding tilapia in rice fields were continuing to provide important contributions to nutritional security, and potentially low-input systems were likely have a lower environmental footprint compared to other fish-producing systems.

This research is designed with two key objectives, the first is to investigate the environmental impacts of aquaculture systems in Bangladesh and the second is to measure the nutritional outcomes of various culture systems, and to assess the trade-offs between these sustainability dimensions with a key focus on tilapia systems. The main research questions behind these objectives will be approached using Life Cycle Assessment (LCA) methodology and food systems thinking. This chapter will thematically review literature related to this research and aims to provide the reasoning behind the research and an understanding of the significance of the outcomes.

1.2 Food and Nutrition Security in Bangladesh

In 1996 world leaders came together at a summit and pledged to end world hunger and ensure food security for everyone (FAO, 1996). Goals were set and governments took steps towards achieving this aim. A summit was held again in 2006 to report the developments, however, results were underwhelming as little progress had been made (FAO, 2006). A third summit was held in 2015 to document the progress and results were more positive but unevenly spread across the globe (FAO, IFAD, and WFP, 2015). Currently, approximately 2 billion people are malnourished, caused by a continuous lack of access to the appropriate quantity of good quality food. Since the early 2000s, public health research shifted focus away from infectious diseases towards non-communicable diseases (United Nations, 2011;

WHO, 2013), and more recently diet related non-communicable diseases (United Nations, 2016). All forms of malnutrition, micronutrient malnutrition, undernourishment, and obesity, have been recognised as a major health concern, especially in LMICs. As a result, agricultural interventions and policies are increasingly being designed in a nutrition-sensitive way with an aim of improving dietary outcomes, and ultimately food and nutrition security (Ruel and Alderman, 2013). This shift in public health research has led to an increased awareness about the quantity and quality of individual nutrients in foods, emphasising the importance of the nutritional content of the whole diet in ensuring people remain food secure and healthy.

There are 4 recognised pillars of food security: availability, accessibility, utilisation, and stability (FAO, 1996). Availability addresses food production and supply, accessibility relates to the ability of the household and individual to access food, utilisation highlights how food is prepared and consumed by the individual, and finally stability conceptualises the need for the other 3 pillars should always remain positive. The food security status of people can change from secure to insecure at any moment and can be chronic or transitory in nature. Those who suffer from chronic food insecurity are persistently unable to meet their minimum food requirements and those who suffer from transitory insecurity are those who are affected by a sudden change in any of their circumstances which relate to the pillars of food security, often these changes are unpredictable.

Food and nutrition security in Bangladesh are monitored by several national and international agencies which collect data to guide policies and interventions aimed at overcoming food and nutrition insecurity and the associated issues. The Food Security and Nutritional Surveillance Project (FSNSP) (JPGSPH, 2016) , which began in 2010, is one of the most reliable sources of information on the food security, nutrition, and health status of people in Bangladesh. A nationally representative sample of the population were surveyed for 5 consecutive years with a focus on women and children, and the information collected was used to measure various food and nutrition security indicators such as child wasting, stunting, underweight and obesity prevalence. The FSNSP survey was carried out 3 times each year to take into consideration the impact of seasonality. The results from each year make it clear that food and nutrition security fluctuates depending on the time of year. For example, in 2010 wasting in children doubled from 8% to 16% between the first (January-

April) and second (June-August) round of surveys (JPGSPH, 2016). Location can also impact food and nutrition security of a household. Bangladesh is a relatively flat country with an extensive network of rivers and has varied agroecological landscapes, flooding patterns, social and economic climates depending on the geographic zone. The coastal belt is characterised by a varied ecology depending on the coastal zone and an ever-changing geomorphology which has been attributed to climate change (Sarwar & Woodroffe, 2013 & Allison, 1998). The West is the most drought prone area, the Northeast faces flash floods which cause damage to crops and housing and, although the Northwest is characterised by fertile lands and relatively equitable land ownership (JPGSPH, 2016) the area is prone to droughts, floods and other natural disasters which can impact peoples livelihoods. The characteristics of each of the zones can impact household food and nutrition security. In addition to geolocation and seasonality, household characteristics affect the nutrition security of everyone in the household, i.e. number of household members, household head occupation, education level, household religion/cultural practices, income, and age and health status of each household member. Harris-Fry *et al*. (2015) demonstrate increased levels of wealth and literacy were closely linked to increased food security and dietary diversity during their survey of women across rural Bangladesh. Having a diverse diet means one is consuming a variety of micronutrients and measuring dietary diversity levels are a good indicator of food and nutrition security (FAO, 2018). Mridha *et al*. (2018) found socioeconomic status and education levels positively correlated with dietary diversity in Bangladeshi adolescents. In addition to the differences in diets of adolescents from different social classes, there are dietary differences found between the sexes. A large scale study of Bangladeshi adolescents aged 9-15 found male adolescents were more likely to consume a more diverse diet compared to females (Thorne-Lyman et al., 2019). Moreover, Mridha *et al*. (2018) confirm the nutritional vulnerability of female adolescents in Bangladesh in their study where they find a high prevalence of malnutrition of pregnant 15-19 year olds. Infants and young children are another nutritionally vulnerable groups in Bangladesh. Between the ages of 6-12months children require a highly nutritious diet yet in low-income countries children of this age are often fed nutrient-poor, cereal-based diets (Dewey, 2013). This is typical in Bangladesh where Thorne-Lyman *et al*. (2017) found fish and shellfish were being withheld from infants. They identify several possible reasons for mothers withholding fish from children and note the concern about fish bones. This highlights a particular view about fish in children's diets, however, food knowledge and behaviour can be improved through dietary communication programs. These types of programs in Bangladesh have already been seen to effectively educate people on dietary diversity and improved malnutrition rates (Roy et al., 2007, 2005). Promoting fish consumption using outreach programs could encourage fish utilisation at all life stages, helping overcome malnutrition from birth onwards. However, reliable data on the nutritional composition of fish and fish consumption patterns should be well understood to guide dietary or educational interventions. Small indigenous fish species (SIS) have been promoted across Bangladesh but reports suggest consumers are moving towards more cultured species, possibly due to affordability and availability issues of SIS (Belton et al., 2011; Bogard et al., 2017a).

In addition to FSNSP reports, the Bangladesh Demographic and Health Survey (BDHS) also reports the nutritional status of the Bangladeshi people. The BDHS, began in 1993 and is implemented by the National institute of Population Research and Training (NIPORT) with assistance from USAID. The first BDHS survey carried out in 1993 (NIPORT *et al*., 1995) did not consider the nutritional status of the population but over the years the data collection regime expanded, and now the survey includes activities on food consumption patterns and micronutrient intakes of participants (NIPORT *et al*., 2015). The 2017-18 BDHS report (NIPORT and ICF, 2020) is the most recently published report however the survey was carried out again in 2020 but has yet to be published. This 2017-18 report and the latest FSNSP report (JPGSPH, 2019) show an improvement in nutrition-related health indicators such as rates of child wasting and stunting and rates of undernourishment in women and children. The reports suggest a variety of reasons for these improvements and JPGSPH (2016) noted the increase in availability (measured as an increase in production) of a diverse range of crops, particularly animal source foods which rose 56% between 2008-2015. Although nutrition security is improving, there are still major nutrition-related health problems for many populations across Bangladesh. For example, although the proportion of women, aged 19-59, who were reported to be undernourished fell from 30% to 12% between 2007 and 2016, the proportion reported to be overweight rose form 12% to 32% (NIPORT and ICF, 2020). Additionally, there are still 41% of households that are considered food insecure, 28% of children and 20% of adolescent girls are chronically undernourished while 8% of adolescent girls are overweight, and 35% of men are overweight/obese (JPGSPH, 2019).

The above-mentioned reports make clear many people in Bangladesh consume an inadequate diet. The Bangladesh National Micronutrient Status Survey (BNMSS) implemented by the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDRB, 2013), which was designed to collect data on the micronutrient status of the Bangladesh population, details the problems associated with these inadequate diets. The BNMSS is supported by UNICEF and the Global Alliance for Improved Nutrition (GAIN) and collects nationally representative data using a 3-stage sampling technique. The survey uses questionnaires to gather household and retailer information and takes biological samples from household members for micronutrient analysis. The data collection included all household members however a focus was put on women and children as they are most vulnerable to malnutrition. The 2019-2020 survey has not yet been published but a press release by the ICDDR,B has confirmed the major micronutrient deficiencies include iron, zinc, iodine, folate, vitamin D, vitamin B12 and vitamin A (ICDDRB, 2020). This is specifically relevant for the research presented in this thesis since these nutrients are commonly found in fish and other blue foods.

1.3 Micronutrients of Significance in Bangladesh

There are several micronutrients which are well-known to be deficient in the Bangladeshi population owing to large scale biomarker testing and dietary surveys (Ahmed et al., 2016; Ara et al., 2023; Arsenault et al., 2013; Grieve et al., 2023; ICDDRB, 2013; NIPORT and ICF, 2020). Table 1 shows the national prevalence of micronutrient deficiencies per population as per studies using biomarkers as way of deficiency detection.

Table 1. National prevalence of nutrient deficiencies per population type.

Nutrient	Pre-school age children	6 – 14-year-olds	NPNL women
Iron	15% [a]	18.1% [b]	14% [a]
Zinc	31% [a]	Not available	43% [a]
Iodine	20% [a]	40% [b]	30% [a]
Vitamin A	7% (moderate deficiency) [a]	20.9% (moderate deficiency) [b]	7% (mild deficiency) [a]
Vitamin D	22% [a]	Not available	70% [a]
Vitamin B12	Not available	Not available	20% [a]

*NPNL: non-pregnant and non-lactating

[a] Data taken from ICDDRB (2020)

[b] Data taken from ICDDRB (2013)

In addition to the micronutrients in Table 1, it is clear from consumption surveys calcium is another micronutrient which is lacking in the Bangladeshi diet (Sununtnasuk and Fiedler, 2017). Calcium levels were not measured during the BNMSS sampling however it is known that dairy foods are often the main source of calcium but consumption of these types of foods are low in Bangladesh. For these reasons, calcium should also be considered as a micronutrient of interest during food and nutrition studies.

Several micronutrients of interest which have been reported by I,CDDRB (2013 & 2020) to be deficient in certain populations in Bangladesh are linked to major health issues. For example, anaemia is considered a public health concern in Bangladesh as one third of women and 50% of children are living with the condition (ICDDRB, 2013). The condition is often caused by iron deficiency, of which 15% of children under 5 and 14% of women suffer (Table 1). Anaemia is highly prevalent throughout the world so understanding dietary intake of iron is of global importance. Anaemia is one of the key nutrition indicators set out in The Global Nutrition Report (IFPRI, 2018), but levels of the condition have risen to 32.8% of the global population and currently no country is on course to meet their ‘Anaemia Target’ set out in the United Nation’s Sustainable Development Goals (SDGs) (IFPRI, 2018). The Global Nutrition Report (IFPRI, 2018) also identifies the need to prioritise and invest in developing more accurate databases on global diets and consumption patterns, especially in low-income countries. Understanding food consumption habits of people suffering malnutrition is a crucial step in being able to guide consumers towards environmentally friendly, nutritious food choices.

Another major health issue related to micronutrient deficiencies seen in Bangladesh is rickets. Rickets can be caused by calcium and vitamin D deficiencies and in some parts of Bangladesh up to 8% of children have been reported to suffer from the disease (Craviari et al., 2008). Various other health issues are related to food and nutrition insecurity, both transitory and chronic.

1.4 Fish Production and Consumption in Bangladesh

The demand for fish in Bangladesh is high year round with reports suggesting between 95-99% of all households consume fish at least once every 2 weeks (Belton et al., 2011; Bogard et al., 2017a). The aquaculture sector has rapidly expanded in Bangladesh to meet the increasing demand for fish which has been attributed to plateauing capture fisheries catches, increasing incomes across the country and a growing population (DoF, 2017; Toufique and Belton, 2014 and GoB & FAO, 2014). Around 94% of the reported 2.6 million MT (DoF, 2022) of aquaculture production in Bangladesh remains in the country for domestic consumption (Hernandez *et al*., 2018).

The fish production statistics published yearly by the Bangladeshi government are collected using methodology which is outdated and consequently unable to account for the recent expansion of the aquaculture sector**.** Belton *et al*. (2011) therefore collated and reviewed a substantial amount of published and unpublished literature with the aim to provide a clearer image of fish production and consumption in Bangladesh. The authors suggest aquaculture pond production area is in fact 28% greater than reported and overall production is 23% higher, bringing the annual total aquaculture production to over 3.1 million tonnes. This discrepancy in published government datasets may lead some researchers to underestimate the impacts of aquaculture production on food security and other societal and environmental impacts when using national datasets to calculate domestic micronutrient consumption. On the other hand, although improvements have been made in some nutrient deficiencies over the years in Bangladesh, questions remain over whether aquaculture is contributing to food and nutrition security since national datasets have been underestimating total production, yet insecurities still persist.

The main species cultured in Bangladesh are tilapia, carps, catfishes, shrimp, prawns, and a various other freshwater species. As demand grew, several species which were mainly produced by capture fisheries transitioned to cultured production to meet the domestic consumption demands. Tilapia has become one of the main commodity species in Bangladesh as production and consumption has increased steadily over the past decade and is now the second most produced species after pangas (ABD, 2006; DoF, 2022; Hernandez et al., 2018). Fish consumption differs between rural and urban consumers and between different social classes. In general, those living in urban areas consume more fish and fish consumption increases with increasing household income (Belton *et al*., 2011). Gupta *et al.* (1992) claimed that 70% of tilapia produced by the household was consumed by the household. However, there has been a rapid transformation of the aquaculture sector and Hernandez *et al*. (2018) claim at most only 10% of all aquaculture products produced by the household are consumed, however they do not offer details of consumption patterns. Understanding the consumption patterns of each species from each farming system will help determine how aquaculture contributes to nutrition security.

The Bangladeshi diet is mainly composed of rice and fish as these staples are readily available due to the river infused landscape which is the ideal environment for fish production. The floodplains are highly productive, and aquaculture is widespread leading to a huge range of fish species produced and consumed throughout the country. Bangladesh is the fifth largest aquaculture producer in the world (FAO, 2022) and fish contributes 63% of the protein in an average Bangladeshi diet (Jahan *et al*., 2010) with production contributing to the livelihoods of millions of people across the country (Belton *et al*., 2011). As aquaculture produces over half of all fish in Bangladesh (DoF, 2022), it is important that fish farming is economically, socially and environmentally sustainable to ensure improvements are made to food and nutrition security without compromising natural resources or livelihoods.

Bangladesh was acknowledged by FAO, IFAD and WFP (2015) for the rapid improvements in food security made within the country which was credited to the development of a National Food Policy in 2006 (GoB, 2006). This government policy confirmed the county's commitment to ensuring the expansion of fish production and detailed several ways in which this could be achieved, e.g., improving fisheries research, development of the fisheries and livestock feed industry, expansion of integrated rice plus fish production systems, promoting environmentally friendly systems, and the development of market infrastructure. When considering the importance of aquaculture and fisheries to Bangladesh it is easy to see why this was a major focus of food policy.

Ensuring food and nutrition security is important for the health of an individual and national economic performance as malnutrition has many adverse health effects for individuals which can effect on the productivity of the workforce if widespread. It is estimated malnutrition negatively impacts domestic product by up to 3% (Branca *et al*., 2015 & ICDDRB, 2013). To achieve nutrition security for all, a diverse range of foods should be available and be adequate in both quantitative and qualitative terms (Bose and Dey, 2007). In rural areas of LMICs where access to markets may be restricted and purchasing power low, government policies should encourage the adoption of diversified food systems (Miller and Welch, 2013). Efforts should be made to ensure a diverse landscape of food production systems remain in order to maintain diverse nutrient production (Herrero et al., 2017). Rice-fish farming systems, for example, offer a diverse production of crops and has been shown to play a role in food security, particularly for the resource-poor (Karapanagiotidis *et al*., 2010, Haque *et al*., 2010). The rice-fish farming systems in Bangladesh have been well-established in the Northwest area for almost 10 years and have had positive impacts on the consumption of fish among low-income households (Haque *et al*., 2014).

Polyculture is common in Bangladeshi fish farming for both homestead and commercially operated farms. Recently, researchers have suggested farmers in Bangladesh adopt carp and small indigenous fish species (SIS) polyculture systems as a way of increasing production of nutrient rich fish (Castine et al., 2017; Karim et al., 2017). A study by Bogard *et al*. (2018) reviewed indicators which can be used to determine the nutritional quality of agriculture system and applied these indicators to 18 carp polyculture systems commonly found in Bangladesh. The study concluded 2 polyculture systems, with varying fish species, provided the best nutrition to the greatest number of people. However, fish production is only a small part of the food and nutrition security system (Figure 1). Animal source foods are often processed, marketed, cooked, and consumed in a variety of ways. The nutritional quality of a food can be impacted by many factors.

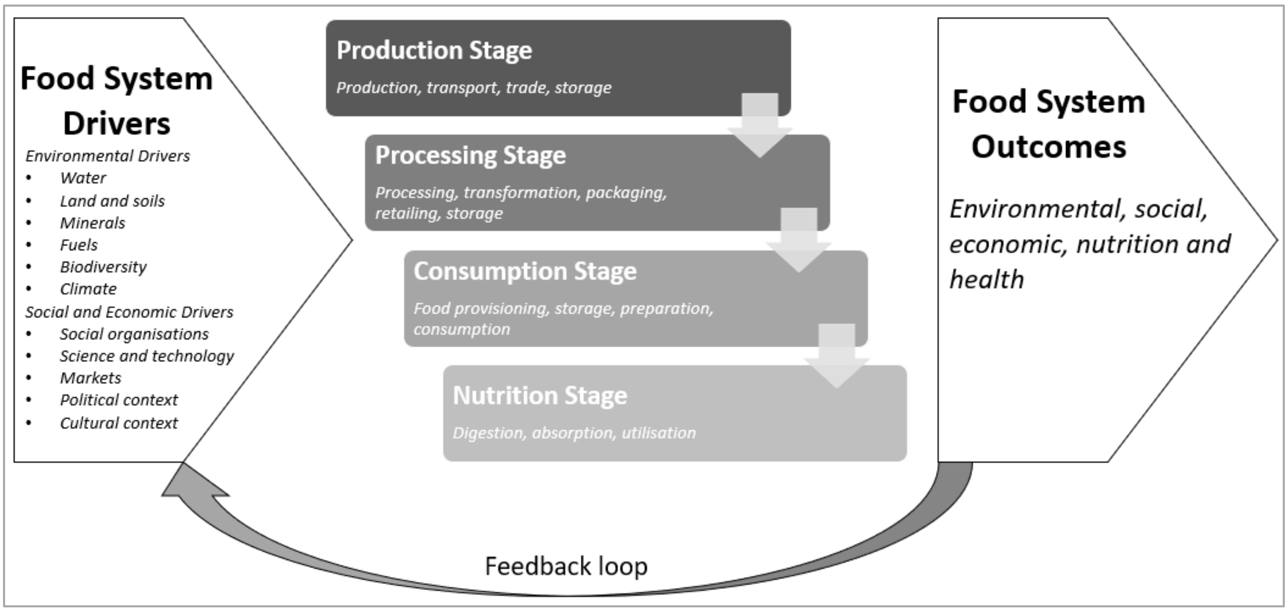


Figure 1. Food and nutrition system framework showing the 4 main subsystems, and the system drivers and outcomes. Adapted from Sobal et al. (1998), Ingram and Zurek (2018), Bogard *et al*., (2018) and Heywood and Lund-Adams, (1991)).

Researchers have described various types of food system conceptual frameworks since the end of the last century (Heywood and Lund-adams, 1991; Sobal et al., 1998). These frameworks are useful guides for research which aim to assess the performance and/or impacts of the dimensions of a food system (Glopan, 2016; Ingram, 2011; Ingram and Zurek, 2018; Rutten et al., 2011). For instance, selecting the appropriate indicators for an impact assessment is a crucial process and frameworks, such as that in Figure 1, can help researchers identify indicators relevant to the dimension and stage of the food system (Lele et al., 2016). To encourage food system transformations, high quality, data-driven research which appropriately assesses the outcomes and changing trends of food systems is urgently required (Herforth et al., 2022).

1.5 Fish Nutrient Composition

Since good quality data on fish and shellfish nutrient composition were often missing from national and international food composition databases, FAO attempted to address this by developing the uFish database containing the nutritional composition for important fish species produced throughout the world (FAO, 2016). The database contains macro and micronutrient content of the raw and cooked edible portions of fish and documents the different nutrient compositions of fish found in different countries. The database was formed using an extensive list of resources such as published and grey literature, official government databases, NGO databases and recommendations from experts. The nutritional composition of Nile tilapia includes raw and cooked tilapia from several countries, including Bangladesh. However, the sources used to construct the Bangladeshi tilapia nutrient composition are to some extent unreliable. The sources include an unpublished MSc thesis, nutrient composition of tilapia from Thailand and the US and an article examining flesh quality of tilapia produced in Africa. The final source used for the data for Bangladeshi tilapia is an article by Bogard *et al*. (2015), which shows the nutrient content of both tilapia and juvenile tilapia/ tilapia fingerlings, often referred to as “majhari” tilapia. This is important as tilapias are prepared and eaten differently depending on size. Often small tilapias are eaten whole, and since micronutrients are stored in certain parts of the fish body, the consumption behaviour may alter the nutritional quality of the tilapia. For example, vitamin A is stored in cells throughout the body of the fish including the kidney, intestine and gills (Roos, 2001), therefore if the viscera is removed, vitamin A content in that meal will decrease. Therefore, it is important to understand the consumption patterns of any species by size to be able to determine which nutrients are consumed. Fish consumption patterns in Bangladesh are relatively well-understood and the nutrient composition of tilapia has been described in the literature (Belton et al., 2011; Bogard et al., 2015; FAO, 2016). However, *majhari* tilapia are often consumed differently compared to larger tilapias. Consumption patterns and nutrient composition of *majhari* tilapia is understood to a lesser extent, possibly leading to an underestimation of the contribution of these fish to nutrition security.

Studies by researchers such as Belton *et al.* (2011), Bogard (2015) and Thilsted *et al*. (2016) measure and estimate the nutritional impacts from fish in Bangladesh in well-designed studies using nationally representative datasets such as the Bangladesh Household Income and Expenditure Survey (BBS, 2016) or the Bangladesh Integrated Household Survey (IFPRI, 2019). These datasets have been shown to be a reliable source for guiding policies and have even been shown to use estimates (Adult Male Equivalent estimates) of food intake that are comparable with real consumption data collected in a follow-up study (Sununtnasuk and Fiedler, 2017). However, these datasets lack crucial information regarding fish preparation and consumption as the size of fish and preparation/cooking techniques are often disregarded in the data collection process. Data on meal composition is crucial in understanding nutritional outcomes of food production systems and being able to link nutrition security to dietary intakes. Having accurate data on tilapia nutrient composition is valuable to policy makers since tilapia is one of the main commodity species in Bangladesh and is known to be widely consumed. Tilapia is also produced in a range of systems with varying degrees of intensity, and across geographies which include saline, brackish and freshwater (Mamun, 2016). As the above-mentioned studies base the nutrient content of tilapia on results from samples of 'edible parts' which exclude the bones, viscera, fins, scales, and gills, it is necessary to conduct further research into tilapia consumption patterns and nutrient contents. A study by Haque *et al*. (2010) shows tilapia (produced in rice-fields) can contribute greatly to the food security of poorer people as the free-breeding small tilapias in the system can be consumed during 'hunger months', in other words, during periods of low income people consume fish from their own ponds. The wide range of tilapia producing systems and the variety of genetically different strains within Bangladesh are further reasons for this research.

Studies have revealed the chemical compositions of cultured fish are strongly influenced by the diet of the fish (Ayisi et al., 2017; Eljasik et al., 2020; Rosenlund, 2001; Sissener, 2018). It is also evident from the literature that the farming system can affect the nutrient composition of the fish. For example, Karl et al. (2010) demonstrated how conventional pangasius fillets had significantly less protein than organically farmed pangasius. The nutritional composition of Nile tilapia (*Oreochromis niloticus*) was also found to have significant differences depending on the origin of the fish. In a study by Samy El-Zaeem et al. (2012), the compositions of Nile tilapia populations from 3 different lakes in Egypt were analysed. Moisture, protein, and fat content was shown to differ depending on the lake where the fish was caught and whether the fish was wild or cultured. Similarly, Rasoarahona et al. (2005) found lipid content of 3 species of tilapia differed according to the species, diet and location of origin of the fish, and between the winter-spring-autumn seasons. These tilapia species are known to significantly contribute to the essential polyunsaturated fatty acid intake of highlanders in Madagascar. Furthermore, it is well-known age, and to an extent sexual maturity, changes the micronutrient contents of fish (Guan et al., 2018) which is clear from the nutrient profiles of tilapia and juvenile tilapia published by Bogard et al. (2015).

1.6 Aquaculture and Nutrition Security

Many of the essential micronutrients required for good health can be found in fish and shellfish. There is a large body of literature showing the nutritional value of fish (Bogard, 2015; Karapanagiotidis et al., 2010; Kawarazuka and Béné, 2010; Olsen et al., 2018; Roos, 2001; Roos et al., 2007b, 2007a) and the potential role fish and shellfish can play as part of a healthy diet (Carboni *et al*., 2019; Gibson et al., 2003; Lund, 2013; Sidhu, 2003). It is generally accepted that aquatic food consumption can contribute to nutritional security therefore fisheries and aquaculture can contribute to food and nutrition security. The impacts of aquaculture on food and nutrition security have been shown to be positive and linked to poverty alleviation (Béné et al., 2015b; Little et al., 2012; Little and Bunting, 2015; Tacon and Metian, 2013). However, there is a gap in the literature defining the contribution aquaculture has made to micronutrient security. In addition, a review of published literature by Campling *et al*. (2015) confirmed there is a lack of valid and rigorous studies of the contribution of fisheries and aquaculture to global food security. The authors call for further investigation into the nutritional benefits of aquaculture, with a focus on discovering who benefits from growth of the industry. The contribution of aquaculture to food and nutrition security in Bangladesh is complex and interlinked with the capture fisheries sector and sits within the broader food system where other food production sectors play a role in food and nutrition security. The pathways in which aquaculture and fisheries can affect food security is set out in Figure 2.

There has been debate around the contribution of different fish production systems to poverty alleviation and food and nutrition security in the Global South. Belton, Bush and Little (2018) argue against the narrative that necessarily promotes small-scale fish farming by claiming that an important ‘middle’ segment of aquaculture enterprises have rapidly developed in some contexts such as Bangladesh and are now responsible for a significant amount of fish production and sector growth which is being overlooked. They argue that this segment of fish production contributes greatly to food security in LMICs. Similarly, Filipski and Belton (2018) claim small and medium commercial enterprises (SME) are the driving force behind aquaculture growth in LMICs and contribute to poverty reduction through indirect benefits for the poorest households. Kassam and Dorward (2017) also highlight the importance of SMEs for aquaculture growth in LMICs. They also highlight the importance of appropriately categorising farms in future studies to ensure benefits from different aquaculture enterprises are fully understood. Categorising tilapia farms appropriately will be critical in studies assessing the environmental and nutritional impacts of tilapia culture. Belton and Azad (2012) identify the main characteristics of pond aquaculture in Bangladesh in their review and highlight the recent transformation of the aquaculture sector. Inland pond aquaculture makes up 79% of all aquaculture production in the country, highlighting the importance of tilapia farming since the majority (80.5%) of production come from ponds (DoF, 2022). Due to varied socioeconomic situations of farmers and agroecological conditions across Bangladesh, the tilapia pond farming typology is complex. There are a number of different defining characteristics of farm enterprises, for example farming can be extensive, semi- intensive or intensive depending on farming practices and, most recently, Bangladeshi aquaculture has been described as either quasi-peasant or quasi-capitalist depending on the level of commercialisation (Belton *et al.*, 2012).

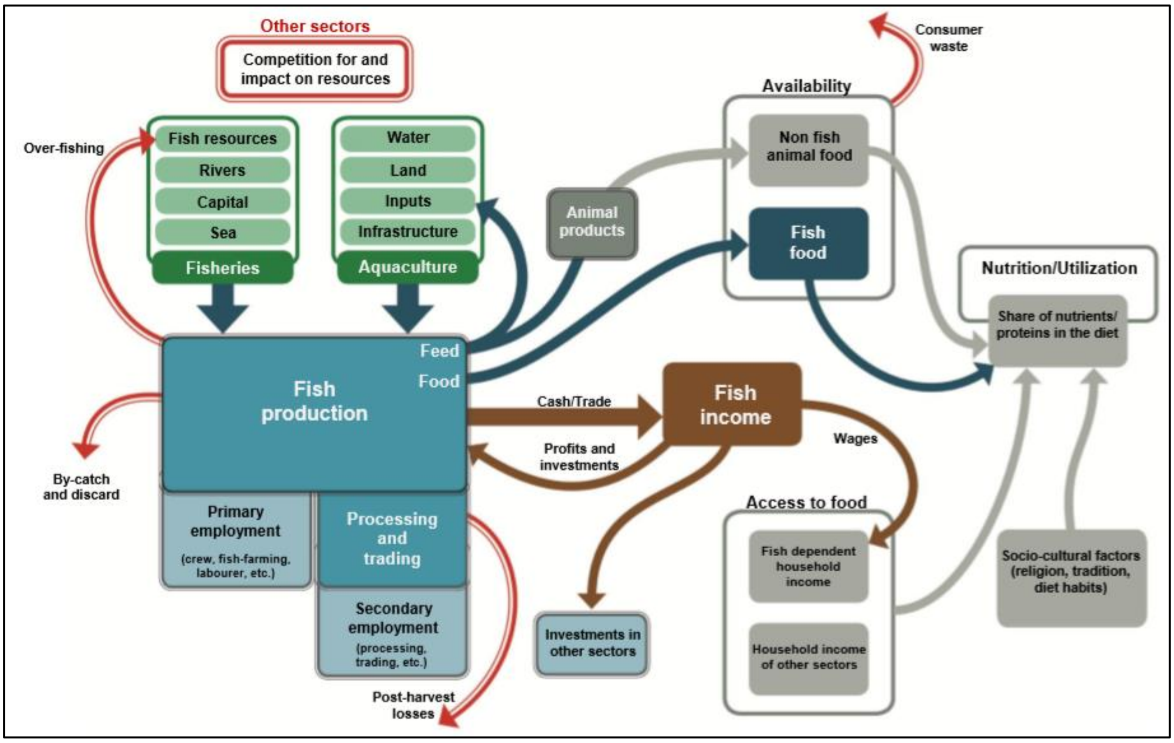


Figure 2. Pathways between fish and food security. Source (HLPE, 2014).

1.7 Combining Nutrition and Environmental Impact Assessments

The need to provide food for an increasing global population has created rising demand and competition for energy, water, and land. The global food production system needs to be transformed into a environmentally sustainable, equitable and resilient system and to do this we must measure and minimise our impacts on our natural resources. One of the most widely used environmental impact assessment methods employed by the global food production sector is LCA. LCA is a tool used to advise producers and consumers on the environmental performance of a product. The tool has been standardised by the International Standard Organisation (ISO) and described in their ISO 14044:2006 ‘Environmental Management – Life Cycle Assessment – Requirements and Guidelines’ (ISO, 2006). The aquaculture LCA literature is relatively limited compared to other agricultural disciplines, and the available studies vary in terms of the methodology used (Henriksson et al., 2012). Moreover, of the aquaculture LCAs that are available, most are focused on production in the global North even though the majority of global aquaculture takes place in LMICs (Bohnes et al., 2019). When an LCA is carried out for an agricultural product the functional unit (FU) is crucial to the assessment results. The FU describes the function of the system being measured and as nutrition is the ultimate function of aquaculture and other food products effort should be made to incorporate the nutrition of the system into the assessment. For this reason, there is a growing body of literature calling for interdisciplinary methods aims at integrating the nutritional quality of a product into LCA studies (Bianchi et al., 2022; Hallström et al., 2019; McLaren et al., 2021). However, the lack of standardised methodology makes it difficult to identify the best approach for combining the nutrition of a food product within its LCA.

There are various ways in which nutrition can be integrated into LCAs. The majority of studies which have combined nutrition and environmental assessments have carried out the analysis at diet level (Auestad and Fulgoni, 2015; Hallström et al., 2015; Heller et al., 2013; Saarinen et al., 2017) and some have opted for meal or individual product level (e.g. Masset et al., 2014; McAuliffe et al., 2020; Saarinen et al., 2012; Smedman et al., 2010). The methodology used to combine nutrition into LCAs is varied, for example researchers can combine the nutrition and environmental scores by using a nutritional index as the functional unit for the LCA (McLaren et al., 2021). Alternatively, separate scores can be used to interpret the relationship between nutritional quality and climate impact. Researchers using separate scores often show the relationship between nutrient density and greenhouse gas emissions using at least 2 separate scores rather than assigning a single score as a way of rating food products (Drewnowski et al., 2015; van Dooren et al., 2017).

In addition to dietary level and methods for combining scores, there are many other factors of a nutritional life cycle assessment (nLCA) (McLaren et al., 2021) which should be considered, for example the type of nutrition scoring system. Nutrient profiling of a food product is designed to use an algorithm to assign a score which shows the nutritional quality of the food. There are many factors to consider when deciding on the correct algorithm (Arsenault et al., 2012), such as the nutrients which will be included in the assessment, the unit of measurement (often 100g of edible portion of the food product), the nutrient intake amount (usually daily recommended nutrient intake (RNI) as per international standards), whether the nutrients should be capped at 100% of the intake amount and whether the nutrients should be weighted. Capping is limiting the points given to the food product at 100% RNI, meaning foods with high levels of one nutrient does not obtain a higher score as only 100% RNI of each nutrient is required (Hallström et al., 2018). Weighting is the process of assigning importance to particular nutrients, most important nutrients have a higher weighting, which in turn will have a greater impact on the final score.

There has been progress within the literature of the food-health-environment nexus towards building and improving the necessary tools and methodologies for evaluating the interactions between human nutrition and the environment. For example, Ro and Sundberg (2014) and Sokolow *et al*. (2019) propose novel methods which can be used to determine the environmental and nutritional impacts of a food product by calculating the impacts independently and then combining the scores. Hallström *et al*. (2019) also offer a way of combining LCA measurements with the nutritional performance of food products by integrating the two scores. Their method is used to measure the impacts of various seafood products found in Sweden and create a scale which determines which seafood products offer the highest nutritional quality with the least environmental impact. Lukas *et al*. (2016) propose a novel 'Nutritional Footprint' tool designed to evaluate the impacts of diets. Their methodology uses robust environmental and health quality indicators and offers a calculation to combine the environmental (LCA) and nutritional (dietary quality) 'score' which gives the 'footprint'. However, there are a number of limitations, for example, the tool is best suited to measure a meal rather than single food items and rather than being useful for policy makers, seems more geared towards consumers. Additionally, micronutrients are not considered, only 4 environmental and nutritional impacts areas are measured which heavily influences the results, as does the weighting given to each impact. Hallström *et al.* (2018) identified 24 studies which integrated the nutritional and environmental impacts of food. They show that there are novel methods offering new ways to measure the nutritional and environmental impact of food but the majority of studies in their review have one thing in common, the use of LCA. It is obvious LCA is the best tool for determining environmental impacts and instead of offering new methods, some researchers incorporate the nutritional aspect of the product into the LCA calculations. Recently there has been an increase in the use of a nutrient index as the FU within the LCA calculations (Kernebeek et al., 2014; Saarinen et al., 2017; Sonesson et al., 2019, 2017). Van Dooren (2017) has shown how different nutrient density indexes can be used as the functional unit for LCAs and demonstrates how nutrition can be incorporated into the measurements. The author uses a Nutrient Density Unit (NDU) as the functional unit which reflects the total protein, fatty acids, fibre, and energy of the food being assessed. Although nutrition as a FU is fast becoming a tool for LCA measurements, there have been limited LCAs focussed on aquaculture products which adopt this approach.

Although there are clear advantages of using nutrient quality metrics such as providing an easy-to-understand score of nutritional quality of a food product which can be combined with other types of performance assessments or used on food packaging to describe the nutritional quality of the food product, there are also several disadvantages to the metrics which are currently available. For example, interpretation of the score by consumers, researchers, or other stakeholders might differ depending on opinion. Additionally, the most appropriate metric needs to be chosen otherwise the indicator may not actually reflect the nutritional quality of the product. There are strengths and limitations of each nutrition metric available in the literature which should be considered when selecting a metric for inclusion in research or for commercial use i.e. on food packaging. One of the main issues with nutrient metrics is the amount and quality of data which is required. This varies depending on the metric therefore the availability of high-quality data needs to considered when selecting the most appropriate metric. The increasing aquaculture production in Bangladesh has been well-documented over the past decade (Belton et al., 2011; FAO, 2022; Hernandez et al., 2018; Hu et al., 2017). It is assumed the rapid increase in fish production has had impacts on natural resources (Henriksson et al., 2018) however environmental impact assessments of aquaculture in Bangladesh are rare within the literature. One study measured the potential environmental impacts of aquaculture intensification in Bangladesh using LCA methodology and found multidirectional outcomes (Henriksson et al., 2018). They found aquaculture intensification has no impact on land occupation and global warming, is positively correlated with acidification, ecotoxicity and eutrophication and is negatively correlated with water consumption. Although Henriksson et al. (2018) did not integrate a nutritional profiling into their LCA, a more recent study took the data from Henriksson et al. (2018) and integrated nutritional composition of the aquaculture systems into the results (Shepon et al., 2020). The authors demonstrated how aquaculture systems in Bangladesh can be transformed into more nutritious systems by altering the fish species composition of the system. Although these studies have shown the potential environmental impacts and offered insights into the nutritional quality and environmental performance of Bangladeshi aquaculture, there are a lack of in-field studies measuring real-time inputs and outputs, species composition of the systems and the nutrient composition of each species produced in the different systems.

The majority of aquaculture systems in Bangladesh are polyculture (Jahan et al., 2015) and performing a nutritional life cycle assessment (nLCA) for a multi-output system is complex. The allocation of environmental impacts to each species/crop produced under polyculture and/or integrated agriculture-aquaculture systems is critical in the calculations (Henriksson et al., 2012; Phong et al., 2011; Viglia et al., 2022). Additionally, the functional unit, system boundary, data quality, and impact and interpretation methods all affect the outcome of a nLCA therefore should be well considered during the goal and scope stage of the LCA (Henriksson et al., 2012; McLaren et al., 2021). Designing consistent and transparent nLCAs will be essential in identifying low-impact, nutritious food systems. This is especially important for species such as tilapia which are produced worldwide and can have far reaching nutritional and environmental implications. Within the aquaculture LCA literature, there are several studies which focus on tilapia (Pelletier and Tyedmers, 2010; Robb et al., 2017). Yacout *et al*. (2016) found that intensive and semi-intensive tilapia farming in Egypt had different environmental impacts. Intensive aquaculture had less impacts on global warming potential, acidification potential and cumulative energy demand but had greater impacts on eutrophication potential. Of the few tilapia LCAs within the literature none attempt to draw conclusions related to the nutritional status of the system or product. To address this knowledge gap, future research should aim to use appropriate methodological choices mentioned above, including a functional unit based on tilapia nutritional profiles.

1.8 Affordability

The EAT-Lancet report was a global effort to summarise the best available science and constructed a global diet which was healthy and sustainable (Willett et al., 2019). However the highly regarded report left out one very vital aspect, affordability (Hirvonen et al., 2020). Backlash to the report prompted others to investigate the cost of the benchmark diet and it was found that 1.58 billion people could not afford the diet (Hirvonen et al., 2020).

Additionally, it has also been suggested that the diet would likely increase the risk of micronutrient deficiencies for specific populations.

Poor dietary diversity is one of the main reasons people become malnourished, and a major driver of poor dietary diversity is food affordability (Ryckman et al., 2021a). Identifying low-cost foods can help with malnutrition rates, however the foods must be nutritious. Therefore, affordability cannot only consider food products as a whole, they should also combine the nutritional quality of the food.

Fish is highly affordable and accessible in many LMICs and can help contribute to food and nutrition security (Robinson et al., 2022b). Understanding the cost of fish and the related nutrients is an important step in identifying a healthy, sustainable diet. To do this, a food affordability index (FAI) can be used which is the ratio of wages to the price of a food product (Lele et al., 2016). Data for such an index is easy to collect and interpret as the score given is equal to the number of hours worked to earn a specific quantity of food. Usually, the wages of unskilled workers are used for the calculation (ILO, 2020), and staple food products are chosen, which gives insight into the purchasing power, and hence food security status, of poor people. Alternatively, a food affordability metric has been developed by Ryckman et al. (2021). which accounts for the cost of food products in relation to their nutrient composition- the "average share of priority nutrients" metric. Identifying appropriate indicators and metrics is important for assessing the affordability and nutritional quality of diets.

1.9 Significance of this Research and Thesis Objectives

Food systems which use natural resources sustainably, benefit society and are equitable are key to achieving the United Nations Sustainable Development Goals and ultimately global food and nutrition security. Substantial changes are required to develop and promote systems which sustainably produce nutrient-rich foods in a way which can overcome the current human and environmental health concerns (Gordon *et al*., 2017). Combining nutrition security and environmental assessments of food is crucial to holistically measure the outcomes of an aquaculture system, especially in a LMIC context where aquaculture provides food and nutrition, income, and employment for millions of people.

The expanding aquaculture sector in Bangladesh offers the opportunity to improve people's nutrition security however more research is required to understand the ways in which aquaculture development can achieve this. Knowledge on consumption patterns and fish nutrient composition is necessary for understanding the contribution of each species to nutrition security. However, data on global fish consumption patterns are lacking and, as a result, nutrition-sensitive policies are currently inadequate. Data on the environmental impacts of tilapia farming in Bangladesh are also unknown along with the nutritional outcomes of the various tilapia culture systems. Being able to determine the consumption patterns and how tilapia can contribute to human nutrition is critical for guiding policy makers towards promoting healthy, diverse diets.

The lack of rigorous studies into the contribution of fisheries and aquaculture to food security is concerning and without this knowledge we won't be able to fully recognise the gains which can be made from these important food producing sectors. Identifying the level at which we can sustainably exploit of our natural resources will enable us to identify the ways in which aquaculture can contribute to nutrition security.

The main objectives of this research were to assess the nutritional outcomes of tilapia production systems in Bangladesh and the associated environmental impacts. There was a focus on the nutrients significant to the Bangladeshi population: iron, zinc, calcium, iodine, vitamin A, vitamin B12 and vitamin D. The thesis investigates the nutritional quality of tilapia systems in terms of these important nutrients, and aimed to identify systems which can provide significant amounts of these nutrients at a low-cost to the environment. These objectives were addressed through the below research questions:

1. What is the nutritional value of tilapia produced and consumed in Bangladesh?
2. What are the environmental impacts of common tilapia production systems in Bangladesh?
3. How do aquaculture systems perform when a nutrition metric is integrated into the Life Cycle Assessment?
4. How do tilapia farming systems contribute to food and nutrition security?

Chapter 2

General Methodology

2.1 Introduction

This research project aimed to assess the performance of the environmental, nutritional and economic dimensions of aquatic food systems in Bangladesh, specifically tilapia production systems. There were three production systems selected as tilapia are commonly produced within these three systems and because they have been excluded from previous performance assessments. The typical fish-only system was selected for assessment alongside two integrated agriculture-aquaculture systems: rice-fish systems and poultry fish systems.

Integrated agriculture-aquaculture systems are common in Bangladesh and are a useful strategy for maximising available land and water resources (FAO, 2023). Rice-fish farming systems are widespread across Bangladesh and are an efficient farming strategy to maximise natural resources. Rice-fish systems are mostly polyculture and there are two archetypal system designs: i) a pond embedded directly into the rice field where fish can swim throughout the field, and ii) a pond separated from the rice field by dykes often with a channel through the dyke connecting the field and pond. The management practices at rice-fish farms are usually extensive with lower levels of commercial fish feed used compared to other types of farming systems (Jahan et al., 2015).

The sub-systems of the poultry-fish farms (poultry-shed/ fishpond/ crop field) are connected in a way which allows the nutrients the flow between each other. For example, the waste from the poultry-shed is washed into the pond and acts as a form of fertiliser, and the water from the pond is a source of irrigation for the crop field.

To measure the environmental performance of the systems, LCA methodology was used, where various impact categories were considered. Key to the LCA was understanding the impact related to nutritional performance of tilapia production systems, which was assessed using various indicators at each stage of the food system. A food and nutrition system approach was taken which guided the appropriate selection of indicators for each stage of the assessment. This chapter will describe the overall methodology used to examine nutritional and environmental performance of food systems, specifically the LCA methodology and nutrition metric choices.

LCA methodology is presented in this chapter and Life Cycle Inventories (LCIs) for specific processes used throughout the thesis are presented. LCIs detail the raw material inputs of the systems and products and are integral in defining the data required to construct the LCA model. The surveys used to collect the data to construct the LCIs are outlined in this chapter.

More specific methodological choices related to each individual chapter are described in the relevant chapter. There were four main sub-projects throughout this PhD project which had distinctive methodologies which will be described in this chapter:

1. Experimental tilapia production trials (2.3)
2. Tilapia nutrient composition analysis (section 2.4)
3. Integrated nutrition and environmental performance assessments (section 2.5)
4. Household food and nutrition security assessments (section 2.6)

2.2 Site Selection

Two agro-ecologically distinct districts were selected for this study: Rangpur and Noakhali. Rangpur (4791mt tilapia/year production (DoF, 2022)) in Northwest Bangladesh has a history with small tilapia production and consumption due to the large Rice-Field Fish Seed Production (RFFSP) systems (Barman et al., 2011; Haque et al., 2010). Decades of research on aquaculture, and rice-cum-fish culture in Rangpur means this district was ideal for this study since historical production and consumption data were known. Additionally, the on-going presence of NGOs in the area allows for easy access to key informants and the identification of farming clusters. The rice-fish production systems are one of the most important systems in this district (Jahan et al., 2015), providing food security and income for some of the poorest farmers in Bangladesh (Haque, 2007). Although the social and economic impacts of integrated rice-fish systems have been documented(Haque et al., 2014; Hayat et al., 2015), there is a lack of environmental performance and nutrition security outcome assessments of these systems. This is another reason this district has been chosen for inclusion in this research.

Noakhali (3586mt tilapia/year production (DoF, 2022)) in the South of Bangladesh has a growing aquaculture industry, however the district has been excluded from recent fish production and consumption assessments (Henriksson et al., 2018; Jahan et al., 2015) and there has never been any LCA performed for the poultry-fish systems commonly found in this area. For these reasons, the poultry-fish systems in Noakhali were chosen for inclusion in this research. In addition, staff at the Noakhali Science and Technology University were available to support the experimental trials, and there was a wide network of fish value chain actors based in Noakhali who were consulted during the project design stage. Poultry-fish farmers (*n*=20) across Noakhali were visited to collect farm input-output data for a LCA. Household food consumption surveys were also conducted with these farming households and after the data cleaning process there were 14 production surveys and 18 consumption surveys retained for analysis.

2.3 Experimental Tilapia Production Trials

The objective of the experimental trials was to investigate tilapia strain and system-type interactions for identification and comparison of nutritional, environmental and economic performance using nutrient quality metrics and LCA methodology. There were two trials, Trial 1 compared two commercial strains of genetically improved monosex tilapia farmed under intensive and semi-intensive management practices, and Trial 2 compared a genetically improved strain with a local strain grown in mixed sex populations under intensive and semi-intensive conditions.

A participatory approach was taken for these trials whereby resource-poor farmers were engaged as collaborators alongside researchers and other university staff (Biggs, 1989). This approach ensured the trials were client-oriented and the organisation and implementation of the research was modelled on current farming practices. Focus group discussions and key informant interviews were held alongside individual farmer interviews to establish the current pond preparation, fry transportation and stocking, feed management, harvesting and daily husbandry practices.

Trials were conducted on-station at Noakhali Science and Technology University in twelve identical experimental earthen ponds. Prior to the trials, key informant interviews were held with the district Ministry of Fisheries (MoF) officers to gather macro level data on fisheries production in Noakhali. This was followed by focus group discussions (FGD) with 35 inland tilapia farmers to gain an understanding of local production practices (Figure 3). One FGD was arranged by the MoF, and the rest were arranged using other key informants within the tilapia production sector in Noakhali. All farmers involved in the FGDs and interviews were males aged between 28-68 and had varying degrees of experience in aquaculture (ranging from 2 to 45 years). The FGDs and individual interviews were carried out in the local language, using local units of measurement, and were translated into English by the team members present at discussions/interviews. A semi-structured questionnaire was used during the FGDs to guide discussions and included questions regarding the overall farming scene in the village and common farming practices and management techniques however did not directly ask about incomes or expenditures. This information was collected if brought up by the FGD participants. Following the FGDs, 5 individual tilapia farmer interviews were conducted to gather micro level production data using a structured survey designed for Life Cycle Inventory (LCI) data collection.

The surveys with key actors in tilapia farming provided valuable information regarding tilapia production practices and management techniques in the area. This enabled the identification of common culture systems in the area which were comparable with the aquaculture technologies described by Jahan et al. (2015).

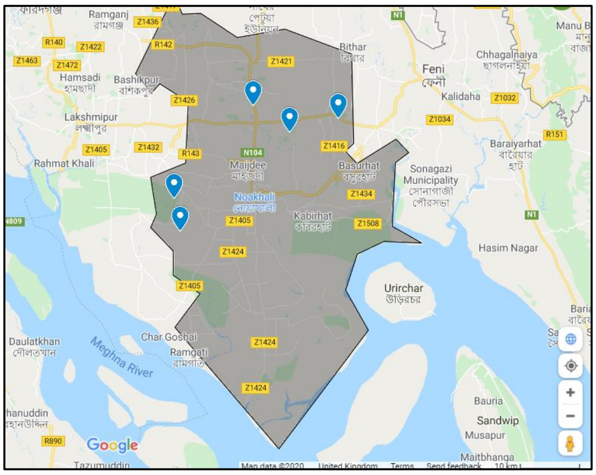


Figure 3. Map of Noakhali with markers showing village locations of focus group discussions (Google Maps, 2023).

As seen from Table 2, there were two separate trials, Trial 1 was a 6-month GIFT vs non-GIFT trial using all-male monosex populations farmed under intensive and semi-intensive conditions. Trial 2 compared a local strain of mixed sex tilapia populations with mixed sex GIFT under intensive and semi-intensive conditions over 15 months. The experimental procedures at each stage for both trials are described below.

Table 2. Outline of two experimental tilapia production trials conducted at NSTU.

Trial Code	Strain	Management	Harvesting Technique	Duration	Culture Type	Replications
T1-GI	GIFT	Commercial pellets	1 x partial harvest and 1 x final harvest	6 months	Polyculture with carps (rui, mrigal and catla)	3
T1-GS	GIFT	Ricebran + fertilisation	1 x partial harvest and 1 x final harvest	6 months	Polyculture with carps (rui, mrigal and catla)	3
T1-NI	Commercial	Commercial pellets	1 x partial harvest and 1 x final harvest	6 months	Polyculture with carps (rui, mrigal and catla)	3
T1-NS	Commercial	Ricebran + fertilisation	1 x partial harvest and 1 x final harvest	6 months	Polyculture with carps (rui, mrigal and catla)	3
T2-GI	GIFT	Commercial pellets	Harvest weekly starting 4 months after stocking	15 months	Monoculture	3
T2-GS	GIFT	Ricebran + fertilisation	Harvest weekly starting 4 months after stocking	15 months	Monoculture	3
T2-NI	Local	Commercial pellets	Harvest weekly starting 4 months after stocking	15 months	Monoculture	3
T2-NS	Local	Ricebran + fertilisation	Harvest weekly starting 4 months after stocking	15 months	Monoculture	3

T1-GI; Trial 1-GIFT strain farmed intensively, T1-GS; Trial 1- GIFT strain farmed semi-intensively, T1-NI; Trial 1-Non-GIFT strain farmed intensively, T1-NS; Trial 1-Non-GIFT strain farmed semi-intensively, T2-GI; Trial 2- GIFT farmed intensively, T2-GS; Trial 2-GIFT farmed semi-intensively, T2-NI; Trial 2-Non-GIFT farmed intensively, T2-NS; Trial 2-Non-GIFT farmed semi-intensively.

2.3.1 Trial 1

2.3.1.1 Tilapia Strains

Two commercial hatcheries were identified as producing strains of tilapia which were genetically distinct. The first strain was derived from the GIFT project and the second strain was another genetically improved strain which had been categorised as a non-GIFT strain.

The GIFT strain was obtained from a Tilapia Breeding Nucleus (TBN) in Mymensingh which had received the latest GIFT generation from WorldFish, Jitra, Malaysia. The TBN used improved farming practices to organise and manage their broodstock, ensuring there was no inbreeding. The TBN had 60 'foundation families' which were separated into eight cohorts and males from each cohort were bred with the females of a different cohort each year.

The non-GIFT strain originated from a commercial hatchery in Comilla in South Bangladesh. This strain was selected because it was identified by WorldFish Bangladesh as being a non-GIFT strain during a recent country-wide survey of tilapia hatcheries. The strain had not been identified further than "non-GIFT". The hatchery was well-managed, similar to the TBN hatchery whereby broodstock were separated by family and breeding was planned to reduce the possibility of inbreeding.

Broodstock management at both the GIFT and non-GIFT hatcheries were similar. Ponds, wherein broodstock remained throughout the year were prepared by draining, drying, and applying lime (0.02kg m^{-2}), urea (0.2kg m^{-2}) and Triple Superphosphate (0.1 m^{-2}). Both hatcheries bred fish using a 1:3 male: female ratio and moved fish during breeding season to breeding hapas. All breeding fish weights ranged between 250-500g, and fish were fed on commercial floating feeds with a crude protein of 35%.

2.3.1.2 Tilapia Fry Management

Upon hatching, GIFT fry were transferred into concrete cisterns (2.3m x 1.8m x 0.3m; water depth 0.22m; water exchange rate was 2L min^{-1}) and, after egg-sac absorption, were fed a commercial powder feed (crude protein 35%) which had been treated with 17αmethyltestosterone (17α -MT) to induce an all-male monosex population (Mair and Little, 1991). Fry were kept in the cistern for 7 days and were fed 30% biomass day^{-1}, then were transferred to a hapa in pond on day 8 where feeding with hormone treated feed continued. At 21-day post-hatch, the fry were transported from the hatchery to NSTU by car, in oxygenated polyethylene bags (120g fry 10L^{-1}), which took 11 hours.

Non-GIFT fry were also kept in a cistern after hatching and fed a hormone-treated powder feed (crude protein 35%) at a rate of 30-40% biomass day^{-1} for the first 7 days, then fed 15% biomass day^{-1} thereafter. At 21-day post-hatch the fry were transported in oxygenated bags (120g fry 10L^{-1}) which took 4 hours to reach NSTU.

2.3.1.3 Nursing Stage

GIFT and non-GIFT fry arrived at NSTU at 21-day post-hatch and were stocked into hapas in a pond which was not used in the trial. There was one GIFT hapa and one non-GIFT hapa of equal size (6.1m x 3m x 0.9m) and 5660 fry were stocked into each hapa. The fry were kept in the hapas and fed a commercial powder feed at a rate of 30% biomass day^{-1} which was adjusted every 7 days after a weight sample had been taken. Fish mortality numbers were also recorded to ensure accurate recalculation of feed amounts.

Water quality parameters were measured before the fry were stocked into the hapas and twice daily thereafter. Parameters measured included temperature, dissolved oxygen, pH, salinity, transparency, ammonia, phosphate, nitrate, and nitrite and all remained within the acceptable ranges for tilapia culture (El-Sayed, 2020).

2.3.1.4 Pond Preparation

Before beginning the trial all 12 experimental ponds, which were 75m^2, were drained and dried then fertilised and treated with rotenone to remove unstocked fish (Table 21) before being filled to 1.2m depth using water filtered through a fine mesh net from an adjacent pond. Water quality measurements were taken from the adjacent pond before taking water to fill the trial ponds. All key water quality parameters were within the acceptable ranges for tilapia production (El-Sayed, 2020).

There were two pond management practices implemented during the trial, intensive and semi-intensive. Table 3 shows the pond management regime for Trial 1. The design for these trials was based on information collected from local farmers and data from Karim and Little (2018).

Table 3. Fertilisation regimes for intensively managed and semi-intensively managed ponds during Trial 1.

Input	Intensive Ponds	Semi-intensive Ponds
Lime (kg/pond)	1.85	1.85
Application rate	*Once (pond prep)*	*Once (pond prep)*
Urea (kg/pond)	0.07	0.15
Application rate	*Once (pond prep)*	*Bi-weekly*
Dry cattle manure (kg/pond)	5.5	1.85
Application rate	*Once (pond prep)*	*Weekly*
TSP (kg/pond)	0.15	0.1
Application rate	*Once (pond prep)*	*Bi-weekly*
Potash (kg/pond)	0.11	-
Application rate	*Once (pond prep)*	-
Rotenone (kg/pond)	0.1	0.1
Application rate	*Once (pond prep)*	*Once (pond prep)*

2.3.1.5 Experimental Procedure

There were 4 experimental systems set up in triplicates:

1. Monosex GIFT farmed in a polyculture system under intensive conditions (T1-GI)
2. Monosex Non-GIFT farmed in a polyculture system under intensive conditions (T1-NI)
3. Monosex GIFT farmed in a polyculture system under semi-intensive conditions (T1-GS)
4. Monosex Non-GIFT farmed in a polyculture system under semi-intensive conditions (T1-NS)

At the beginning of the pond stage of the trial, the fish in both hapas were sampled weighed, then 370 fish were stocked into each pond (stocking density of 0.01 kg m^{-2}). in March 2020. The fish were fed using a commercial floating feed (crude protein 35%) twice per day, seven days a week. The feed volumes were readjusted weekly after weight sampling had taken place (Table 4). A partial harvest took place half-way through the grow-out period, and at the end of the 6-month cycle all ponds were drained and all fish were harvested in August 2020. All ponds in Trial 1 were polyculture with tilapia stocked alongside 3 species of carps.

Table 4. Feeding regimes for all 4 experimental systems for Trial 1, including total mean feed volumes (mean ± SE) and feed rates (BW refers to fish bodyweight, i.e. pond biomass).

System	Feed Type	Feed Rate	Total volume delivered across whole trial (kg)	Feeding frequency
T1-GI	Powder feed Starter feed Grower feed	30% BW in nursing hapa 5% BW first 30 days 3% BW thereafter	0.044 ± 0 3.7 ± 0.5 34.6 ± 1.8	2 feeds/day (9am + 4pm)
T1-NI	Powder feed Starter feed Grower feed	30% BW in nursing hapa 5% BW first 30 days 3% BW thereafter	0.067 ± 0 5.7 ± 0.4 47.3 ± 6.1	2 feeds/day (9am + 4pm)
T1-GS	Powder feed Rice bran	30% BW in nursing hapa 5% BW	0.044 ± 0 50.7 ± 0.7	2 feeds/day (9am + 4pm)
T1-NS	Powder feed Rice bran	30% BW in nursing hapa 5% BW	0.067 ± 0 43.1 ± 2.2	2 feeds/day (9am + 4pm)

2.3.2 Trial 2

2.3.2.1 Tilapia strains

Two strains of tilapia were chosen for Trial 2, a known GIFT derived strain and a strain which was considered a “local” strain as it had been stocked into a farmer’s pond in 2001 and had remained isolated with no intentional introductions of new stock/ families.

The GIFT strain used in Trial 2 was taken from a hatchery which produced GIFT-derived tilapia and was identified using the aforementioned WorldFish tilapia hatchery survey. This hatchery produced an older strain of GIFT compared to TBNs and is a government-run, commercial operation.

The non-GIFT strain was taken from a farmer’s pond in Noakhali who had been farming tilapia alongside carps in several ponds since the start of the millennium. The farmer had purchased mixed sex tilapia seed from a local seller in 2002 and had allowed the fish to free breed in the ponds. The farmer produced tilapia for food-fish and did not supply tilapia seed to other farms, however agreed to supply fry for Trial 2.

2.3.2.2 Tilapia Fry Management

At the GIFT hatchery, hatchlings were moved to tanks after egg-sac absorption and were fed a commercial powder feed (crude protein 35%) at 30-40% biomass day^{-1} for the first 7 days, then were stocked into hapas where they were fed 15% biomass day^{-1}. Fry were transported to NSTU at 2.1g, therefore were kept in the hapa until then. Transportation from hatchery to NSTU took 8.5 hours and fry were transported by pick-up truck in oxygenated polyethylene bags which were stocked at 120g fry 10L^{-1} water.

The non-GIFT fry came from a farmer’s pond thus were not hatched in tanks or cisterns as with the previous fry involved in these trials. Broodfish at the Trial 2 non-GIFT farm were kept in ponds and breeding happened naturally between fish in the ponds. As with natural tilapia reproduction, eggs would have been incubated in the mother’s mouth and hatchlings released from the mouth into the pond to survive on their own. Fish feed was added to each pond daily. However powdered feed was never supplied to the fry and there were no records kept on feeding rates. As with the GIFT fry, non-GIFT fry were transported to NSTU at 2.1g. Fry were stocked into metal drums (120g fry 10L^{-1}) with fresh water from a tubewell and driven, by pick-up truck, for 1 hour to NSTU.

2.3.2.3 Nursing Stage

Unlike Trial 1, the GIFT and non-GIFT fry arrived at NSTU for commencement of Trial 2 when the fish weighed 2.1g. This meant there was no need for nursing in hapas before being stocked into trials ponds. However, for acclimatisation purposes, the fry were stocked into hapas in the trial ponds as soon as they arrived, and were released into the pond after spending one day in the hapa.

2.3.2.4 Pond Preparation

Similar to Trial 1, all 12 experimental ponds (75m²) were drained and dried then fertilised and treated with rotenone to remove unstocked fish before being filled to 1.2m depth using water filtered through a fine mesh net from an adjacent pond. Water quality measurements were taken from the adjacent pond before taking water to fill the trial ponds. As with Trial 1, there were two pond management practices implemented during the trial, intensive and semi-intensive (Table 5).

Table 5. Fertilisation regimes for intensively managed and semi-intensively managed ponds during Trial 2.

Input	Intensive Ponds	Semi-intensive Ponds
Lime (kg/pond)	1.85	1.85 start
Application rate	*Once (pond prep)*	*Once (pond prep)*
Urea (kg/pond)	0.74	0.15
Application rate	*Once (pond prep)*	*Applied every 3 weeks*
Dry cattle manure (kg/pond)	5.5	1.85
Application rate	*Once (pond prep)*	*Applied every 1.5 weeks*
TSP (kg/pond)	0.15	0.1
Application rate	*Once (pond prep)*	*Applied every 3 weeks*
Potash (kg/pond)	0.11	-
Application rate	*Once (pond prep)*	-
Rotenone (kg/pond)	0.1	0.1
Application rate	*Once (pond prep)*	*Once (pond prep)*

2.3.2.5 Experimental Procedure

There were 4 experimental treatments set up in triplicate:

1. Mixed sex GIFT farmed in a monoculture system under intensive conditions (T2-GI)
2. Mixed sex Non-GIFT farmed in a monoculture system under intensive conditions (T2-NI)
3. Mixed sex GIFT farmed in a monoculture system under semi-intensive conditions (T2-GS)
4. Mixed sex Non-GIFT farmed in a monoculture system under semi-intensive conditions (T2-NS)

Ponds were 75m² and were stocked with 370 fish (stocking density of 0.01 kg m^{-2}). Fish were fed to satiation (Árnason et al., 2009; Li and Lovell, 1992) using a commercial floating feed (crude protein 35%) twice per day, seven days a week and the amount of feed delivered was recorded for every feeding session. Mean total feed volumes delivered are outlined in Table 6 for each experimental system.

Harvesting regimes differed from the first trial since this trial was a mixed sex population. As with local farming practices, small lift nets (2m²) were installed in each of the 12 experimental ponds to harvest fish weekly. Fish were stocked in October 2020 and allowed to free breed in ponds before harvesting began in April 2021. Small crops of food-fish sized tilapias were taken from each pond weekly during the harvesting sessions which continued until the final harvest when the ponds were drained and emptied in Feb 2022.

Table 6. Feeding regimes for all 4 experimental systems for Trial 2, including total mean feed volumes (mean ± SE).

System	Feed Type	Feeding frequency	Total mean volumes of delivered across whole trial (kg)
T2-GI	Starter feed	2 feeds/day (9am + 4pm)	8.8 ± 0.16
	Grower feed	2 feeds/day (9am + 4pm)	232.4 ± 6.4
T2-NI	Starter feed	2 feeds/day (9am + 4pm)	12.7 ± 1.5
	Gower feed	2 feeds/day (9am + 4pm)	259.8 ± 10.3
T2-GS	Rice bran	2 feeds/day (9am + 4pm)	236.4 ± 3.6
T2-NS	Rice bran	2 feeds/day (9am + 4pm)	239.1 ± 3.6

2.4 Tilapia Nutrient Composition Analysis

Focus group discussions were held with groups of women in Noakhali and Rangpur to understand the consumption patterns of tilapias. Additionally, food consumption surveys conducted with 68 households in Rangpur and 20 households in Noakhali and had a section on tilapia consumption. Fish producing and non-producing households (rice-only farming households) were surveyed to gather information on fish consumption habits with a focus on tilapia. A semi-structured, one-off survey was used to obtain information on plate waste and intrahousehold food distribution. The main aim of the survey was to determine the consumption patterns of tilapia and obtain information on food and nutrition security status of the household. The household member responsible for food preparation was asked to take part in the survey and food purchase and consumption data was collected. Every household involved in the survey was a tilapia-consuming household, and 87% of households stated they often eat tilapias which are small enough to consume whole (including bones but excluding viscera). The survey data established that tilapia consumed whole must be <15cm. Following this length threshold being established, tilapia weights and lengths were taken during tilapia sampling activities. A total of 4003 fish were measured and the length-weight relationship was calculated using regression analysis (Figure 4). This length-weight data alongside consumption data has allowed the identification of the weight of tilapia which are often consumed whole. Since households ate tilapia whole up to 15cm, tilapias under 50g have been assumed to be eaten whole.

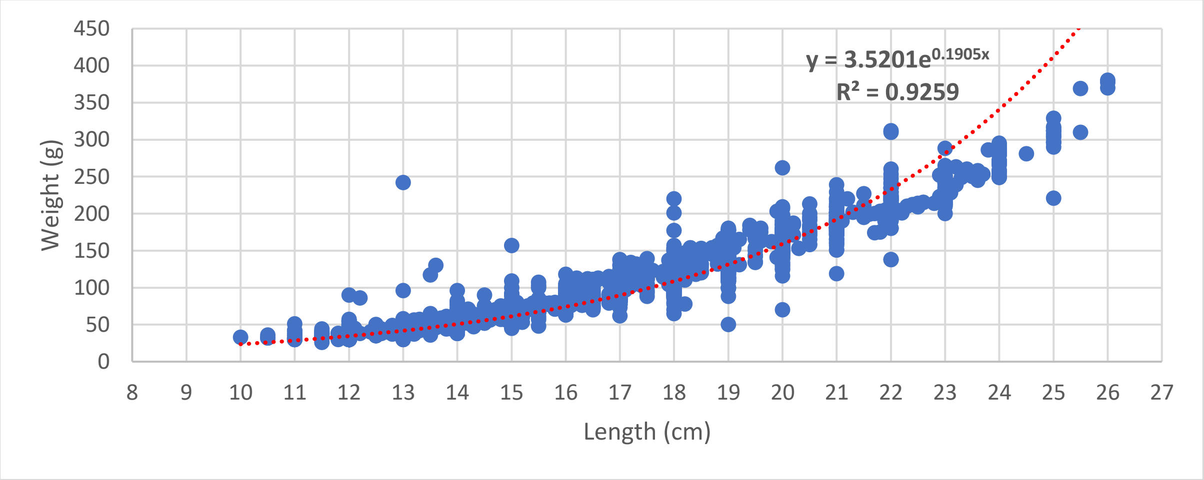


Figure 4. Length-weight relationship of tilapia samples collected from various farms and experimental systems (R square value of 0.93).

Composite samples of 1kg large and small (majhari) tilapia samples were taken for nutrient composition analysis under three separate sampling regimes i) samples from the experimental ponds at the trials at NSTU, ii) samples from rice-fish systems and fish-only systems in Rangpur, and iii) samples taken poultry-fish systems in Noakhali. Majhari tilapia preparation was well-understood through the FDGs and consumption surveys, so only the edible portions of large tilapia and majhari tilapia were taken for analysis. Table 7 outlines the edible portions and Figure 5 shows how majhari tilapia is prepared by locals for consumption.

Table 7. Overview of sampling tissues.

Fish	Tissue	Sample
Majhari	Whole fish excluding viscera, scales, fins, gills, opercula, and jaw/lips (Figure 4)	Composite of 1kg of fish
Large	All flesh including skin but excluding scales.	Composite of 1kg of fish

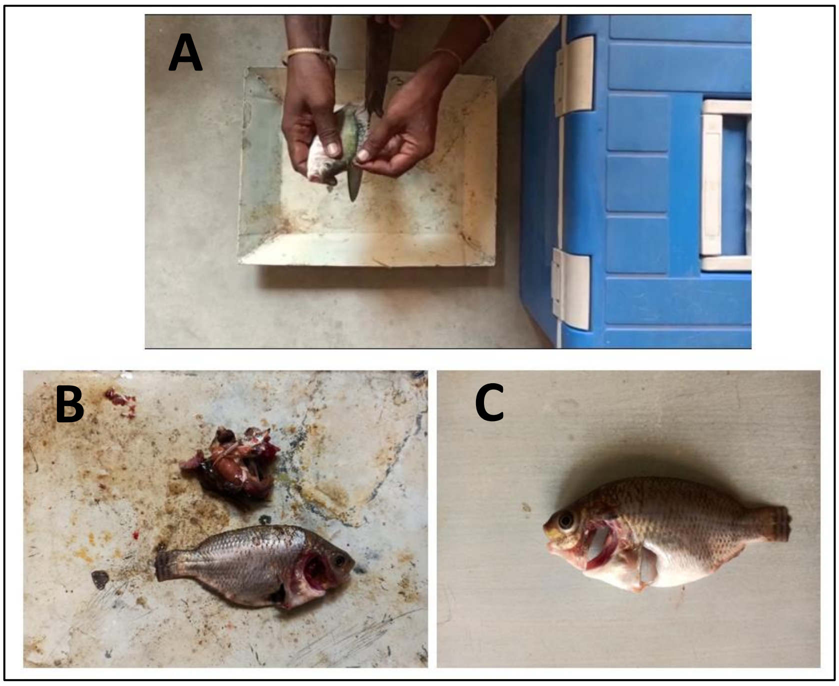


Figure 5. Example of majhari tilapia being prepared. Photograph **C** shows final product to be homogenised and analysed.

2.5 Nutritional Performance Assessments

Before assessing the nutritional performance of a food system, the nutritional requirements for the population of interest should be known. Since the majority of aquaculture production stays inside the country, the nutritional requirements of the Bangladeshi population were used for the calculations for the nutrition metric. To ensure the nutrient metric was population specific, essential nutrients known to be important in the Bangladeshi diet were chosen for inclusion in the metric. The most reliable and representative source of information on nutritional status of Bangladeshis is the National Institute of Population Research and Training reports (NIPORT et al., 2015), but a more comprehensive source of information on dietary practices and food insecurity in Bangladesh is the Food Security and Nutritional Surveillance Project (HKI and JPGSPH, 2016). Both sources were consulted when determining the priority micronutrients for this study.

Table 8 shows the recommended nutrient intakes (RNI) of the priority nutrients for adults in Bangladesh. The majority of vitamin and mineral requirements were taken from FAO and World Health Organization (1998), energy and protein requirements were taken from Waid et al. (2017), and zinc requirements from (IZiNCG, 2004). Zinc availability was assumed to be moderate, consistent with a cereal-based diet, iron bioavailability was assumed to be 10%, and adults were assumed to be moderately active. The average between male and female RNIs were taken for calculations in nutritional performance assessments.

Table 8. Daily recommended nutrient intakes (RNI) for female and male adults in Bangladesh all data taken from Data taken from FAO and World Health Organization (1998) unless otherwise stated.

RNIs	**Adult female (19-50)**	**Adult male (19-50)**
Iron (mg/day)	29.4	13.7
Zinc (mg/day)	9[a]	19[a]
Calcium (mg/day)	1000	1000
Vit A (µg RE/day)	500	600
Vit B12 (µg/day)	2.4	2.4
Vit D (µg/day)	5	5
Iodine (µg/day)	150	150
Protein (g/day)	39.12[b]	46.72[b]
Energy (kj/day)	9494[b]	12051[b]
Fat (g/day)	77	88

[a] Data taken from IZiNCG (2004)
[b] Data taken from Waid et al. (2017)

There are three main types of nutritional metrics which can be used in the assessment of nutrition-sensitive aquaculture, nutrient quantity metrics, nutrient quality metrics, and nutrient diversity metrics (Green et al., 2020). Nutrient quantity metrics are often used in n-LCAs as data are easy to collect and interpret and are useful for investigating the nutrient supply from a food product. Nutrient quality metrics assess the quality of a selected nutrient in the food item, however they have rarely been used in n-LCAs. A nutrient diversity metric has been chosen for this assessment since diversity metrics measure the diversity of nutrients available in a single food item but can also measure the nutrient diversity of a whole production system. Since the focus of this study is a variety of aquaculture systems, a diversity metric is the most appropriate option here. Nutrient diversity metrics require significant data collection activities and can be complex to calculate, but they provide important insights into the nutritional quality of food systems (Remans et al., 2011). The diversity metric used in this study is Potential Nutrient Adequacy (PNA). This metric will allow the measurement of nutrient diversity, as well as nutrient adequacy since the equation behind the metric includes the nutritional yields of the production system.

The use of functional trait metrics for measuring the nutritional quality of a food system allows researchers to measure multiple dimensions of a system. For instance, Potential Nutrient Adequacy (PNA) is dependent on species specific properties and the abundance of the species within the system (Wood, 2017). By selecting the priority nutrients for use in the metric enables the calculations to be population specific. Recent reviews of micronutrient deficiencies in various populations across Bangladesh have shown the nutrients of concern are iron, zinc, calcium, iodine, and vitamins A, D, and B12 (Ahmed et al., 2016; Arsenault et al., 2013).

2.5.1 Nutritional Yield

DeFries et al. (2015) proposed “nutritional yield” as an indicator and described it as the “number of adults who would be able to obtain 100% of the recommended nutrient intakes (RNI) of different nutrients for one year from a food item produced annually on one hectare”.

The average production yields for each treatment were used to calculate the nutritional yields for energy, protein, total fat, iron, calcium, zinc, iodine, vitamin A, vitamin B12, and vitamin D. The nutritional composition of tilapia from each system was used in the calculation with the exception of energy, wherein the values were taken from Bogard et al. (2015). The nutrient composition of the other fish included in this study were taken from Bogard et al. (2015), Mohanty et al. (2016), Paul et al. (2018), Golgolipour et al. (2019), Paul et al. (2019), Alahmad et al. (2021), INFS (2013), Paul et al. (2019), and Mohanty et al.

(2012). Data for nutritional composition of crops and poultry involved in this study was taken from INFS (2013) and McCance and Widdowson (2021). The nutrient compositions for all species involved in this study are outlined in Annex 2.

The below equation was used to determine the nutritional yield.

$$NY_{ij} = \frac{Fraction\ of\ RNI_i}{100_{gj}} \times \frac{Tonnes_j}{ha/yr} \times \frac{10^4}{365} \qquad (1)$$

Where,
i= nutrient of interest
j= food item
RNI for nutrient i = average recommended nutrient intake (RNI) of a female (not pregnant or lactating) and male adult, aged 19–50 years
Fraction of RNI for nutrient i = contribution to RNI from 100g of the food item of interest (*j*).

2.5.2 Potential Nutrient Adequacy (PNA)

This indicator builds on the NY calculations. The PNA score is the combination of the magnitude of the fraction of people potentially nourished, weighted by the evenness of the PNA score across all nutrients of interest. Wood (2018) introduced this indicator as a functional trait metric since the purpose of food is to nourish people and the PNA score is dependent on the quantities of nutrients in each food product and the yields of each food product, not solely on the presence or abundance of different foods produced by the system.

The below equation is used to calculate the PNA score.

$$\frac{\sum_{i=1}^{N}[s_i > 1]}{N} \times \bar{s} \qquad (2)$$

Where,

$\boldsymbol{N}$ = the number of nutrients

$\bar{\boldsymbol{s}}$ = average of all *N* nutrients

$[\boldsymbol{s_i} > \boldsymbol{1}]$ = number of nutrients whose value exceeds 1

This equation fits well with the research objectives since it recognises humans require a range of nutrients simultaneously, i.e., the PNA score would be higher for a system which provides a constant proportion of the population's total nutritional requirements compared to a system which delivers a higher proportion of the population's requirement for a small number of nutrients.

2.5.3 Food Affordability Index

The food affordability index (FAI) is the ratio of average wages to the price of a food product (Lele et al., 2016). Data for such an index is easy to collect and interpret as the score given is equal to the number of hours worked to earn a specific quantity of food. Usually, the wages of unskilled workers are used for the calculation (ILO, 2020), and staple food products are chosen, which gives insight into the purchasing power, and hence food security status, of poor people.

To maintain emphasis on the nutritional quality of a food product, a food affordability metric has been developed by Ryckman et al. (2021) which accounts for the cost of food products in relation to their nutrient composition- the "average share of priority nutrients" metric. In this study, the Average Share of Priority Nutrients (ASPN) relates to the price for the portion size (g) of fish needed to provide an average of one third of the recommended intake (RNI) values for the chosen 7 priority micronutrients (iron, zinc, calcium, iodine, vitamin A, vitamin B12 and vitamin D).

To calculate the ASPN for each fish species, the quantities of each priority nutrient in one portion (100g) of fish were determined, and the quantity (portion size in grammes) of fish required to achieve 33% of the daily recommended intake for each nutrient was determined. The costs per portion size were then calculated by scaling the market price for 1kg fish. The below equation shows how the ASPN score was determined:

$$ASPN_{i,j} = \frac{1}{|A|} \sum_{a \in A} \min \{\frac{nutrient\_density_{a,j} * i}{nutrient\_requirements_a}, 1\} \tag{3}$$

Where,

A= average share of priority nutrients

i = portion size of food

j= food product

2.6 Life Cycle Assessment

Poultry-fish, fish-only, and rice-fish farms were selected for an environmental and nutritional performance assessment. Life Cycle Inventory data were collected from farms using a structured survey design. The survey had been piloted, reviewed, edited, and piloted again before being implemented by a team of trained enumerators. In addition to the LCI survey, a household food consumption survey was carried out with the main food preparer of the household, and height, weight, gender, and age data were collected for every household member for Body Mass Index (BMI) calculations for a food and nutrition security assessment. Further details of the food and nutrition security assessments is given in Chapter 5.

Life cycle assessment (LCA) is standardised environmental accounting tool designed to measure inputs, outputs, and wastes of a production system. The conceptual framework behind LCAs is shown in Figure 5. According to the International Standards Organisation (ISO 2006) there are four phases of an LCA as seen in Figure 6, i.e. the goal and scope, which is followed by the inventory analysis, then the impact analysis and the fourth stage which is related to the these three stages which is the interpretation of results and data throughout the process. The LCA should be divided into the below sections to ensure the assessment if carried out appropriately:

1) Goal and scope definition of the LCA

2) Life Cycle Inventory (LCI)

3) Life Cycle Impact Assessment (LCIA)

4) Life cycle interpretation

5) Reporting and critical review of the LCA

6) Limitations of the LCA

7) Relationship between the LCA phases

8) Conditions for use of the value choices and optional elements

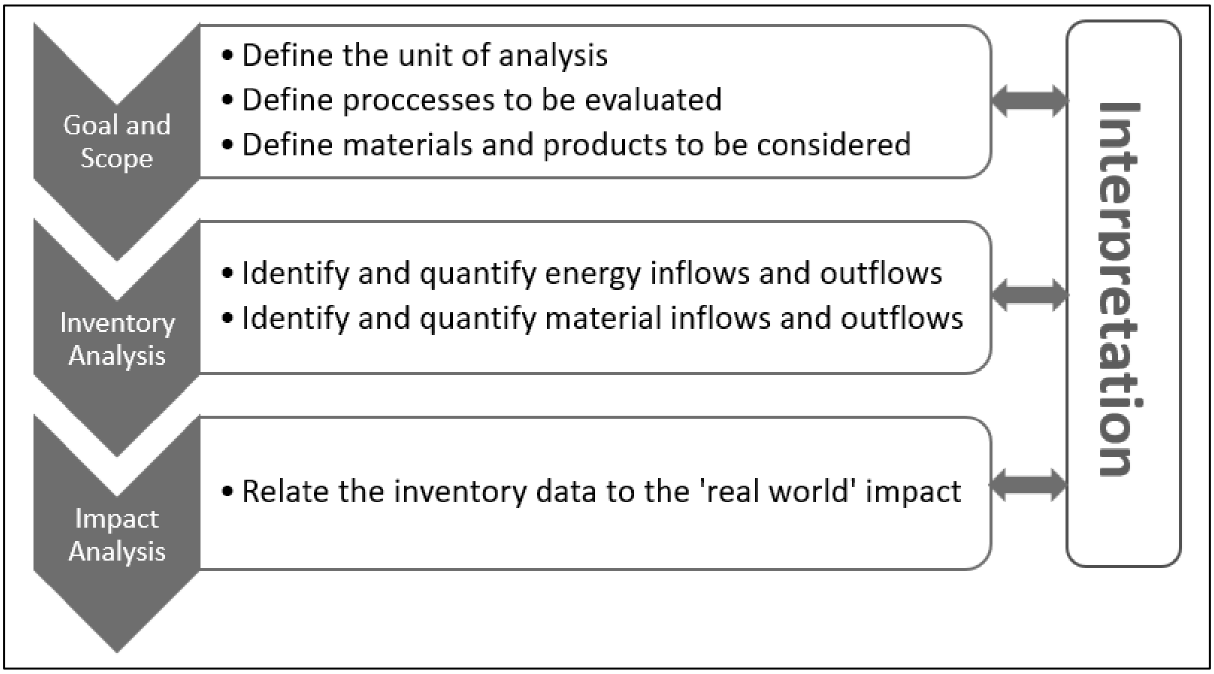


Figure 6. Conceptual Framework for LCA.

The goal and scope of each LCA in this thesis is outlined in the relevant chapters, alongside the other relevant information such as “functional units”, “allocation”, and “system boundaries”. The functional unit (FU) is a reference unit of measurement by which the impacts are quantified. “Reference flows” quantify the flow of goods, resources, and emissions between processes. The system boundary refers to the limits of the system under study which specifies the processes to be included in the assessment. Allocation refers to the way inputs or outputs are divided so that impacts can be assigned to different "co-products". Common allocation methods include economic allocation, mass allocation and energy content. For all LCAs in this thesis, where allocation was required, economic allocation was used.

The Life Cycle Inventory (LCI) is the detailed input and output data required to compile a LCA, for example the raw materials, economic and environmental flows. The LCI for fish and poultry feeds and tilapia seed are outlined below in Tables 9, 10, 11 and 12. Table 9 shows the LCI for the commercial pelleted feed used in the experimental trial. This data was collected from a local feed manufacturer using a structured survey. All fish feed used in the processes throughout this thesis utilised this dataset. The majority of fishmeal used in Bangladeshi fish feeds come from domestic sources, however there are significant imports from Peru, India, Malaysia and Viet Nam (Robb et al., 2017), therefore domestic and Peruvian fishmeal was used in the feed LCI because data on local fish meal and fish oil is scarce. The LCI for a tilapia hatchery is shown in Table 10. All data was collected during a visit to the hatchery using a structured questionnaire. Due to time and budget constraints, only one hatchery was surveyed so the LCI data in Table 10 was used for all tilapia hatchery processes throughout this study. Table 12 shows the LCI for rice bran production in Bangladesh, secondary data from Henriksson et al. (2014) was used to create this process.

Table 9. Life Cycle Inventory for 1 tonne of tilapia fish feed and the assumed origin of each input.

Input	Unit	Value	Origin
Fishmeal, domestic	kg	61.17	BD
Fishmeal, imported	kg	0.12	PE
Fish oil	kg	0.18	PE
Dry fish	kg	8	BD
Soybean meal	kg	358.23	Global
Corn gluten meal	kg	6.2	US
Rice polish	kg	72.87	BD
Maize	kg	254.67	BD
Maize flour	kg	1.76	BD
Vegetable oil	kg	17.42	BD
Mustard oilcake, domestic	kg	18.76	BD
Mustard oil cake, imported	kg	59.59	IN
Ricebran	kg	96.85	BD
DDGS	kg	4.92	BD
Salt	kg	1.46	Global
Limestone	kg	7.85	BD
Freshwater	m3	112	BD
Diesel	L	4.1	Global
Natural gas	m3	2.7	BD
Electricity	kWh	26.6	BD
Polypropylene bag	kg	3	Global

PE (Peru), BD (Bangladesh), IN(India) and US (United States of America).

Table 10. Life Cycle Inventory for tilapia hatchery production of 1 million tilapia fry.

Input	Unit	Value	Origin
Tilapia broodstock	kg	422.5	BD
Broodstock feed	kg	563.4	BD
Powdered fish feed	kg	2816.9	BD
Lime	kg	539.7	Global
Ethoxylated alcohol	kg	140.8	Global
Diesel	L	41.9	Global
Electricity	kWh	1760.6	BD

BD (Bangladesh).

Table 11. Life Cycle Inventory for 1 tonne of poultry feed and the assumed origin of each input.

Input	Unit	Value	Origin
Fishmeal, imported	kg	2.2	PE
Soybean meal	kg	204.83	Global
Soybean meal	kg	45.98	BR
Soybean meal	kg	74.35	US
Rice polish	kg	15.71	BD
Maize	kg	632.34	BD
Ricebran	kg	19.05	BD
Vegetable oil	kg	12.65	Global
Mustard oilcake	kg	0.33	BD
Salt	kg	2.01	Global
Lime	kg	27.88	Global
Corn gluten meal	kg	1.22	US
Freshwater	m3	50.4	BD
Diesel	L	2	Global
Natural gas	m3	0.03	BD
Electricity	kWh	12	BD
Polypropylene bag	kg	3	Global

PE (Peru), BD (Bangladesh), BR(Brazil) and US (United States of America).

Table 12. Life Cycle Inventory for production of rice bran on 1 hectare of land (from farm to mill) which was used at the experimental sites. Rice bran is a co-product of rice production.

Input	Unit	Value	Origin
Rice seed	kg	10.61	BD
Urea	kg	34.5	Global
Phosphate fertiliser	kg	28.62	Global
Potassium fertiliser	kg	12.94	Global
Ammonium sulphate	kg	2.81	Global
Gypsum	kg	0.73	Global
Cattle manure	kg	227.2	Global
Compost	kg	1.64	Global
Diesel	L	20.8	Global
Machinery lubricating oil	L	0.2	Global
Electricity	kWh	254.29	BD
Output			
Rice grain	kg	574	
Rice polish	kg	22.5	
Rice bran	kg	58.5	
Broken rice	kg	148.5	

BD (Bangladesh).

Transportation of inputs by road was assumed to be by a diesel-powered lorry with a maximum carrying capacity of 32 tonnes and a standard 0.38tkm per kg input was used. A default estimate of 300km was used for inputs for which the transport distance was not stated during data collection.

The main fuel source for electricity production in Bangladesh is natural gas and electricity available on the medium voltage level for Bangladesh was used as standard throughout this study (Henriksson et al., 2014).

The systems investigated in this thesis include fishponds (FO), poultry-fish farm (PF) and rice-fish farms (RF). The poultry shed on PF farms is situated above the fishpond and the shed is built in such a way that poultry litter falls through the shed floor and into the pond. Although all farmers used fertilisers, the PF farm has a constant supply of fertiliser in the form of poultry manure. The resulting fertilisation regimes in PF farms are unlike those in the FO and RF farms. Additionally, RF farms grow rice alongside fish, allowing the fish to swim into the paddy and feed on crop pests. FO farms using commercial pellets have a different fertilisation regime compared to FO farms feeding rice bran, which likely results in a variable abundance of natural food sources such as plankton or various invertebrates. These diverse production methods can give rise to an array of food sources (natural or otherwise) which, from the results, may lead to differences in nutrient profiles.

2.6.1 Environmental Indicators

The environmental indicators were based on the CML Baseline assessment methodology (CML, 2016). A list of the indicators involved in this thesis and definitions and units are outlined in Table 13.

Table 13. Definition of the environmental indicators included in the LCAs throughout this thesis.

Indicator	**Unit**	**Definition**
Global warming potential (GWP)	kg CO2eq	Greenhouse gas emissions based on a 100-year time period, otherwise known as carbon footprint.
Land use	m2a crop eq	Land used at production site and for inputs.
Abiotic depletion (FF)	MJ	Characterises the depletion of fossil fuel resources.
Water consumption	kg CO2 eq	Refers to water consumed at each stage of the production process and for all inputs.
Human toxicity	kg 1,4-DB eq	Describes the fate, exposure, and effects of toxic substances over an infinite time period.
Fresh water aquatic ecotox.	kg 1,4-DB eq	The effect of a substance to aquatic species.
Marine aquatic ecotoxicity	kg 1,4-DB eq	The effect of a substance to marine environments.
Terrestrial ecotoxicity	kg 1,4-DB eq	The effect of a substance on terrestrial species.
Photochemical oxidation	kg C2H4 eq	Describes the amount of secondary air pollution emitted from a process.
Acidification	kg SO2 eq	Describes the acidifying effect on water and soils.
Eutrophication	kg PO4--- eq	The enrichment of waterbodies with excess nutrients.
GWP LUC	kg CO2 eq	Associated greenhouse gas emissions related to land use change.
O3 Depletion	Kg CFC-11 eq	Describes the quantity of substances emitted which can destroy the ozone layer.

2.6.2 Nutritional-Life Cycle Assessment

Although nutritional-LCA methodology (n-LCA) has become more established in recent years (McLaren et al., 2021), there has been few n-LCAs performed on aquatic products, especially in LMICs. Previous studies which have assessed nutrition within LCAs have used different methodologies to combine the nutrition and environmental dimensions of the food system. For example, nutrient indexes have been used as the functional unit, alternatively others have combined the environmental and nutritional scores after the analysis to examine their correlation (Hallström et al., 2018). The Food and Agriculture Organization of the United

Nations (FAO) recognised the urgent need to develop methods for n-LCAs and initiated a project aimed at building consensus and creating best practice guidelines for such studies (McLaren et al., 2021). Meanwhile, Green et al. (2021) recognised there were several factors which should be considered during the method selection process for an n-LCA, specifically, the type of nutrition metric to be used in the analysis, and the points of differentiation for that metric (i.e. selection of nutrients, weighting, capping, reference amount, inclusion of disqualifying nutrients, validation and the specificity of the metric) (Green, 2022).

The points of differentiation in the selection of the nutrition metric can influence the outcome of the nutritional quality calculation and the Life Cycle Assessment. For these reasons the methodological choices should be explicitly outlined. The selection of nutrients to be included in the metric is key and more recently there has been a realisation that the selected nutrients should be specific to the population of interest. Similarly, capping and weighting can influence the outcome of the assessment and should be considered carefully. Weighting is used to give some nutrients priority over others in the metric mathematical equation, and capping is used to limit the influence one nutrient can have on the overall nutrition score, i.e. some nutrients might be capped at 100% of daily RNI. The inclusion of “disqualifying nutrients” should also be considered as some researchers include nutrients which are considered unhealthy as a disqualifying nutrient which acts as a negative towards to final nutritional score. Additionally, validation and the specificity of the metric should be considered, i.e. has the metric been validated by a governing body and is it applicable “across-the-board” or is it food / food group specific.

These points of differentiation and the framework were set out by Green (2022) to guide researchers in the identification of the appropriate nutrition metric to be used for a nutritional Life Cycle Assessments. The nutrition metric selected for use in this study is the Potential Nutrient Adequacy, described above in 2.2.9. Table 14 outlines the specificities of the metric used in the nutritional and environmental performance assessments throughout this thesis.

Table 14. Points of differentiation for the selected nutrient diversity metric used in this study. Adapted from Green (2022).

Nutrition Metric	Specifications	Differentiation	Justification
Potential Nutrient Adequacy	Selection of nutrients	Selection criteria: inclusion of macronutrients and specific micronutrients known to be deficient in study population, and which are relevant to the production system	Selection of specific nutrients for adequacy metrics is suitable when nutrients are relevant to population.
	Weighting	Unweighted	When data quality is uncertain, unweighted metrics are considered less biased. PNA metric is already context and dietary specific.
	Capping	Uncapped	This study is a product level study. Any excess nutrients found in a food can compensate for a lack of nutrients in another food product in the diet.
	Across the board or group specific	Across-the-board (ATB)	ATB metrics can be useful for identifying food systems which can positively impact micronutrient deficiencies. The assessments within this study consider multiple foods therefore an ATB metric is more appropriate.
	Disqualifying nutrients	Not included in metric	Avoids negative scores by excluding disqualifying nutrients. Only considering ‘natural’ foods in this assessment.
	Validation	Not validated	Validation is not practical for nutrient adequacy metrics at production level.
	Context and dietary specific	PNA is both context-specific and dietary-specific	Context- specific metrics can lead to results which guide context-specific interventions / innovations.
	Reference value	100g edible portion	Most food serving sizes are set at 100g portion, so this allows ease of comparison. “Edible portion” is considered since the edible parts of different fish species can vary.

Chapter 3

Analysis of nutritional quality of tilapia aquaculture systems in Bangladesh

3.1 Introduction

Food composition databases are sources of detailed information on the nutrient content of foods. The databases are used by health and nutrition experts, food manufacturers, consumers, educators, and policy makers to inform and guide decisions. In the 1970s the advantages of the development and organisation of food composition tables were recognised by various users across Europe, which led to an improvement in the way these tables were managed (Church, 2005). Composition tables became further advanced once nutritional composition databases (NCDB) were transferred online, and now there is a wealth of food composition data freely available. Online databases have enhanced and facilitated nutritional epidemiology and human nutrition research as understanding the chemical content of food is the crucial first step of these types of studies (Greenfield & Southgate, 2003). However, data on the nutrient content of seafood were severely lacking, then in 2014 the FAO Committee of Fisheries highlighted the need to incorporate globally important fish and shellfish into food tables (FAO, 2016). Alongside various other large-scale efforts to collate information on Blue Food nutrient profiles, for example FishBase (Froese & Pauly, 2022), FAO developed the FAO/INFOODS Global Food Composition Database for Fish and Shellfish Version 1.0- uFiSh1.0, which contains the nutritional content of 78 fish, crustacean and mollusc species produced by fisheries and aquaculture around the world (FAO, 2016). The database was formed using an extensive list of resources and contains nutritional content of raw and cooked edible portions however, as with any food table, the methods of nutrient analysis differ between the resources used, where some methods are more reliable than others. The document describes the various nutrient compositions of the same species found in different countries which makes clear how geography can impact chemical contents of food. Nutrient content (NC) can be affected by various factors, for example the way in which a food item is prepared or cooked or the changes in production methods. Accurate food composition datasets are necessary for a wide range of health and welfare assessments, food supply and safety investigations, environmental impact studies, food production research and development, and various other essential areas of research (Church, 2006).

Blue Foods are often produced, processed, and consumed in various ways therefore identifying the edible portion of fish, and the variety of production methods is crucial in determining the nutritional quality of the product. Therefore, food system characterisation and consumption behaviour studies should be performed when assessing the NC of a food item.

Tilapia is sold in markets at various sizes, and size often determines the way in which the fish is consumed. Small tilapias are often eaten whole, drawn, or dressed, whereas larger tilapias are likely to be consumed as steaks or fillets and only the flesh is edible. More robust data on production system types and preparation practices of tilapia will support researchers and policymakers in identifying the nutritional quality of tilapia, and the environmental performance and nutritional quality of tilapia production systems. However, the available nutrient data on tilapia in Bangladesh does not reflect the diversity of production and consumption practices. Considering tilapia is one of the most consumed fish in Bangladesh (Hernandez et al., 2018), and has the second highest production values (DoF, 2022), there is an urgent need to identify the role tilapia has in food and nutrition security. Although research has suggested the rise of farmed tilapia has had negative impacts on nutrition security in Bangladesh (Bogard et al., 2017b, 2017a), such studies have suggested tilapia has a relatively poor nutrient quality compared to small indigenous fish species (SIS). Although tilapia does provide less micronutrients than many SIS fish (Bogard et al., 2015) it remains an important source of protein and energy. Additionally, the consumption of whole tilapia (Haque et al., 2010) has been overlooked during previous nutritional quality assessments.

The production systems in which tilapia is produced in Bangladesh vary greatly, for example, tilapia are reared in backyard ponds, poultry-fish ponds, rice fields and intensive cage culture. Tilapia produced in different systems under varying feeding regimes have been are likely to have different nutritional profiles (Suhaimi et al., 2022). For this reason, tilapias produced in ponds, rice-fields and poultry-cum-fish plots were assumed to have different nutrient profiles. However, there are no studies which have identified the nutritional differences of small tilapia (eaten whole) and larger tilapias which have been produced in a range of systems.

For the above reasons, the nutritional composition of tilapia produced in several important food systems and prepared and eaten in two distinct forms have been analysed. The main objective of this research was to identify and document the nutritional composition of tilapias consumed in Bangladesh to enrich the literature in a way that helps researchers and policymakers understand the risks and benefits of tilapia production. In addition to improving the NCDB literature, this research also aims to assess the quality of various tilapia production systems. The nutritional yields (NY) and potential nutrient adequacy (PNA) of each tilapia production system involved in this study were calculated as a measurement of nutritional quality. These functional trait metrics are ideal indicators for comparing the nutritional quality of agriculture and aquaculture systems (Bogard et al., 2018; Lopez-Ridaura et al., 2021) yet are rarely used in aquaculture impact assessments. Only one study was found which used NY and PNA to assess the nutritional quality of aquaculture systems (Bogard et al., 2018). This study will use NY and PNA to compare the nutritional quality of the focal systems in this study and will exhibit the benefits of using ecological trait metrics for future studies.

3.2 Methodology

According to official Bangladesh government statistics, 80.5% of tilapia produced was cultured in ponds, with a large proportion of the remaining 19.5% originating from seasonal waterbodies (DoF, 2022). For this reason, tilapia cultured in monoculture and polyculture ponds, poultry-fish ponds, and rice-fish plots (considered seasonal waterbodies) were selected for nutritional composition analysis and a systems-based nutritional performance analysis. Table 15 outlines the tilapia sampling regime, *majhari* tilapia refers to small-sized tilapias which are often consumed whole (including bones but excluding viscera, fins, and jaw).

Table 15. Outline of systems from which tilapias were sampled. Season refers to the time of year when tilapia sample was taken. Commercial feeding regime refers to use of commercial fish pellets, other refers to a regime using a mix of feeding methods, i.e. ricebran + fertilisation, commercial pellets + ricebran or ricebran + pellets + fertilisation.

Fish Type	**Location**	**System**	**Season**	**Feed Regime**	**Sample size (*n*)**
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	12
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	12
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	12
Majhari Tilapia	NSTU	Monosex, polyculture ponds	We	Other	12
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	12
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	12
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	12
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	12
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	12
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	12
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	12
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	12
Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	3
Tilapia	Rangpur	Polyculture ponds	Dry	Other	3
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	3
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Other	3
Tilapia	Rangpur	Polyculture rice-fish plots	Dry	Commercial	3
Tilapia	Rangpur	Polyculture rice-fish plots	Dry	Other	3
Majhari Tilapia	Rangpur	Polyculture rice-fish plots	Dry	Commercial	3
Majhari Tilapia	Rangpur	Polyculture rice-fish plots	Dry	Other	3
Tilapia	Noakhali	Polyculture poultry-fish ponds	Dry	Commercial	4
Tilapia	Noakhali	Polyculture poultry-fish ponds	Dry	Other	1
Majhari Tilapia	Noakhali	Polyculture poultry-fish ponds	Dry	Other	2

3.2.2 Sampling Protocol

Duplicate composite samples were taken from each pond in the experimental trials, and triplicate composite samples were taken from each farm. To obtain composite samples, 1kg of fish was randomly selected from each system, prepared as per local practices and the edible tissues were homogenised in a mixer. Full sampling processes are outlined in Table 16 and 17.

Local women were employed to prepare the fish as per local practices to ensure only the edible tissues of small tilapias (<50g) and large tilapias (>80g) were collected for analysis.

Table 16. Overview of sampling tissues for small (majhari) and large uncooked tilapias (large).

Fish	Tissue	Sample
Majhari	Whole fish excluding viscera, scales, fins, gills, opercula, and jaw/lips (Figure 1)	Composite of 1kg of fish
Large	All flesh including skin but excluding scales.	Composite of 1kg of fish

Table 17. Sample conditions for small (majhari) and larger sized tilapias (large).

Sample	Storage		Final sample amount used in analysis
	Wet	Freeze-dried	
Majhari	Frozen at -20°C	Room temp in a dark space (inside box)	50g of freeze-dried material
Large	Frozen at -20°C	Room temp in a dark space (inside box)	50g of freeze-dried material

All tilapia samples were freeze-dried and shipped to the Institute of Marine Research in Norway (IMR) and University of Stirling (UoS), Scotland for nutrient content analysis. IMR performed analysis of vitamins A, B12 and D, and Fe, I, Zn, Ca, Mg, P, K and Na as per methods outlined in Moxness Reksten et al. (2020), and UoS performed analysis of ash, amino acids and fatty acids. All analyses were performed using methods accredited to ISO 17025:2005, except energy and iron as these methods are validated but not yet accredited (Moxness Reksten et al., 2020). A summary of the analytical method is presented in Table 18.

Table 18. Overview of analytical methods, measurement range and uncertainty.

Analyte	Method Reference	Measurement range	Unit	Uncertainty (%)
Crude protein	Block digestion (AOAC, 2023)	0.1– 0.7 0.7 - 16	g/100g	40 6
Crude fat	Acid hydrolysis (AOAC, 2023)	0.1 - 5 5 - 15	g/100g	12 8
Ash	Direct method (AOAC, 2023)	0.1 - 18	g/100g	12
Vitamin A1	HPLC (Moxness Reksten et al., 2020)	0.003 – 100 100 - 400	mg/kg	20 15
Vitamin A2	HPLC (Moxness Reksten et al., 2020)	0.005 – 100 100 - 400	mg/kg	20 15
Vitamin B12	Surface plasmon resonance (AOAC, 2023)	0.001 – 1.2	mg/kg	30
Vitamin D3	HPLC (Moxness Reksten et al., 2020)	0.1 – 0.5 0.5 – 10 10 - 40	mg/kg	20 15 15
Fe	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	0.1 – 1 0.2 1 - 1800	mg/kg	40 25
I	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	0.04 – 0.4 0.4 - 5	mg/kg	40 20
Ca	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	35 – 13000	mg/kg	15
Zn	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	0.5 – 5 5 - 1400	mg/kg	40 20
Mg	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	10 - 3125	mg/kg	15
P	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	3 - 10000	mg/kg	15
K	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	50-17000	mg/kg	15
Na	Inductively coupled plasma/mass spectrometry (Julshamn et al., 2007)	110-6250	mg/kg	15

HPLC; High performance liquid chromatography

3.2.3 Statistical Analyses

RStudio version 4.0.3 was used to conduct statistical analysis of tilapia nutrient composition data. ANOVA was used to investigate the differences in nutrient contents of tilapia produced in different systems using the lm() function (Chambers, 1992), controlling for tilapia strain and time of year. Tukey tests were performed using the TukeyHSD() function (Odeh & Evans 1974) to investigate the interactions between system, feed and tilapia form (large tilapia and small tilapia which are eaten whole). ANOVA was also used to analyse the differences between PNA scores between each system type. Results showing a P-value <0.05 were considered significant. All data are presented as means ± standard deviation.

3.3 Results

3.3.1 Nutritional Composition of Tilapia

The moisture, ash, protein, and total fat of all tilapia samples are shown in Table 19, nutrient content is presented as g per 100g raw edible parts. Table 15 shows the mineral contents for all samples which are expressed as unit per 100g raw edible weight. Table 16 shows the vitamin contents for all tilapia samples, values are presented as µg per 100g raw edible parts. All values in Table 19, 20 and 21 are mean results from the replicate samples taken from each system.

All proximate components and micronutrients, excluding vitamin A, differed significantly between large tilapia (only flesh and skin consumed) and *majhari* tilapia (consumed whole). System type (pond/ poultry-fish/ rice-fish) and feed type (commercial pellets/ other) also had significant effects on various nutrients. Mean ± SD for values of tilapia and *majhari* tilapia from all systems are shown in Table 22.

Table 19. Moisture, ash, protein, and fat content of tilapia sampled from different systems across Bangladesh.

Fish Type	Location	System	Season	Feed Regime	Moisture g/100g	Ash g/100g	Protein g/100g	Fat g/100g
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	76.17	1.07	15.81	5.95
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	78.33	1.22	14.91	4.93
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	74.17	1.88	14.49	8.69
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	72.25	2.51	14.93	9.89
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	72.66	2.57	18.74	5.74
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	74.02	1.93	17.94	5.02
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	70.46	3.20	16.87	7.31
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	68.80	2.66	15.60	9.99
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	73.27	1.31	18.50	6.12
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	75.50	1.57	18.67	3.52
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	71.80	2.57	15.83	8.98
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	71.73	3.26	15.13	9.28
Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	78.24	1.13	18.37	1.83
Tilapia	Rangpur	Polyculture ponds	Dry	Other	78.29	1.19	18.85	0.76
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	71.98	3.74	18.10	4.53
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Other	77.72	1.24	15.34	2.03
Tilapia	Rangpur	Rice-fish	Dry	Commercial	79.09	1.22	18.13	1.18
Tilapia	Rangpur	Rice-fish	Dry	Other	78.88	1.15	18.43	0.95
Majhari Tilapia	Rangpur	Rice-fish	Dry	Commercial	76.80	3.66	15.11	2.89
Majhari Tilapia	Rangpur	Rice-fish	Dry	Other	75.32	3.81	16.60	3.04
Tilapia	Noakhali	Poultry-fish	Dry	Other	76.40	1.56	18.93	2.22
Majhari Tilapia	Noakhali	Poultry-fish	Dry	Other	75.05	2.82	15.56	2.84

Table 20. Mineral content of tilapia sampled from different systems across Bangladesh.

Fish Type	Location	System	Season	Feed	Iron mg/100g	Calcium mg/100g	Zinc mg/100g	Sodium mg/100g	Potassium mg/100g	magnesium mg/100g	Phosphorus mg/100g	Iodine ug/100g
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	1.21	105.52	1.36	49.02	322.75	27.41	197.11	11.81
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	1.69	148.83	1.22	48.16	316.67	28.83	212.88	10.59
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	2.28	475.33	1.66	62.80	261.48	27.99	345.50	14.37
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	3.94	637.42	1.80	71.18	299.62	32.87	427.64	13.33
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	1.13	112.89	1.12	60.59	345.61	29.60	226.41	18.46
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	2.01	181.94	1.47	60.17	337.93	29.42	248.30	24.44
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	4.57	986.24	2.04	71.86	251.96	32.98	527.42	15.29
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	4.83	950.29	2.06	69.15	267.28	32.44	540.21	25.90
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	2.10	93.83	1.22	55.67	310.00	27.00	200.00	7.82
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	2.83	240.83	1.57	69.50	308.33	29.67	266.67	10.83
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	4.75	621.67	1.87	73.67	250.00	30.00	420.00	10.08
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	5.35	1015.00	1.92	80.17	233.33	33.00	583.33	12.78
Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	0.98	45.57	0.93	44.27	399.17	27.58	206.70	1.77
Tilapia	Rangpur	Polyculture ponds	Dry	Other	1.08	23.41	0.73	52.88	448.49	30.40	214.14	2.16
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	3.17	1146.92	1.76	68.24	317.40	31.42	603.88	10.72
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Other	5.41	1256.71	1.67	85.08	304.25	33.44	655.06	4.36
Tilapia	Rangpur	Rice-fish	Dry	Commercial	3.84	122.78	0.91	49.48	390.19	27.88	237.07	2.05
Tilapia	Rangpur	Rice-fish	Dry	Other	1.19	41.18	0.86	39.07	422.33	29.56	206.94	3.17
Majhari Tilapia	Rangpur	Rice-fish	Dry	Commercial	8.83	1333.56	1.66	69.66	278.71	35.54	709.82	9.06
Majhari Tilapia	Rangpur	Rice-fish	Dry	Other	3.78	1332.82	1.51	88.11	296.48	35.39	715.87	27.17
Tilapia	Noakhali	Poultry-fish	Dry	Other	1.41	234.49	1.07	56.80	401.28	29.77	288.89	15.09
Majhari Tilapia	Noakhali	Poultry-fish	Dry	Other	5.52	1749.72	1.96	103.57	299.40	39.97	887.06	43.36

Table 21. Vitamin content of tilapia sampled at different locations across Bangladesh.

Fish Type	**Location**	**System**	**Season**	**Feed Regime**	**Vit A[a] ug/100g**	**Vit D ug/100g**	**Vit B12[b] ug/100g**
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	1.78	41.99	-
Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	2.57	26.74	-
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Commercial	2.01	45.74	-
Majhari Tilapia	NSTU	Monosex, polyculture ponds	Wet	Other	1.74	16.09	-
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	1.29	17.18	2.18
Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	0.78	4.61	2.25
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Commercial	0.61	2.96	2.32
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Dry	Other	0.06	1.20	2.19
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	1.93	43.80	3.03
Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	1.16	18.09	1.94
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Commercial	5.83	31.23	3.81
Majhari Tilapia	NSTU	Mixed sex, monoculture ponds	Wet	Other	1.52	6.63	2.11
Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	1.64	9.72	1.41
Tilapia	Rangpur	Polyculture ponds	Dry	Other	0.71	5.62	1.30
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Commercial	1.93	5.75	3.53
Majhari Tilapia	Rangpur	Polyculture ponds	Dry	Other	3.45	5.44	4.01
Tilapia	Rangpur	Rice-fish	Dry	Commercial	1.04	5.31	2.57
Tilapia	Rangpur	Rice-fish	Dry	Other	0.38	3.06	0.96
Majhari Tilapia	Rangpur	Rice-fish	Dry	Commercial	2.01	1.85	4.27
Majhari Tilapia	Rangpur	Rice-fish	Dry	Other	0.70	2.23	2.09
Tilapia	Noakhali	Poultry-fish	Dry	Other	1.87	4.88	2.06
Majhari Tilapia	Noakhali	Poultry-fish	Dry	Other	3.24	1.87	1.83

[a] µg RAE, retinol activity equivalent.

[b] Vitamin B12 values unavailable for Trial 1 at NSTU due to budget constraints.

Table 22. Mean ± SD values for tilapia and majhari tilapia from all systems for all nutrients.

	Ash g/100g	Protein g/100g	Fat g/100g	Iron mg/100g	Calcium mg/100g	Zinc mg/100g	Sodium mg/100g	Potassium mg/100g	magnesium mg/100g	Phosphorus mg/100g	Iodine ug/100g	Vitamin A ug/100g	Vitamin D ug/100g	Vitamin B12 ug/100g
Tilapia	1.45 ± 0.45	17.93 ± 1.32	3.47 ± 2.14	1.77 ± 0.89	122.84 ± 73.7	1.13 ± 0.27	53.24 ± 8.51	363.89 ± 49.83	28.83 ± 28.83	227.74 ± 29.59	9.83 ± 7.44	1.38 ± .65	16.45 ± 15	1.97 ± 0.65
Majhari tilapia	2.85 ± 0.8	15.78 ± 1.04	6.32 ± 3.24	4.77 ± 1.68	1045.97 ± 374.31	1.81 ± 0.18	76.68 ± 11.70	278.17 ± 27.12	33.19 ± 3.12	583.25 ± 156.16	16.95 ± 11.09	2.10 ± 1.61	11.00 ± 14.58	2.91 ± 0.97

Calcium content varied the most, with the lowest value (23.41g) recorded by tilapia sampled from fishponds in Rangpur, to the highest value (1749.72g) recorded by *majhari* tilapia sampled from poultry-fish farms in Noakhali (Table 15). Similarly, vitamin D content was highly varied between tilapia samples with the lowest (1.20ug) recorded in *majhari* tilapia fed ricebran at NSTU and the highest value (45.74ug) recorded in *majhari* tilapia fed commercial pellets at NSTU (Table 16). Vitamin D contents from samples taken during the wet season were significantly higher than those taken in the dry season, even when controlling for location of sample ($p < 0.05$).

Statistical analysis showed nutrient content differences were significantly influenced by tilapia form (large tilapia/*majahri* tilapia), system type and feed type (Figure 7). Using the Tukey Test, results showed ash, protein, fat, and zinc content were significantly influenced by system type and tilapia form. Calcium, iron, and vitamin D were significantly influenced by system type, feed type and tilapia form, and vitamin B12 content was significantly influenced by feed type and tilapia form. No significant differences were found within or between the vitamin A contents found across all tilapia samples.

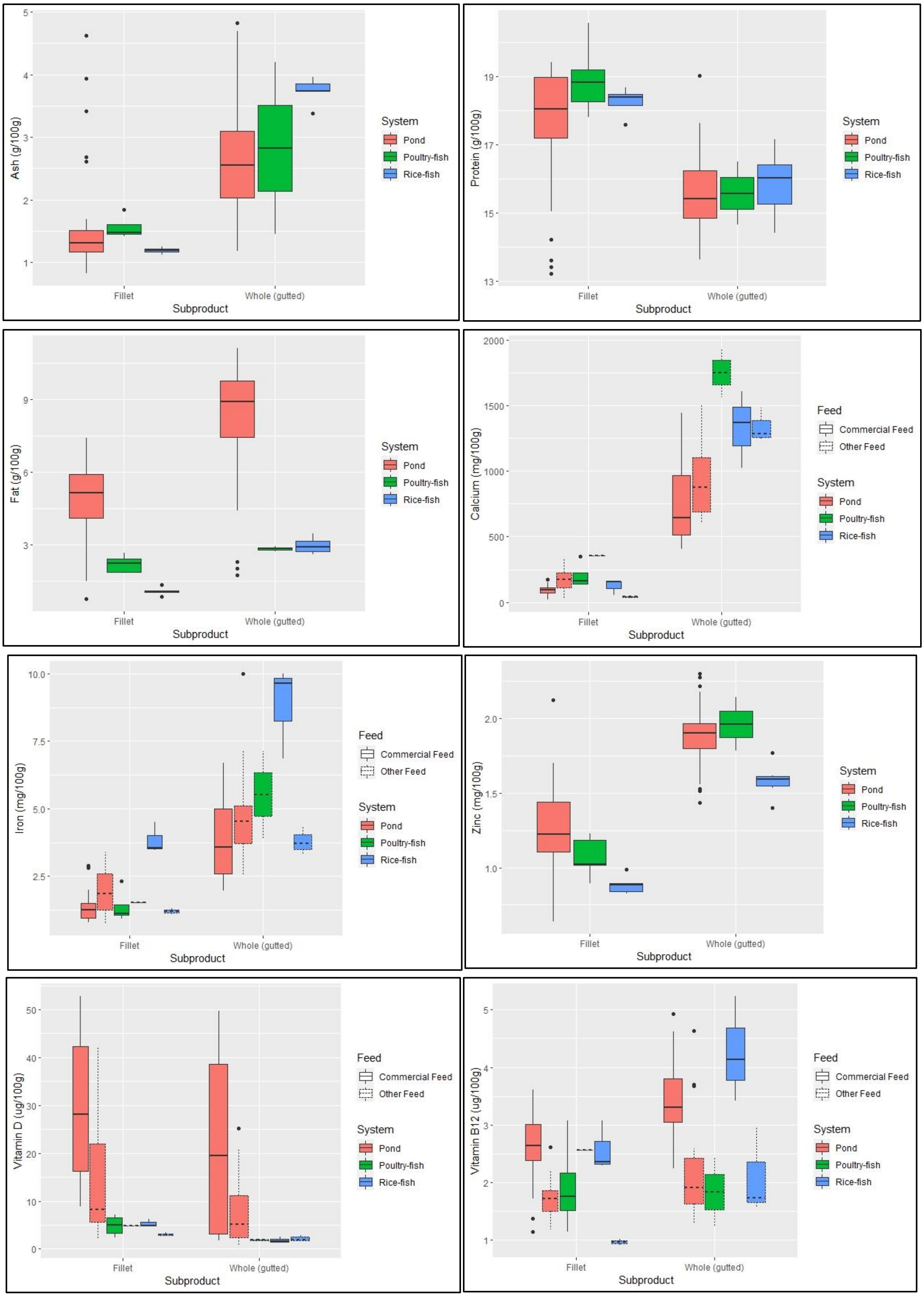
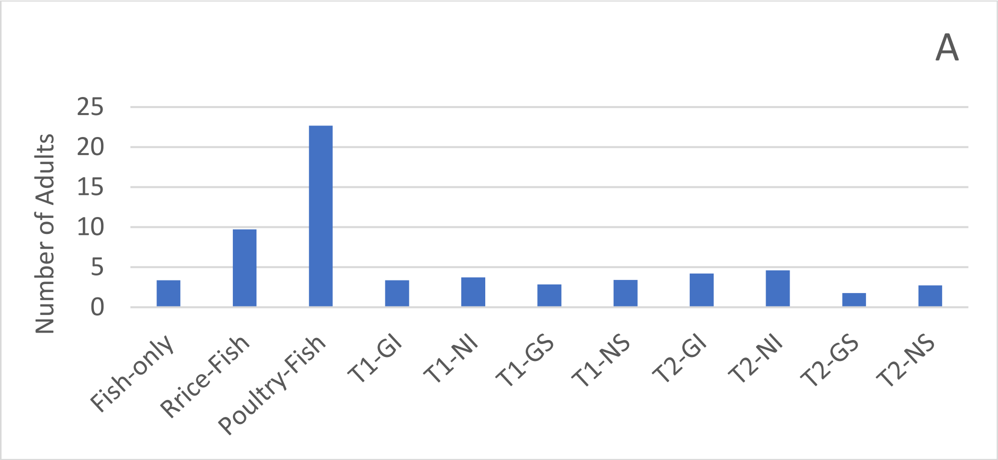


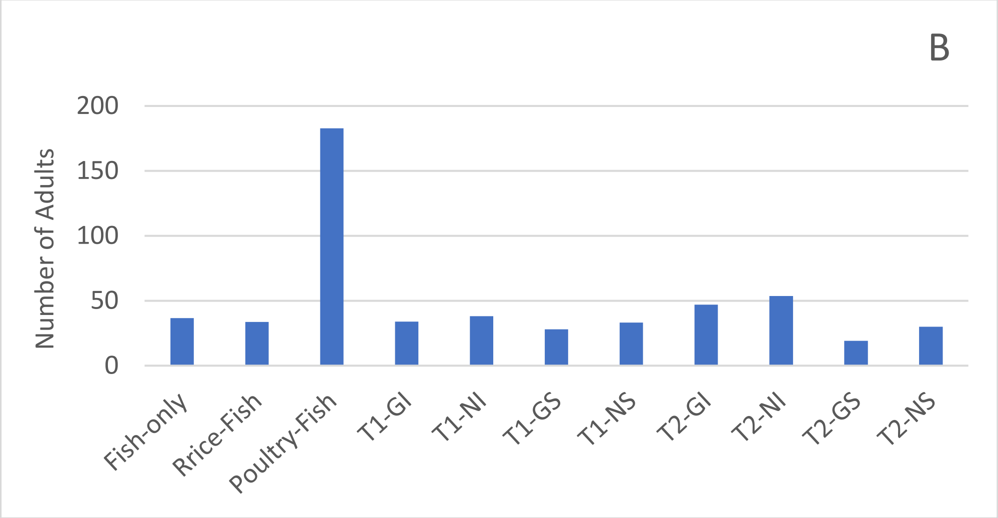
Figure 7. Boxplots showing variations in ash, protein, fat, calcium, iron, zinc, vitamin D and vitamin B12 by system, feed type and tilapia form.

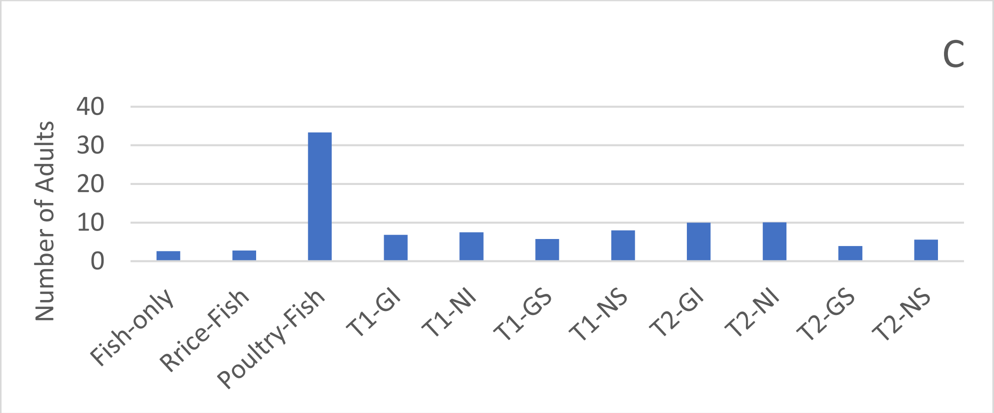
Due to the high vitamin D found in some of the samples, further analysis was carried out on randomly selected samples (*n*=10) to validate the results. The HPLC methods was used for all samples and the secondary analysis was performed by applying liquid chromatography tandem mass spectroscopy (Oberson et al., 2020). Results from this secondary analysis were the same as the results found in the HPLC analyses, confirming the results were correct.

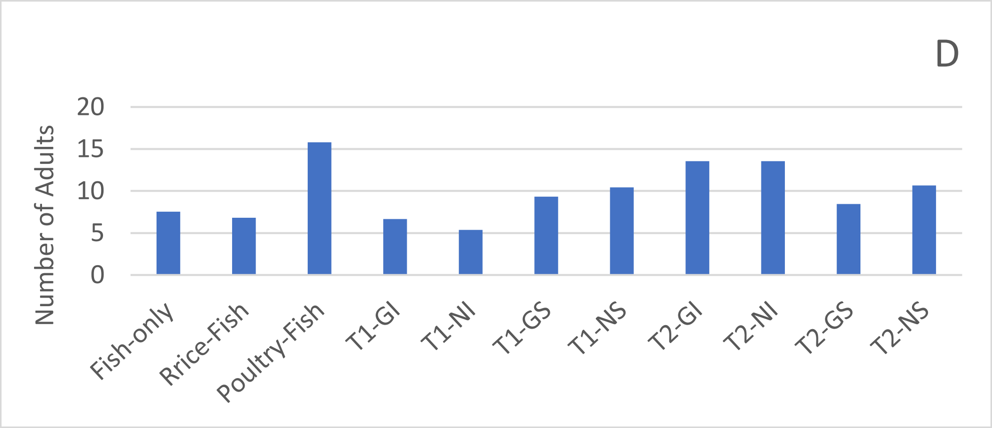
3.3.2 Nutritional Quality of Tilapia Production Systems

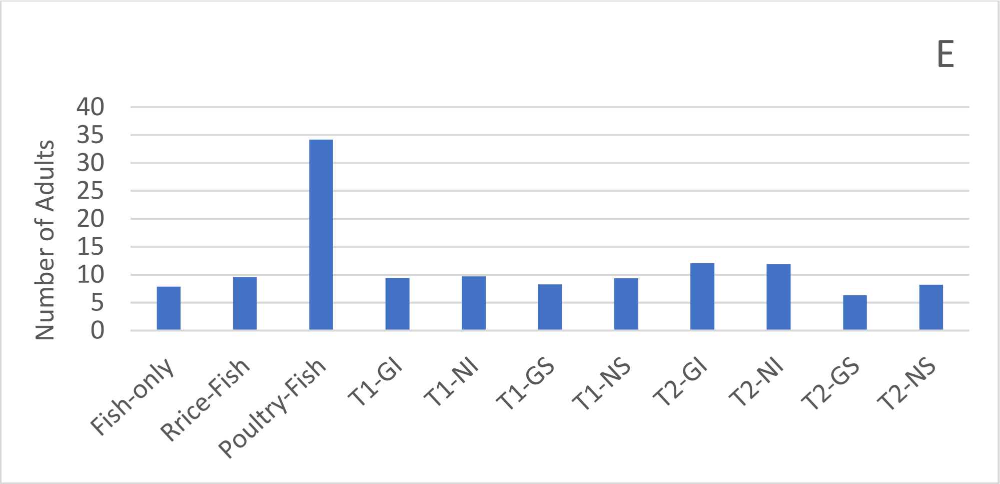
Nutritional yields are presented as the number of adults who can obtain 100% of their daily recommended nutrient intakes (RNI) of selected priority nutrients (energy, protein, total fat, iron, calcium, zinc, iodine, vitamin B12, vitamin A and vitamin D) for one year from the annual production from one hectare of a food system. The nutritional yields of the selected priority nutrients for each system are shown in Figure 8. Dyke cropping is often used by farmers and increasing the diversity of crop production on the farm plot can have an impact on the nutritional yield, therefore all crops were included in the nutritional analysis, i.e. all fish species, crops, and poultry.

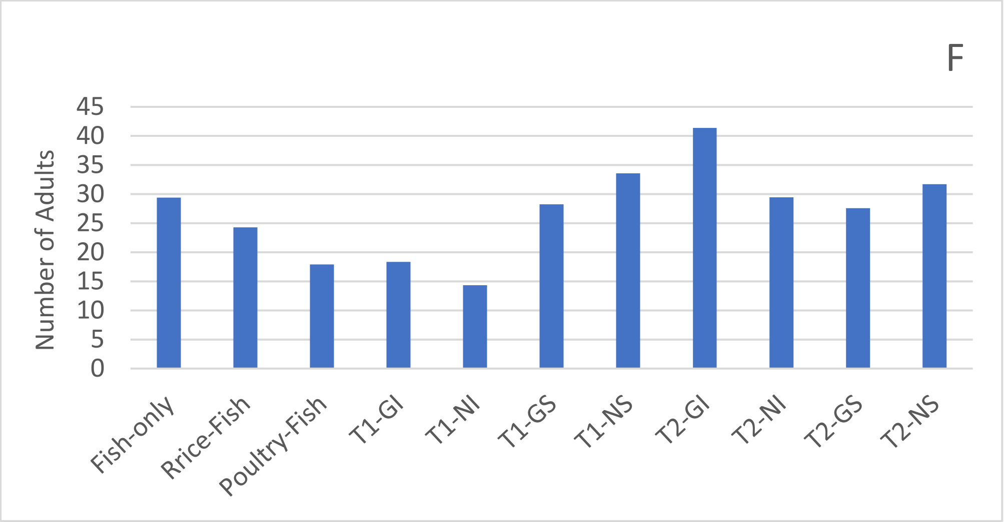

A
Number of Adults
25
20
15
10
5
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS

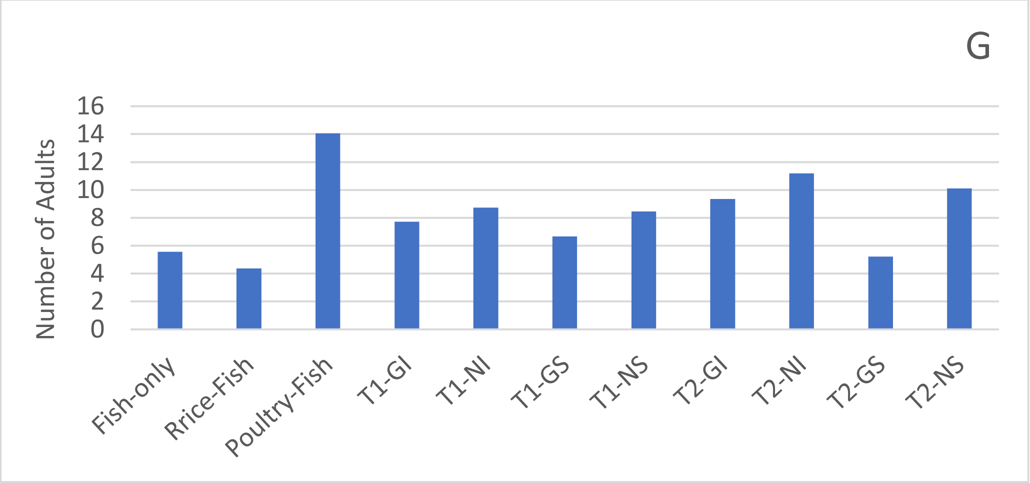

B
Number of Adults
200
150
100
50
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS


C
Number of Adults
40
30
20
10
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS


D
Number of Adults
20
15
10
5
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS


E
Number of Adults
40
35
30
25
20
15
10
5
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS


F
Number of Adults
45
40
35
30
25
20
15
10
5
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS


G
Number of Adults
16
14
12
10
8
6
4
2
0
Fish-only
Rrice-Fish
Poultry-Fish
T1-GI
T1-NI
T1-GS
T1-NS
T2-GI
T2-NI
T2-GS
T2-NS

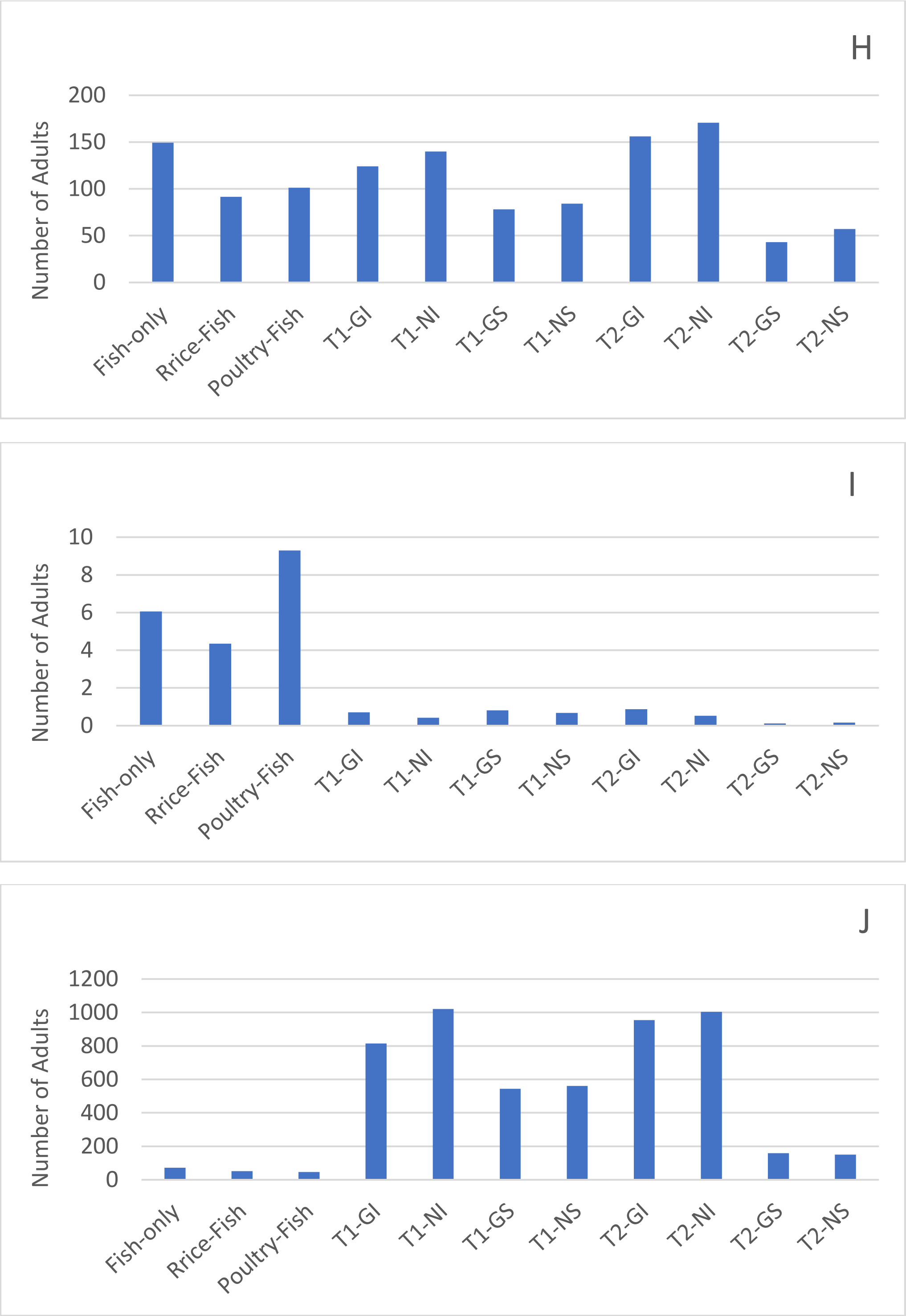


Figure 8. Mean nutritional yields for energy (A), protein (B), fat (C), iron (D), zinc (E), calcium (F), iodine (G), vitamin B12 (H), vitamin A (I), vitamin D (J) for each production system. Includes all fish, crops, and poultry production. Each nutrient is on a separate graph for aesthetic reasons since the scales are different between nutrients.

T1-GI; Trial 1-GIFT strain farmed intensively, T1-GS; Trial 1- GIFT strain farmed semi-intensively, T1-NI; Trial 1-Non-GIFT strain farmed intensively, T1-NS; Trial 1-Non-GIFT strain farmed semi-intensively, T2-GI; Trial 2- GIFT farmed intensively, T2-GS; Trial 2-GIFT farmed semi-intensively, T2-NI; Trial 2-Non-GIFT farmed intensively, T2-NS; Trial 2-Non-GIFT farmed semi-intensively.

To calculate the nutritional yields, nutrient contents of tilapia from each system were taken from the results above, and nutrient content of other fish species and crops were taken from literature as outlined in Annex 1. The experimental systems (T1-GI, T1-NI, T1-GS, T1-NS, T2-GI, T2-NI, T2-GS, T2-NS) produced only fish, whereas FO, RF and PF systems produced a variety of crops. Nutritional yields presented in Figure 8 were calculated for the full production i.e. all fish, rice, fruits, vegetables, and poultry.

The PNA score for fish production and for the full production was calculated for each system (Table 23). The experimental tilapia systems had higher PNA scores than RF, FO, and PF systems due to the higher production yields which resulted in significantly higher vitamin D, calcium, and vitamin B12 levels. Vitamin D values for tilapia sampled during different seasons (wet and dry) differed significantly ($p<0.05$) and since wet season samples were only taken from the trials and not from the FO, RF or PF systems the PNA score was also calculated for the priority nutrients excluding vitamin D. Removing vitamin D from the calculation vastly changed the overall PNA score with PF systems outperforming all other systems. PF systems had similar total fish yields to most of the experimental systems, however tilapia production was lower. Using the average total fish production yields at PF farms, the potential nutritional quality of PF monoculture tilapia systems was modelled. The results show that changing the polyculture PF systems to a tilapia monoculture could raise the PNA score to 9.1 for fish production, and 14.6 for total farm production.

Table 23. Mean production yields for each crop type (T/ha), PNA results for fish production and total production for each farming system (mean ± SE), and PNA results for total farm production excluding vitamin D from the calculation.

System	Fish T/ha	Rice T/ha	Poultry T/ha	Fruit and veg T/ha	Fish Production PNA	Total Production PNA	Total production PNA excluding vitamin D
T1-GI	7.2	0	0	0	15.1 ± 1.6	15.1 ± 1.6	4.1
T1-NI	8.9	0	0	0	18.9 ± 1.4	18.9 ± 1.4	4.4
T1-GS	5.1	0	0	0	8.3 ± 0.9	8.3 ± 0.9	3.2
T1-NS	6.3	0	0	0	9.2 ± 0.4	9.2 ± 0.4	3.7
T2-GI	8.5	0	0	0	22.2 ± 1.2	22.2 ± 1.2	5.7
T2-NI	10.6	0	0	0	26.2 ± 0.7	26.2 ± 0.7	6.7
T2-GS	3.5	0	0	0	4.2 ± 0.3	4.2 ± 0.3	1.9
T2-NS	5.7	0	0	0	5.5 ± 0.2	5.5 ± 0.2	3
PF	7.8	0.57	59.9	0.78	5.6 ± 0.8	10.6 ± 1.1	10.6
FO	4	0	0	0.34	4.2 ± 0.5	5.5 ± 1.1	4.5
RF	2.8	6.1	0	0.91	2.7 ± 0.5	4.1 ± 0.5	3.4

The results show the systems have varying levels of nutritional quality when considering all nutrients, i.e. no single system can provide the greatest levels of all priority nutrients. To enable comparison between systems, a potential nutritional adequacy score has been calculated for each system. This is a single score which combines the nutritional yields and gives a weighting to the evenness of all nutritional yields. T2-NI at the experimental trials at NSTU had a significantly (p<0.05) higher PNA score compared to all other treatments except T1-NI and T2-GI (Figure 8).Excluding the trials, poultry-fish systems had a significantly (p<0.05) higher score than the other 2 systems (Figure 9).

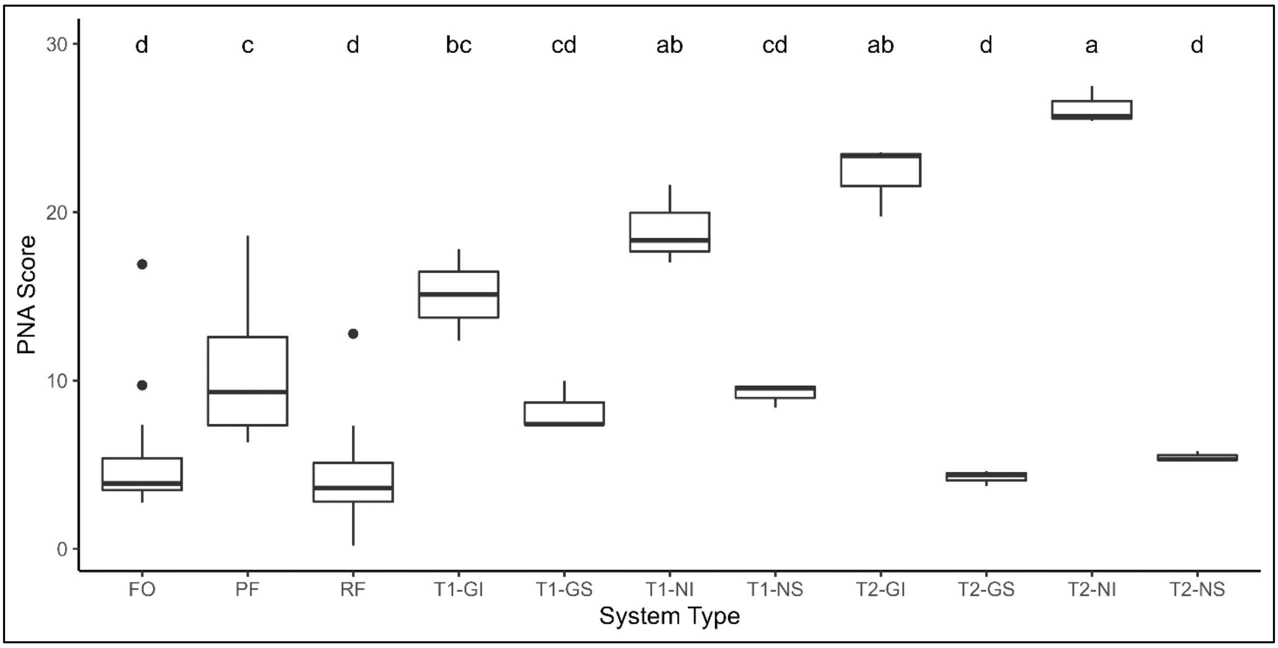


Figure 9. Boxplot showing mean PNA scores for each system type. Columns with different superscripts above boxplot indicate significant differences (*p* < 0.05).

3.4 Discussion

The nutritional profile of tilapia is dependent on the production practices, fish size at harvest and, in turn the way in which the fish is prepared and consumed. Statistical analysis has shown that nutrient contents are influenced by farm system type, fish feed type, tilapia product form, and seasonality. Whole tilapia had significantly higher levels of calcium, iron, and zinc, and vitamin D was significantly higher in tilapia grown in the wet season. The total fat content in was highly varied between the samples with majhari tilapia having a higher fat content and samples taken from ponds having higher fat than samples taken from PF or RF farms. These results are similar to the results found throughout the literature where fat content for *o. niloticus* has been reported between 0.4 to 13% (Karapanagiotidis, 2016).

The high vitamin D content of tilapia found in this study is significant since children and adolescents from both wealthy and poor backgrounds experience vitamin D deficiencies across Bangladesh (Ahmed et al., 2016; Ara et al., 2023). Vitamin D is available in some plant foods such as cabbage, spinach and mushrooms, however one of the most important dietary sources is fish (Belitz et al., 2004). Results from this study show the vitamin D content in tilapia is relatively high compared to plant sources and other freshwater fish found in Bangladesh. This finding is in line with similar studies measuring vitamin D in tilapia (Bogard et al., 2015; Singhato et al., 2022) reaffirming the results found here. The daily RNI of vitamin D for the average adult in Bangladesh is 5ug, meaning tilapia can contribute to vitamin D security as even the lowest vitamin D results found in this study (1.2ug/100g tilapia) would fulfil almost a quarter of required vitamin D.

Highly productive tilapia monocultures performed better than polyculture systems in terms of nutritional quality, even when dyke crops and other livestock (poultry) were included in the nutritional performance analysis. The system with the highest PNA score was T2-NI, the intensively fed, local strain farmed under monoculture conditions in the experimental ponds at NSTU. This was due to the high production yields of both tilapia and majhari tilapia. As seen from the results, this tilapia monoculture had the greatest nutritional quality when compared to polyculture fishponds, rice-fish, and poultry-fish systems, all of which produced dyke crops alongside fish, rice, and poultry. However, when excluding vitamin D from the PNA calculations the experimental systems did not perform as well. This indicates the sensitive nature of using single-score nutritional quality indicators such as PNA, as a high NY for a single nutrient can impact the final score. For this reason, nutritional quality is presented in this chapter using NY and PNA as this allows readers to gain a clear understanding of the nutritional quality of the systems and ensures the granularity is not lost through single scores as all nutrients are presented individually. Although these nutritional quality scores can be used to identify food production systems with high nutritional value, one must consider the implications of promoting one system over another. There are many societal and economic factors which influence adoption of certain farming practices, for example access to credit, size of farm area, access to irrigation and conflict with surrounding farmers (Saiful Islam et al., 2015). Additionally, there are many other factors which should be considered when comparing food systems such as the environmental performance, cultural acceptability, and markets for the food products. Although these results offer insight into the nutritional quality of these systems, the societal benefits of the various systems have not been considered. Farmers usually keep a proportion of their produce for home consumption (Hernandez et al., 2018), and dietary diversity may be impacted if the farming system of choice is a monoculture pond farmed without other crops.

Vitamin D analysis was performed for large and majhari tilapias for the PF, FO, RF farms and the experimental systems, however only the experimental systems were sampled during both summer and winter, known as the wet and dry seasons respectively. The lower dry season results for PF, FO and RF systems may have impacted the results and hence the final vitamin D nutritional yield calculations. Further investigations into the spatiotemporal influences on vitamin D content of fishes would be beneficial for nutritional quality assessments. Additionally, having a better understanding of the mechanisms behind vitamin D production in tilapia can guide tilapia producers towards improving the nutritional quality of their production. The capability of tilapia to synthesise vitamin D from sunlight was examined and it was shown UVB-light exposure can result in significant increases in vitamin D (Rao and Namala Raghura, 1997). However, it has also been suggested the main source of vitamin D for tilapia is from plant- and zooplankton in the environment where the fish are raised (Rao and Raghuramulu, 1996). Future studies aimed at identifying the vitamin D sources for tilapia and other commonly consumed fish species would help guide producers to improving the nutritional quality of their products hence the nutritional security of consumers.

The results presented in this chapter can be compared with previous work by Bogard et al. (2018) and Ignowski et al. (2023) who have performed similar studies with fish production across in Bangladesh and have shown diverse systems often have a high nutritional quality. Bogard et al. (2018) use a generalised production tonnage throughout their study, whereas the production volumes used in this study were actual farm production data. It is unsurprising the controlled, experimental systems had higher fish production yields and therefore a higher nutritional quality score. When excluding the experimental ponds from the analysis, the poultry-fish systems score highest (9) followed by fish-only farms (5.46) and lastly rice-fish systems (4.1). Again, this is due to the high yields of animal-source foods produced by PF farms.

Rice-fish farms had significantly higher zinc NYs since zinc levels in rice were higher than any fish species produced in the study. PF farms had significantly high levels of protein due to the poultry meat, and higher levels of fat due to the pangasius produced in these ponds. Significantly higher levels of vitamin A in FO, RF and PF systems were noted as these systems included SIS fish, such as *mola* which are dense in vitamin A. The experimental systems which produced high tilapia yields had significantly higher levels of vitamin D since the nutrient composition analysis found elevated vitamin D values in tilapia compared to other fish and crop species involved in this study.

The results of this study provide important data for the tilapia nutrient composition literature. NCDBs must be updated regularly and should contain data for foods in all its forms, whether that be preparation and cooking methods or production system methods. Secondly, this study shows researchers the differences in nutritional profiles of tilapia produced under various conditions and encourages others to delve deeper into the possible ways food nutrient profiles can depend on spatial-temporal conditions and production methods. Thirdly, the nutritional quality of various tilapia production systems have been identified and compared which should be used to guide policymakers towards nutrition-sensitive agricultural interventions. For example, vitamin D insufficiency is well documented in Bangladesh and in many other LMICs, yet tilapia is an affordable source of this essential nutrient and is already a well-established species in global aquaculture systems. This presents a unique opportunity for food and nutrition and agriculture decision makers to work together towards increasing awareness of the contribution tilapia can make to vitamin D requirements for vulnerable populations.

Chapter 4

Performance assessment of tilapia production under experimental conditions

4.1 Introduction

Fish play a major role in food and nutrition security in low and middle income countries (LMICs) and is considered the most important animal-source food in Bangladesh (Belton et al., 2014). Research has shown aquaculture development can have positive impacts on income, employment, and fish consumption for the poor in LMICs, and may be an impact pathway to address malnutrition (Ahmed and Lorica, 2002; HLPE, 2014; Filipski and Belton, 2018; Jahan et al., 2010; Portia Villarante et al., 2007; Toufique and Belton, 2014). Aquaculture in Bangladesh has grown rapidly over the last 3 decades which been facilitated by the expansion of aquaculture value chains through investments by hundreds of thousands of actors and a diversification of the main commodity species such as tilapia (Hernandez et al., 2018). Tilapia is now the second most produced species in the country with an estimated production of 392,095 MT per year (DoF, 2022).

Tilapia production systems vary enormously across Bangladesh for example, tilapia is farmed in *beels*, cages on lakes/canals, ponds, and rice-fish systems (Jahan et al., 2015). However, 80.5% of all tilapia production in Bangladesh occurs in managed earthen ponds (Table 24).

Table 24. Bangladeshi tilapia production volumes disaggregated by waterbody type.

Waterbody Type	**Tilapia production (MT)**
Beel	1535
Kaptai Lake	17
Pond	315887
Seasonal/ cultured waterbody	23007
Baor	436
Shrimp/prawn system	42748
Pen/ cage culture	8465

There are various strains of tilapia produced in Bangladesh, the most prominent being GIFT, and numerous GIFT performance assessments have been carried out in Bangladesh at both hatchery and grow-out level and results have shown GIFT out-performs local strains (Haque et al., 2016; Horn et al., 2021; Tran et al., 2021). Recent genetic improvement programs outside of GIFT, such as Genomar and FaST tilapia, have also developed fast growing strains which produce high yields (Hussain et al., 2013). In addition to various waterbodies, tilapia is produced in an array of different systems, such as intensive monocultures, extensive polycultures and as either, mixed-sex or and monosex populations. Although GIFT is considered to perform well, farm management techniques will play a deciding factor in the productivity and profitability of the farm.

Recently, there has been growing number of performance assessments of Blue Foods and there is a realisation that Blue Foods can contribute to sustainable, healthy diets (Crona et al., 2023). It has been highlighted that the production system in which Blue Foods are produced can influence the nutritional quality or environmental impacts of food and this should be considered when assessing the performance of animal-source foods (Koehn et al., 2022). There has also been discussion around the environmental benefits associated with using genetically improved strains of fish since feed conversion ratios (FCRs) are often better for improved strains, however this has not been studied in improved strains of tilapia.

Narratives in the food systems literature discuss the potential of Blue Foods to sustainably nourish nations, often comparing aquatic foods with terrestrial foods, and stressing the importance of marine aquaculture and high-tech culture systems. Henriksson et al. (2021) highlight the need to assess the performance of important, widespread freshwater aquaculture systems and improve the environmental performance of those systems. Although there have been tilapia performance assessments in Bangladesh, there has not been any rigorous, on-station experiments aimed at assessing multiple dimensions of the food system. This is addressed here through a two-year study looking at the economic, environmental, and nutritional impacts of various tilapia farming systems under experimental conditions.

4.2 Materials and Methods

4.2.1 Data Collection and Analysis

4.2.1.1 Nutrient Composition Analysis

Throughout both trials, small-sized tilapia (*majhari* tilapia) and larger tilapias were collected for nutrient composition analysis. The fish sampling procedure and results have been outlined in Chapters 2 and 3.

4.2.1.2 Economic Analysis

A partial budget approach (Tigner, 2018) was taken to perform a cost-benefit analysis for each experimental trial, whereby only the costs which changes under the experimental or treatment are considered, i.e. cost of ponds, labour etc remains the same but feed type and amount, fertilisers and fish seed are all modifiable costs which are considered. This approach is used to determine the financial implications of strain and system type. The net return for each system was calculated by finding the difference between total costs and total returns. Costs considered during this calculation included tilapia fry, feed, fertiliser, and fuel costs. Returns were calculated using farmgate prices for fish and total fish yields.

4.2.2 Life Cycle Assessment

LCAs were carried out to compare the environmental performance of each of the 8 experimental systems. The life cycle assessments were conducted in accordance with ISO standards (ISO, 2006) and all LCAs used standard attributional methodology (ILCD, 2010).

4.2.2.1 Goal and Scope

The goal of the LCAs carried out in this study was to estimate and compare the environmental performance of common tilapia culture systems in Bangladesh. The functional unit used was 1 kg of live fish and the system boundaries were “cradle to farm gate” (Figure 10). The inputs considered in this study included feeds, fertilisers, fish seed, water, electricity, transport and other fuels, and emissions to soil, water and air were included in the study. Economic allocation was used for multi-output processes, and all LCAs were modelled in SimaPro 8.0 using CML-IA baseline methods.

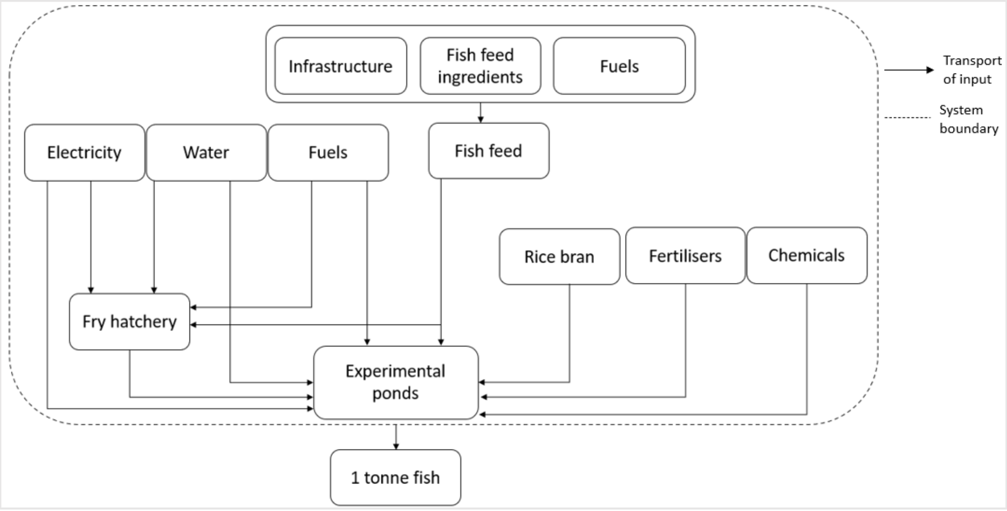


Figure 10. Schematic diagram of the system boundaries used for the life cycle assessment for the experimental pond systems. A cradle to farm gate assessment was conducted.

4.2.2.2 Life Cycle Inventory

LCI data was collected throughout the course of both trials. All material inputs and outputs were measured and recorded for both trials on a daily basis. Feed formulations used in the trials were based on data collected from the feed processor using a structured questionnaire (Chapter 2). LCI data for transportation, fuel, water, electricity, and fertilisers were taken from various literature sources which have been outlined in in Chapter 2.

4.3 Results

4.3.1 Production Performance

4.3.1.1 Trial 1

Table 25 shows the production parameters for Trial 1. Feed amounts per individual experimental pond differed since feed rates were a percentage of pond biomass. T1-NI produced the highest tilapia yields which were significantly ($p < 0.05$) greater than T1-GS and T1-NS but were not statistically significantly different from T1-GI. Additionally, T1-GI generated the highest net incomes, however the results were not statistically significant compared to any other treatment. Although carp yields were only 5 – 12% of total fish production, production was significantly ($p < 0.05$) greater for semi-intensive systems.

Table 25. Production parameters per 75m² pond for all 4 systems in Trial 1 (presented as means ± SE).

Production Parameter	**T1-GI**	**T1-NI**	**T1-GS**	**T1-NS**
Tilapia fry stocked (kg)	1.43 ± 0.1	1.78 ± 0.3	1.04 ± 0.1	1.6 ± 0.1
Mixed carp fingerling stocked (kg)	0.3 ± 0	0.3 ± 0	0.3 ± 0	0.3 ± 0
Total feed (kg)	38.3 ± 1.8	53.1 ± 6.6	0.04 ± 0	0.07 ± 0
Total rice bran (kg)	-	-	43.1 ± 0.7	50.7 ± 2.2
Total tilapia production (kg)	20.9 ± 1.8^{ac}	26.1 ± 1.8^{a}	13.8 ± 1.5^{b}	17.6 ± 0.8^{bc}
Total majhari tilapia (kg)	2.9 ± 1^{abc}	0.6 ± 0.2^{a}	4.7 ± 0.8^{bc}	5.8 ± 1^{bc}
Total large tilapia (kg)	18 ± 1.5^{ad}	25.5 ± 1.9^{b}	9.1 ± 0.7^{c}	11.8 ± 1.3^{cd}
Total carp production (kg)	1.3 ± 0.1^{a}	1.4 ± 0.1^{ac}	2 ± 0.2^{b}	2.2 ± 0.2^{bc}
FCR	1.9 ± 0.2^{a}	2.1 ± 0.1^{ac}	3± 0.3^{b}	2.9 ± 0.1^{bc}
Net income (BDT/pond/6-month cycle)	1501 ± 170^{a}	1342 ± 122^{a}	1023 ± 173^{a}	1327 ± 123^{a}

^{abc} Notations are to compare means and different superscripts indicate a significant statistical difference ($p < 0.05$) between means (horizontal comparison between systems).
Note: Income is calculated using market price data and production yields for each species and included variations in prices for different sizes of tilapia as outlined in Table 35 (Chapter 5).

4.3.1.2 Trial 2

T2-NI produced the highest tilapia yields ($p < 0.05$) and generated the highest net income when compared to the other 3 treatments for Trial 2 however net incomes generated by T2-NS were not statistically lower ($p > 0.05$). T2-GS performed significantly ($p < 0.05$) poorer than all other treatments in terms of production yields, net income, and FCR (Table 25).

Table 26. Production parameters per 75m² pond for all 4 systems in Trial 2 (presented as means ± SE).

Production Parameter	**T2-GI**	**T2-NI**	**T2-GS**	**T2-NS**
Tilapia fingerlings stocked (kg)	0.8 ± 0.0	0.8 ± 0	0.8 ± 0	0.8 ± 0
Total feed (kg)	241.1 ± 6.4	270.1 ± 10.5	-	-
Total rice bran (kg)	-	-	236.4 ± 3.6	239.1 ± 3.6
Total tilapia production (kg)	80.1 ± 4.3^a	99 ± 1.7^b	33 ± 2^c	53.7 ± 1.6^d
Majhari tilapia (kg)	20.2 ± 1.6^a	10.4 ± 3^b	9.3 ± 0.4^b	11.1 ± 0.5^b
Large tilapia (kg)	59.9 ± 3.2^a	88.6 ± 2.9^b	23.7 ± 2.5^c	42.6 ± 1.2^d
FCR	3.1 ± 0.2^a	2.8 ± 0.1^a	7.4 ± 0.4^b	4.5 ± 0.1^c
Net income (BDT/pond/12-month cycle)	2908 ± 408^a	4313 ± 404^b	1280 ± 234^c	3955 ± 188^b

^{abcd} Notations are to compare means and different superscripts indicate a significant statistical difference ($p < 0.05$) between means (horizontal comparison between systems).
Note: Income is calculated using market price data and production yields for each size classification of tilapia as outlined in Table 36 (Chapter 5).

Since the duration of Trial 1 was 6 months and Trial 2 lasted 15 months, the production data has been scaled to 12 months for comparison purposes and results are presented in Table 27. As standard, results have been scaled to tonnes per hectare and net incomes are shown in USD, converted from Bangladeshi taka at a rate of 1 BDT = 0.0094 USD.

T2-NI produced the highest total tilapia yields and T2-GS produced the lowest yields. Net incomes were highest, and FCRs were lowest, in T1-GI ponds. Total tilapia production yields were significantly different ($p < 0.05$) between the systems in both trials (Figure 11). Results from the economic analysis of the systems is shown in Figure 12 where production has been scaled to 1 year and incomes are shown as USD ha^{-1}. Interestingly, the all systems perform similarly except T2-GS which has the lowest net income and is significantly ($p < 0.05$) lower than T1-GS and T2-GI.

Table 27. Production parameters for all systems in both trials. To compare means, the production has been scaled to 1 year (means ± SE).

System	Total Tilapia Yields (T/ha/year)	Income (USD/ha)	FCR
T1-GI	6.7 ± 0.6	4516 ± 512	1.9 ± 0.2
T1-NI	8.3 ± 0.6	4038 ± 367	2.1 ± 0.1
T1-GS	4.4 ± 0.5	3079 ± 520	3 ± 0.3
T1-NS	5.6 ± 0.3	3991 ± 369	2.9 ± 0.1
T2-GI	8.5 ± 0.8	2917 ± 708	3.1 ± 0.2
T2-NI	10.6 ± 0.2	4325 ± 405	2.8 ± 0.1
T2-GS	3.5 ± 0.2	1283 ± 235	7.4 ± 0.4
T2-NS	5.7 ± 0.2	3965 ± 188	4.5 ± 0.1

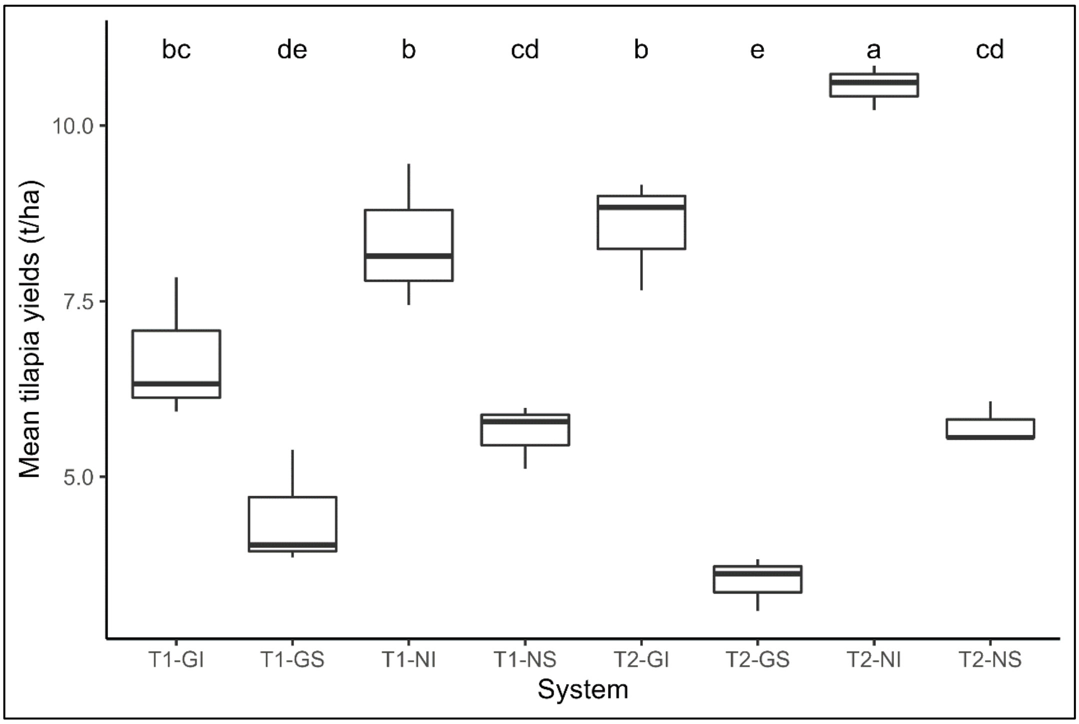


Figure 11. Boxplot showing mean total tilapia yields for each system in both trials. Columns with different superscripts above boxplot indicate significant differences ($p < 0.05$).

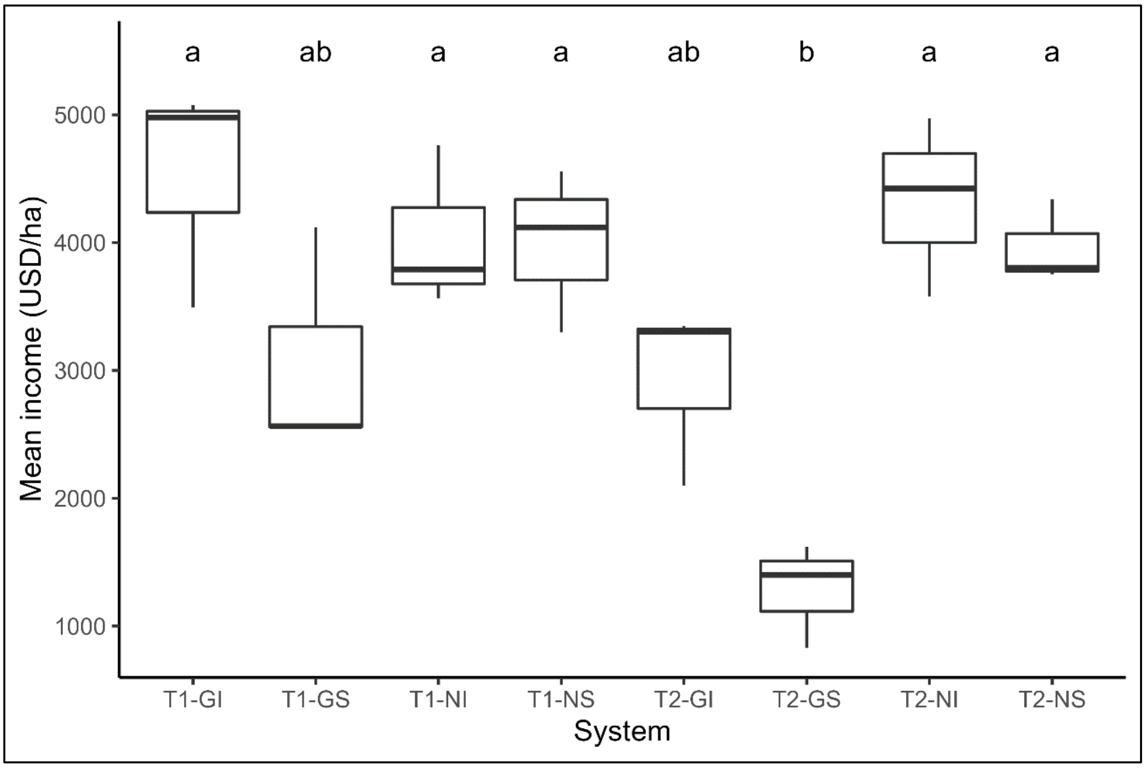


Figure 12. Boxplot showing mean net income for each treatment. Columns with different superscripts above boxplot indicate significant differences ($p < 0.05$).

4.3.2 Environmental Performance

The environmental performance for all systems in both trials are presented in Table 28. T2-NS performed best in 9 out of 14 of the impact categories, and T2-GI performed worst for 9 out of the 14. Generally, intensively managed systems had higher impacts on land use, global warming, human toxicity, photochemical oxidation, freshwater ecotoxicity, acidification, eutrophication, and GWP LUC. In contrast, semi-intensive systems generally had higher impacts on water consumption. When comparing between intensively managed systems, the GIFT strain in Trial 1 performed best for all impact categories except water consumption, land use, terrestrial ecotoxicity, and ozone layer depletion.

A contribution analysis for Trial 1 and Trial 2 is shown is Figure 13 and Figure 14, respectively. Fish feed, consisting of commercial powder, starter, and grower feeds, have the greatest contribution to all impact categories except water consumption for intensive systems in Trial 1 and 2. Fertilisers used for the semi-intensive systems had major contributions (>25%) to GWP, abiotic depletion (fossil fuels) and human toxicity. For Trial 1, fish seed was a major contributor to terrestrial ecotoxicity for all 4 systems. Rice bran in Trial 1, which was given to the semi-intensive systems in place of commercial fish feeds, had major contributions (>20%) to abiotic depletion, abiotic depletion (fossil fuels), and GWP. In

Trial 2 rice bran was the major contributor to all impact categories except GWP LUC and water consumption.

Table 28. Life cycle impact assessment of 1 tonne of mixed fish production using economic allocation (T1 mixed fish = small and large tilapias + carps, T2 mixed fish production = small and large tilapias).

Impact category	Unit	T1-GI	T1-GS	T1-NI	T1-NS	T2-GI	T2-GS	T2-NI	T2-NS
Water consumption	m3	4919.8	6242.9ˆ	4174.0	5212.5	3117.2	5889.7	2617.2*	3643.5
Land use	m2a crop eq	9205.5	6337.9	9248.8ˆ	2480.5*	8807.1	3882.4	8017.0	2528.7
Abiotic depletion	kg Sb eq	0.34	0.25*	0.37	0.26	0.48ˆ	0.44	0.44	0.28
Abiotic depletion (FF)	MJ	1.94E4	2.13E4	2.06E4	2.02E4	2.37E4	2.76E4ˆ	2.21E4	1.82E4*
Global warming	kg CO2 eq	1676.3	1449.5	1809.7	1405.8	2151.9ˆ	1871.7	1999.1	1234.6*
O3 Depletion	Kg CFC-11 eq	2.5E-4	2.5E-4	2.5E-4	2.3E-4	2.6-E4ˆ	2.6E-4	2.4E-4	1.7E-4*
Human toxicity	kg 1,4-DB eq	1799.4	1416.3	1997.1	1381.7	2483.7ˆ	1791.1	2285.5	1145.0*
Fresh water aquatic ecotox.	kg 1,4-DB eq	1127.3	872.7	1256.7	898.5	1454.7ˆ	1040.6	1351.2	687.8*
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.8E4*	2.1E6	1.9E6	1.9E6	2.4E6	2.8E6ˆ	2.2E6	1.8E6
Terrestrial ecotoxicity	kg 1,4-DB eq	106.5	52.5	120.3ˆ	73.5	101.3	13.2*	98.5	19.1
Photochemical oxidation	kg C2H4 eq	1.043	0.5	1.2	0.5	1.5ˆ	0.5	1.4	0.3*
Acidification	kg SO2 eq	10.4	9.4	11.3	9.0	13.7ˆ	12.4	12.6	8.0*
Eutrophication	kg PO4--- eq	10.7	3.8	12.1	4.4	15.8ˆ	4.2	14.5	2.8*
GWP LUC	kg CO2 eq	867.7	123.9	995.3	200.7	1316.8ˆ	48.3	1211.1	45.4*

ˆ Worst performing in the row.
* Best performing in the row.
GWP LUC = Global warming potential land use change.
Abiotic depletion (FF) = abiotic depletion fossil fuels.

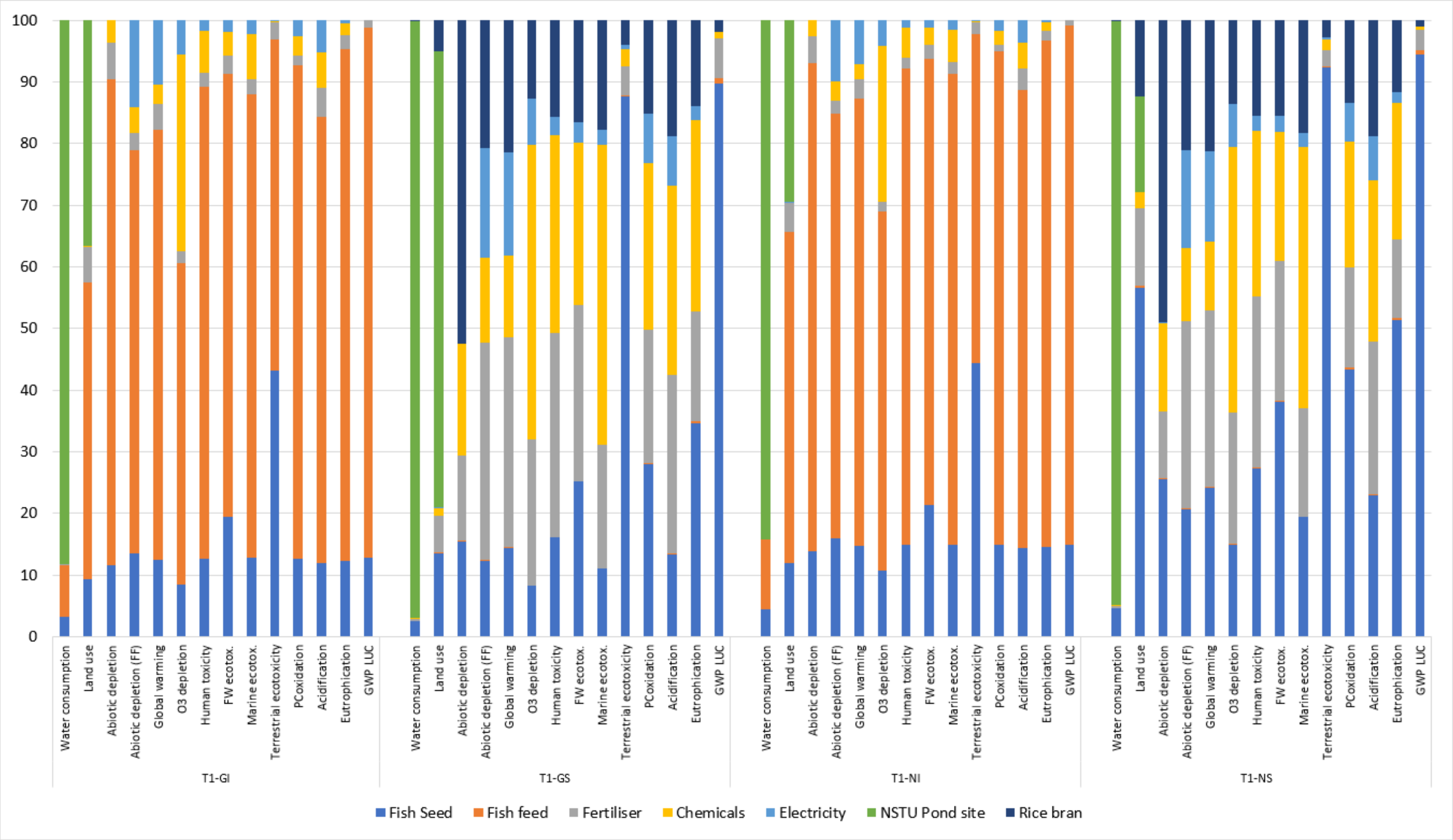


Figure 13. Contribution analysis for all 4 systems in Trial 1. Bars show the percentage of contribution.

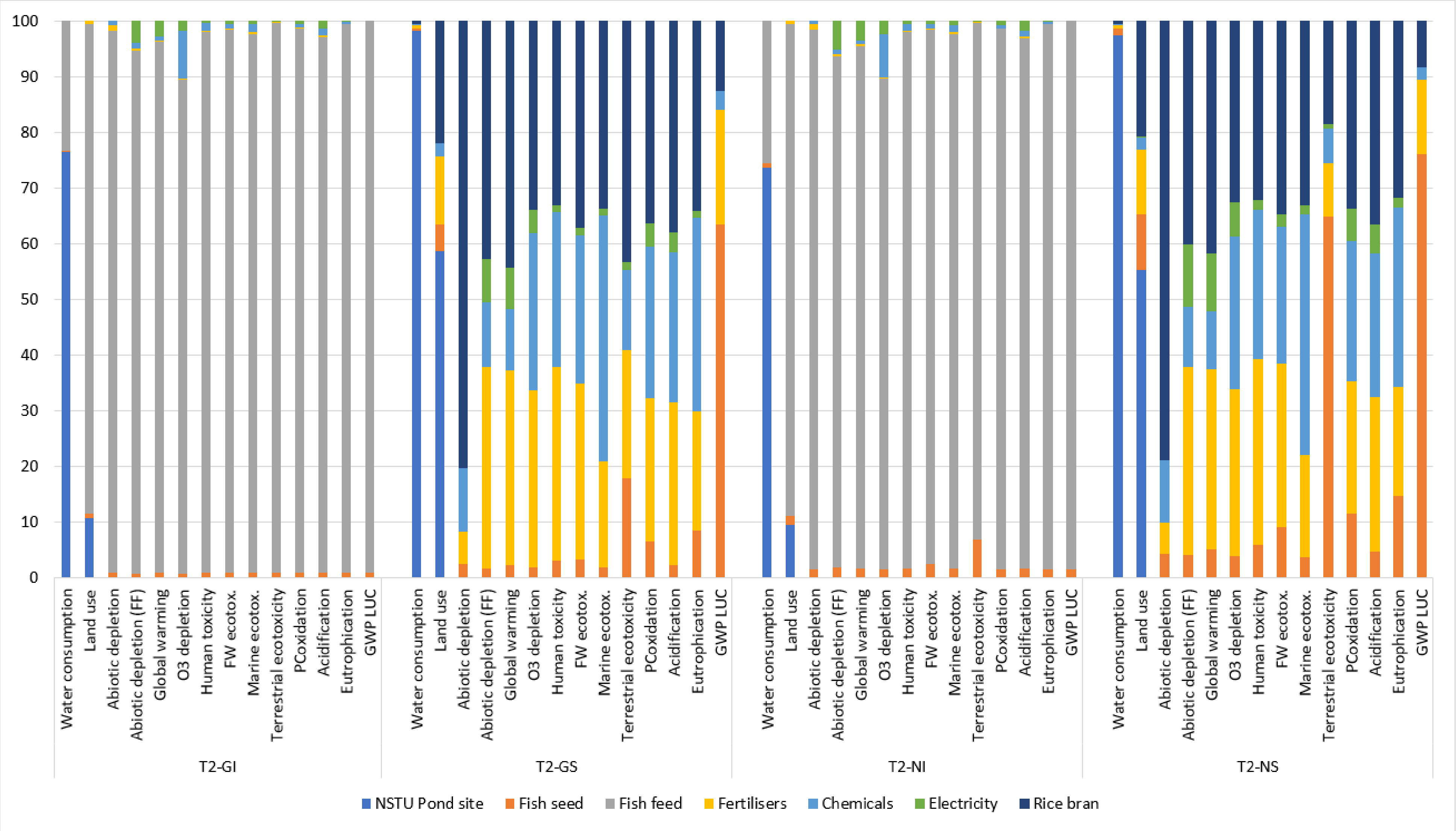


Figure 14. Contribution analysis for all 4 systems in Trial 2. Bars show the percentage of contribution.

4.3.3 Nutritional Performance

As seen in chapter 3, the nutritional yields and potential nutrient adequacy was calculated for each of the 4 systems in both trials. T1-NI ranks highest in terms of overall nutritional quality when using PNA as the nutritional indicator. As a higher PNA score relates to a higher nutritional quality, the systems were ranked as follows:

1. T2-NI (PNA 26.2)
2. T2-GI (PNA 22.2)
3. T1-NI (PNA 18.9)
4. T1-GI (PNA 15.1)
5. T1-NS (PNA 9.2)
6. T1-GS (PNA 8.3)
7. T2-NS (PNA 5.5)
8. T2-GS (PNA 4.2)

Figure 15 shows the PNA score plotted against the greenhouse gas emissions (GHGs) for each experimental treatment with the bubble size representing the mean net income. There is a clear trend in the graph as treatments of a higher nutritional quality have the highest greenhouse gas emissions. However, the net income shows no trend with the lowest emitter (T2-NS) having a similar income to treatments with middle and high levels of emissions, and the two treatments with the highest PNA score having very different incomes levels.

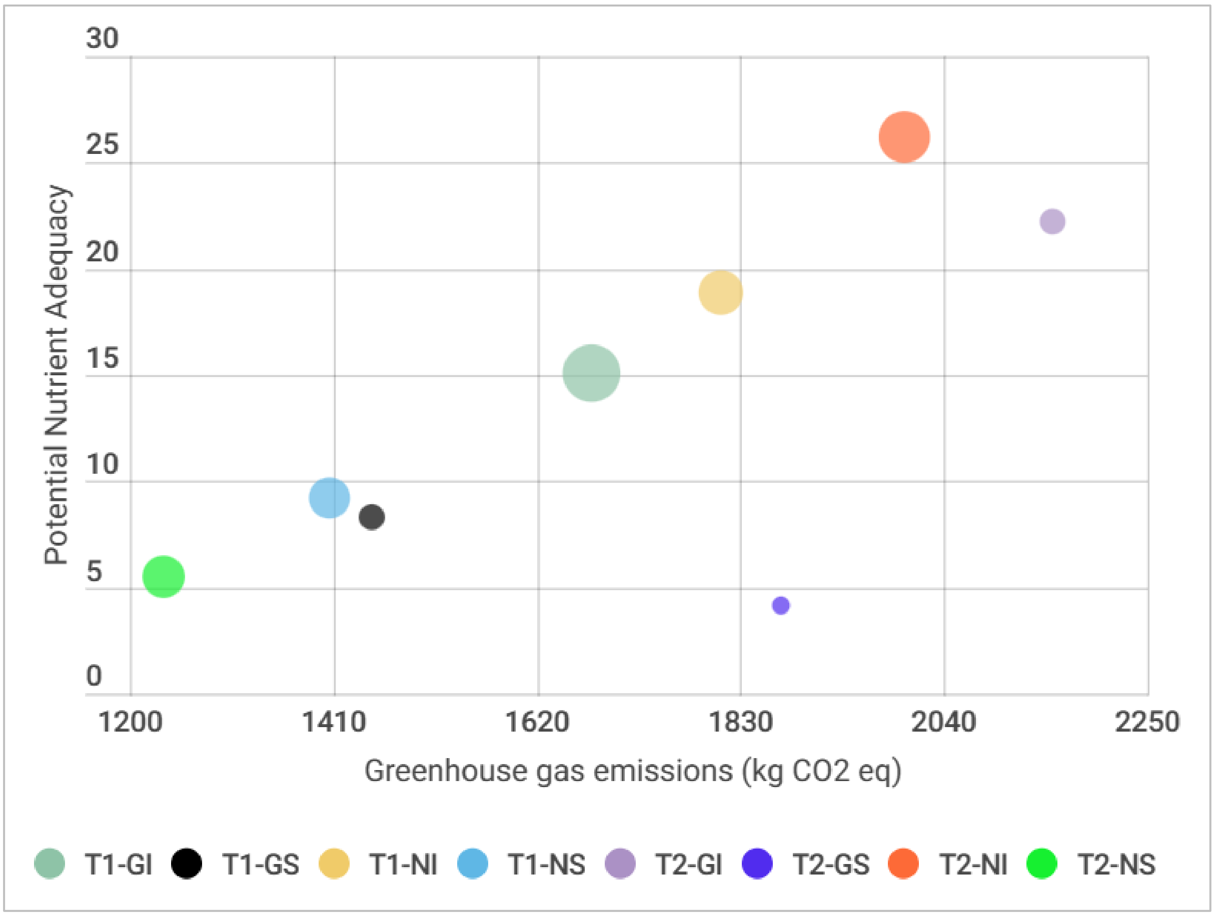


Figure 15. Mean Greenhouse gas emissions and mean PNA score for each experimental treatment at both trials. Size of bubble represents the mean net income.

4.4 Discussion

Intensive tilapia production systems generate the highest tilapia yields and have a higher nutritional quality compared to semi-intensive systems, however semi-intensive systems generally have lower environmental footprints. From the contribution analysis, it is clear the use of formulated feeds led to the higher production yields as well as higher environmental footprints. Clearly formulated feeds can be effective in increasing production of nutrients but improving the environmental performance of commercial feeds is necessary to ensure sustainable aquaculture production is possible.

During the mixed sex Trial (T2), the non-GIFT strain produced significantly ($p > 0.05$) higher yields and incomes compared to the GIFT strain when comparing within system-type, however there was no statistical difference found between the strains in Trial 1. Although

T2-NI produced significantly greater yields than all other systems, T1-GI generated the highest net income. Since T1-GI had the lowest FCR, this highlights the importance of feed conversion ratios as feed was the highest expense during the trials which is often the case at aquaculture facilities (Rana et al., 2009).

In terms of productivity, there were no significant differences found between the non-GIFT and GIFT strain in T1 farmed under intensive and semi-intensive conditions In T2, the non-GIFT strain produced significantly ($p < 0.05$) higher yields and incomes under intensive and semi-intensive conditions. Additionally, T2-NI produced significantly ($p < 0.05$) higher yields than any other system in the study. This suggests the most productive strain of tilapia was the strain taken from a farmer's pond in which there had been no broodstock selection or even management, or purchases of new fish seed for many years. When comparing the two GIFT strains used in the trials, results show the tilapia which originated from the TBN was more productive and profitable. However, T1 was a monosex, polyculture system and was fed rations based on pond biomass, whereas T2 was a mixed-sex, monoculture system fed to satiation therefore it may not be appropriate to directly compare performance.

A recent, in-depth study into GIFT on-farm productivity revealed GIFT outperforms non-GIFT strains in Bangladesh (Tran et al., 2021), which is somewhat contradictory to the results in this study. The productivity results in T1 generally supports these claims, however the non-GIFT strain utilised in Trial 2 significantly outperformed the three other strains. The T2 non-GIFT strain was the only "unimproved" strain which did not originate from a hatchery used in this study. Tran et al. (2021) surveyed over 500 tilapia farmers and collected real-time, farm-level data for their study, but only focussed on tilapia farmers who had purchased fish seed from a hatchery in the year of the survey. There is an unknown proportion of farmers raising tilapias excluded from this study since many farmers will purchase mixed sex seed and allow free breeding in ponds, producing a crop year after year without any regular the repurchase of seed. Other previous tilapia performance assessments have focussed on monosex tilapia and some researchers have commented on the need for comparisons between mono- and mixed sex populations (Horn et al., 2021; Omasaki et al., 2017b). This study has characterised the differences between the two population types, explaining the stocking and harvesting techniques and the differences in yields, where productivity is generally better in mixed-sex populations, likely due to tilapia reproducing in the ponds.

Allowing fish to breed naturally in the grow-out system circumvents the need to repurchase fish seed therefore establishing and operating a mixed sex tilapia farm is usually less expensive (Haque et al., 2010). However, feed administration and water quality should be constantly monitored to ensure pond carrying capacity is not surpassed. Optimising pond productivity is key in maximising the economic, environmental, and nutritional benefits of a culture system.

From the results it is unclear which treatment performs best in all dimensions, however Figure 15 shows two systems which have average GHGs, incomes and nutritional quality, treatment T1-GI and treatment T1-NI. When considering the trade-offs of food production systems, it is important to evaluate dimensions which are important for everyone, i.e. for the producer and consumer. For farmers looking to maximise economic returns, using the newest GIFT strain may be the best option, however commercially formulated feeds should be used alongside appropriate feeding strategies to keep feed expenditures and FCRs low. Otherwise, when the newest GIFT strain is unavailable, non-GIFT strains are better suited according to this study, since T2 results have shown older strains of GIFT perform poorer.

For those aiming to maximise the nutritional quality of tilapia farming systems, intensive pond systems are likely to yield the best results. Both non-GIFT strains performed better in terms of nutritional quality during both trials, and T2-NI performed best compared to all other systems. The PNA score for T2-NI was 26.2, meaning 26.2 households (4.5 people per household) can potentially obtain their yearly nutrient requirements from 1 hectare of T2-NI production. This is about 5 times more households than the two lowest scoring systems, T2-GS and T2-NS. However, from the environmental impact assessment, T2-NS outperformed most other systems for most impact categories.

Formulated fish feed was the major contributor to the LCIA of the intensive systems, and rice bran for the semi-intensive systems, therefore an improvement in feed conversion ratios would likely result in an improvement in the environmental performance of all systems. Feed management strategies and use of appropriate feed ingredients for tilapia may help in improving FCRs (Henriksson et al., 2021; Kabir et al., 2019). However, improvements in feed conversion ratios may not translate directly to better growth, lower environmental impacts and higher nutritional quality. There are other efficiency indicators which can be used for food system performance assessments such as nutrient retention which has been used to compare nutrient contents of feeds with the nutrient content of animal-source foods (Fry et al., 2018). When considering the nutritional content of fish feeds and how this directly translates to the nutritional quality of ASFs, using an nLCA may be the best option for the environmental impact assessment. Combining the two dimensions of the food systems for a performance assessment will enable a better understanding of the impacts.

The results of this study shows the difficulty in addressing the sustainability issues of the global food systems while simultaneously addressing the high rates of global malnutrition. Transforming food systems into sustainable and nutrition-sensitive systems can only be achieved by harnessing the most up-to-date empirical data (Fanzo et al., 2021), however using indicators which independently assess one dimension of the food system might not be the best approach. Therefore, combining LCA results with nutritional quality assessments is more frequently being used for food system assessments (Green et al., 2020; Hallström et al., 2019; McLaren et al., 2021; Weidema and Stylianou, 2019). This will be addressed in Chapter 6 where the results of the environmental and nutritional performance assessments in this study will be combined.

Chapter 5

Performance assessment of Rice-fish Systems in Northwest Bangladesh

5.1 Introduction

Assessing the impacts of tilapia farming across Bangladesh may help identify aquaculture systems with a relatively high nutritional quality and low environmental footprint. Since rice-fish farms are widespread across Bangladesh but have been excluded from previous tilapia production performance assessments (Shikuku et al., 2021; Tran et al., 2021), they have been included in this study. The performance of rice-fish (RF) farming has been assessed in this chapter using a food systems approach whereby performance indicators have been selected to assess each stage of the food system (Ingram, 2015) allowing various dimensions to be considered. The environmental and economic performance of RF farms has been assessed alongside the food and nutrition security impacts at each stage of the food system.

To quantify the impacts, performance of RF farms was compared with performance of rice-only and fish-only farms. In this chapter, the overall performance of the farms and the food and nutrition security status of rice-fish, rice-only, and fish-only farmers were compared using specific indicators which account for each dimension of the food system.

5.2 Materials and Methods

Descriptions of the farming systems studied in this chapter, along with the reasons behind site selection, are outlined in Chapter 2. Key informant interviews were conducted to help identify the most appropriate areas in Rangpur for this study. After several visits throughout the district, it was found that many farmers produced both fish and rice on separate plots, therefore 4 farming household types were included in the study: rice-fish farming households (RF), fish-only farming households (FO), rice-only farming households (RO) and decoupled-rice and fish farming households (D-RF), which included those who farmed fish and rice on completely separated, distant plots.

A total of 68 households were visited and a farm production survey was conducted with the farmer, along with a consumption survey which was carried out with the main food preparer of the household. After the data cleaning process, a total of 58 farm production surveys were kept for inclusion in the study and a total of 66 consumption surveys were retained. Several surveys were discarded after production yields or consumption values did not match-up with expenditures.

5.2.1 Farm Selection

Rice-fish farmers were found to culture fish in rice fields in two distinct ways. Some farmers would dig a deeper ditch in an area of the rice field and stock fish directly in rice fields, allowing the fish to swim throughout the field and retreat into the deeper ditches when water levels were low. Other rice-fish farmers produced fish in ponds attached to rice fields, linked by a channel in the dyke which allowed nutrients to flow between the pond and rice field. Farmers were only included in the study if they farmed tilapia and the majority (>50%) of their fish production was destined for market.

After data collection activities, households were split into wealth categories using annual income data. To do this, the minimum ($330), median ($2530) and maximum ($14850) incomes were calculated and farmers earning below $2200 were classed as low-income households (*n*= 19), above $4400 were high-income households (*n*= 9), and those in between these incomes were considered middle-income households (*n*= 30).

5.2.2 Food and Nutrition Systems Conceptual Model

Food and nutrition system conceptual models describe the food production system and offer researchers a guide to performing impact assessments (Ingram, 2011). The indicators used during a food system impact assessment should encompass food system outcomes, reflect the objectives of the study, and should be underpinned by the dimension which is being assessed.

Since the main function of a food system is to provide nutrition, one of the driving forces behind the selection of indicators for this study was food and nutrition security. The indicators were also chosen to reflect the objectives of the study which were to assess the nutritional and environmental performance of rice-fish systems compared to fish-only and rice-only food systems. Indicators were chosen to assess each of the four sub-systems (Table 29) to understand how each system impacts food and nutrition security for those households.

Table 29. Indicators used at each stage of the food and nutrition system to assess the food and nutrition security impacts.

System Stage	**Indicators**
Production	Nutritional yield Potential Nutrient Adequacy
Processing	Affordability
Consumption	Dietary Diversity Scores Household Food Insecurity Access Scale
Nutrition	Body Mass Index

5.2.3 Rice Production

Rice farmers in Bangladesh often farm two separate crops, the *Boro* crop and the *Amon* crop. *Boro* is the dry season crop which is farmed using irrigation, and *Amon* is produced later in the year during the Bangladeshi wet season where irrigation is not required. Rice production data collected during the farm production survey was collected for 1 full year of rice production.

5.2.4 Household Food Security Impacts

Food consumption data were collected for 66 households using a structured questionnaire (Annex 3). The questionnaires included sections on all food consumption, animal-source foods (ASF) consumption, fish consumption, food acquisition, tilapia preparation and cooking techniques and tilapia consumption preferences.

Structured surveys were also used to collect total household dietary diversity (HDDS) data, women's dietary diversity, and children's dietary diversity for 30 households (18 RF households, 2 FO households, 7 RO households and 3 D-RF households) (Annex 3).

5.2.5 Environmental Performance Assessment

Life cycle assessments were carried out to compare the environmental impact of tilapia production from fish-only systems and rice-fish systems in Northwest Bangladesh. Additionally, to understand the impact of RF systems, rice production in rice-only and rice-fish farms were assessed too. The goal of this study was to quantify and compare the environmental impacts and identify opportunities for improving food production footprints. The functional unit used was 1 tonne tilapia and 1 tonne rice and the system boundary (Figure 16, Figure 17, and Figure 18) is defined as "cradle to farm gate", whereby all raw materials, extraction, processing, transportation, and production of inputs up to the point of leaving the farm were included.

All input-output data were recorded for each farm visited for the year 2021. LCIs have been developed using book values for electricity and transportation emission values, and feed production values were collected from a local feed company. Although various species were stocked into the aquaculture farms, only tilapia hatchery data was collected and used in the LCIA as this is the target species and collection data from all relevant hatcheries was out with the scope of this study. Data from one hatchery was used to model the process for tilapia fry and fingerling production. Economic allocation was used for multi-output processes.

For comparison between RF and FO farming impacts, the FO farms were combined with the fish-only plots from D-RF farms.

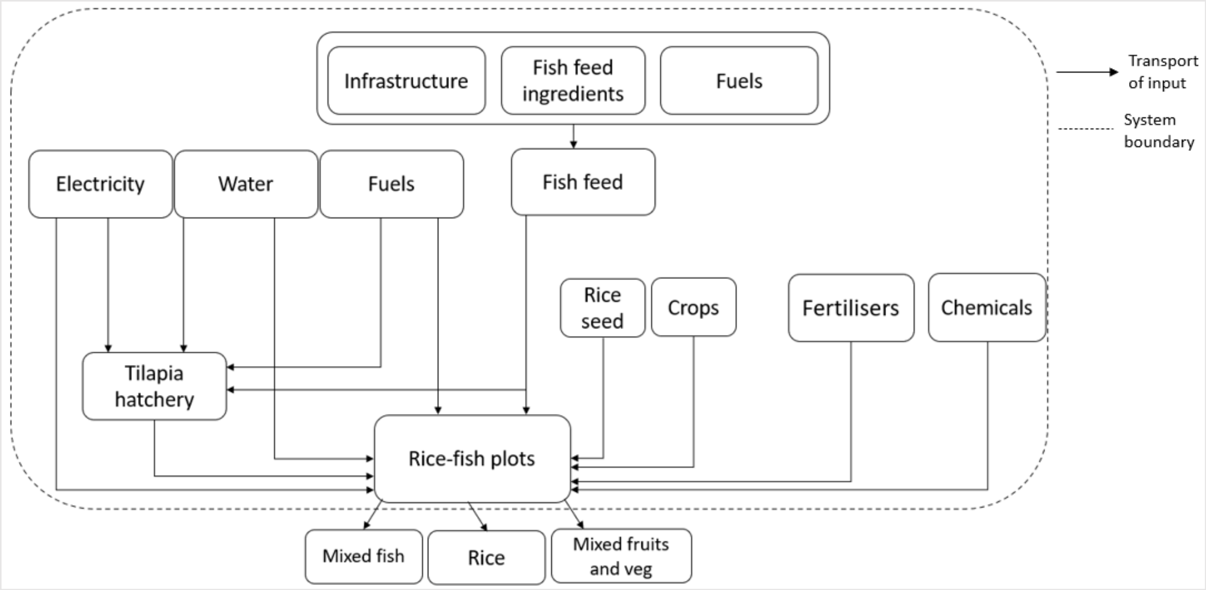


Figure 16. Schematic diagram of the system boundaries used for the LCA for the rice-fish systems. A cradle to farm gate assessment was conducted.

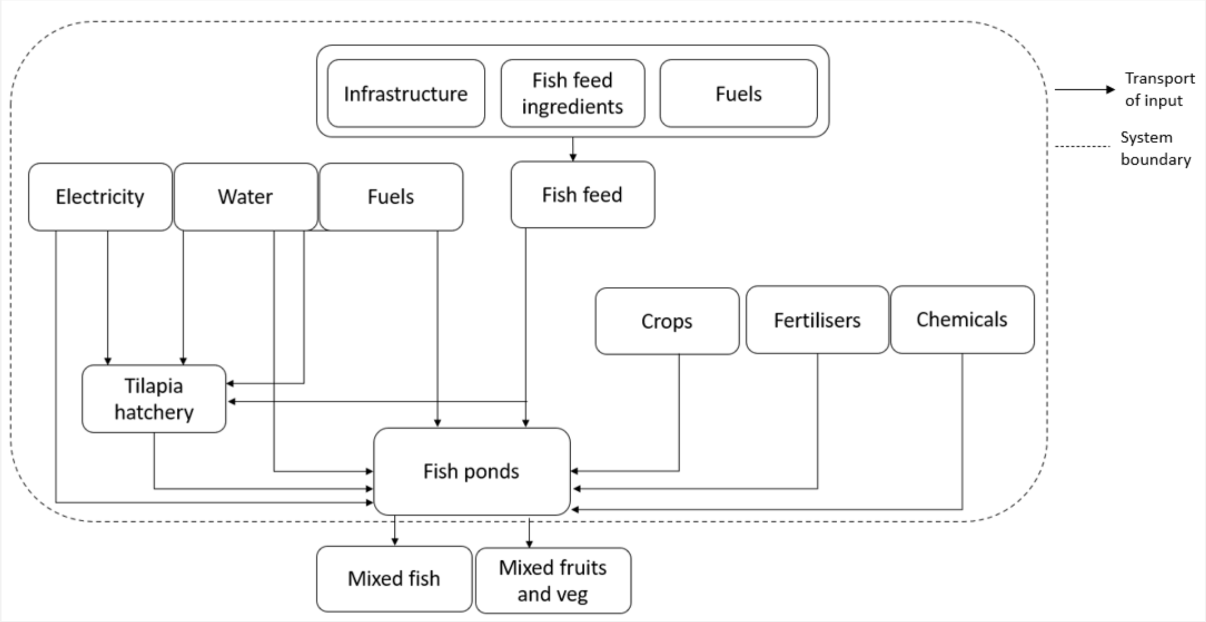


Figure 17. Schematic diagram of the system boundaries used for the LCA for the fish-only systems. A cradle to farm gate assessment was conducted.

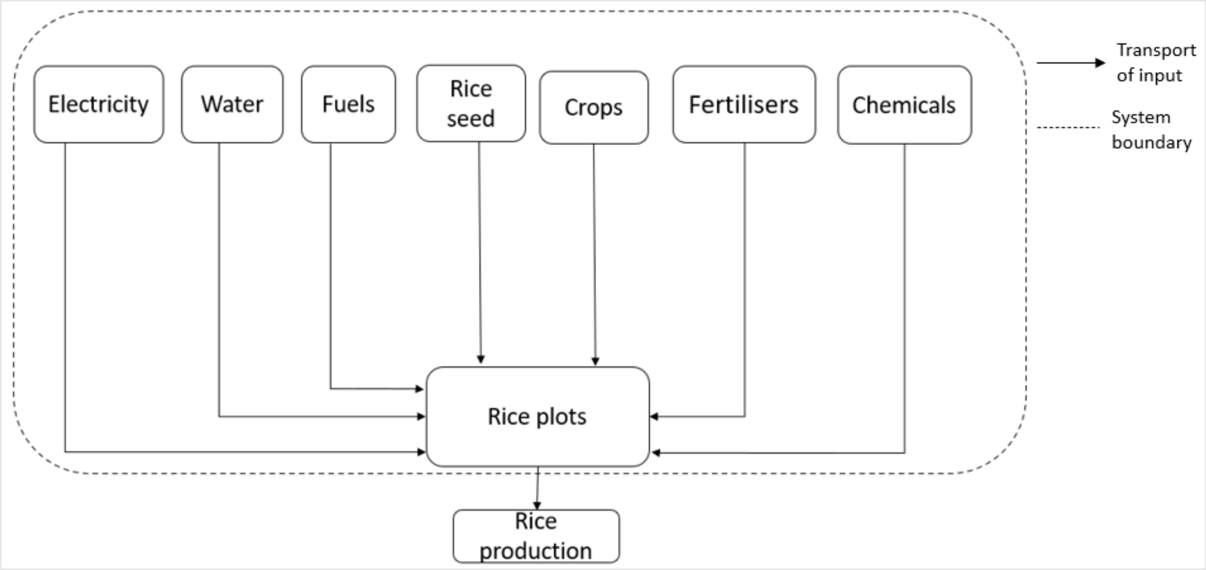


Figure 18. Schematic diagram of the system boundaries used for the LCA for the rice-only systems. A cradle to farm gate assessment was conducted.

5.2.6 Statistical Analyses

RStudio version 4.0.3 was used to conduct statistical analysis of all farm production data, household food security data, food consumption data, and farm system nutritional quality data. ANOVA was used to investigate the differences between and within farming systems using the lm() function (Chambers, 1992). Tukey tests were performed using the TukeyHSD() function (Odeh & Evans 1974) to investigate the interactions between farm systems and wealth categories. Results showing a P-value <0.05 were considered significant. All data are presented as means ± standard deviation.

For the statistical analysis of farm production data, production of farms that produce fish and rice on separated plots (D-RF farms) were grouped with the relevant farm type, i.e. the rice fields of D-RF farms were grouped with the RO data and the fish production was grouped with FO data.

5.3 Results

5.3.1 Farm Characteristics

As seen in Table 30, D-RF farmers had the highest average annual household incomes, owned the most land, had the biggest households but had the least amount of experience in farming and a generally lower education level. All aqua farms involved in the study were polyculture farms, producing between 5 to 19 different species of fish.

Since tilapia was the target species throughout this study, only farmers that produced tilapia were involved. Farmers were asked to recall the last time they purchased new tilapia seed for stocking, of the 45 farmers who could confidently recall the last stocking date, 27 farmers had purchased new stock in the current year (2021), 10 farmers had purchased the previous year, 2 purchased in 2019, 2 farmers purchased in 2018, one farmer in 2015, two farmers in 2009 and one farmer had not purchased new tilapia stock since 2000. There were no statistical differences found between farm types or wealth categories for tilapia production rates, even when controlling for the year of stocking.

Table 30. Farm information disaggregated by farm type (means ± SE).

Farm Characteristic	***Rice-fish (n= 30)***	***Fish only (n= 4)***	***Rice only (n= 15)***	***Decoupled Rice and fish (n= 9)***
Farm Scale (ha)	0.68 ± 0.08	0.33 ± 0.5	0.39 ± 0.07	1.14 ± 0.14
Fish-only plot (ha)	-	-	-	0.23 ± 0.04
Rice-only plot (ha)	-	-	-	0.91 ± 0.15
Household Size (no.)	5.3 ± 1.7	5.8 ± 1.3	3.3 ± 6	6.2 ± 1.4
HH Income (USD/yr)	2750 ± 2558	2750 ± 1337	1100 ± 887	3850 ± 2431
Fish income (USD/yr)	844 ± 144	646 ± 114	-	715 ± 186
Rice income (USD/yr)	1805 ± 257	-	1202 ± 236	2183 ± 278
Fish Species Produced (no.)	10.9 ± 3.1	11 ± 1.4	-	10.8 ± 2.2
Main Occupation				
Agriculture	37%	-	93%	56%
Aquaculture	47%	75%	-	11%
Business	16%	25%	-	33%
Labour	-	-	7%	-
Farming Experience (years)	23.2 ± 13.3	20.2 ± 15.1	26.5 ± 15.2	14.4 ± 13.7
Training Received	43%	25%	7%	33%
Education Level				
Illiterate			13%	11%
Primary	40%	50%	40%	44%
Secondary	47%	25%	47%	44%
Undergraduate	10%	25%		
Postgraduate	3%			

5.3.2 Farm Production Performance

Fish-only farms produced significantly higher total fish yields than rice-fish farms (Table 31). Large fish yields were also higher at FO farms, but SIS fish yields were not found to be significantly different between FO and RF farms. FO farm income from fish sales were greater than RF farm incomes but was not found to be statistically significant.

Total fish yields and large fish yields were greater at farms in the middle- and high- wealth categories compared to low-income farms. Farms from the middle- and high- wealth categories also had higher incomes from fish sales compared to the low-income farms, but this was not found to be statistically significant.

Total farm income from fish and rice sales are presented in Figure 19. FO and RF farms had similar total incomes which were both significantly higher than rice-only farms.

Table 31. Fish production parameters disaggregated by farm type and wealth category (means ± SE).

Fish production	**Farm Type**		**Wealth Category**		
	RF	**FO**	**Low**	**Middle**	**High**
Tilapia (T/ha)	0.64 ± 0.08[a]	0.94 ± 0.2[a]	0.38 ± 0.1[a]	0.77 ± 0.1[a]	0.94 ± 0.26[a]
SIS (T/ha)	0.15 ± 0.006[a]	0.17 ± 0.01[a]	0.16 ± 0.01[a]	0.16 ± 0.007[a]	0.14 ± 0.01[a]
Large fish (T/ha)	2.6 ± 0.07[a]	3.7 ± 0.08[b]	2.5 ± 0.08[a]	3 ± 0.08[b]	3.5 ± 0.09[b]
Total fish (T/ha)	2.8 ± 0.2[a]	3.9 ± 0.2[b]	2.7 ± 0.4[a]	3.2 ± 0.2[b]	3.6 ± 0.3[b]
Income ($/ha)	4652 ± 420[a]	5923 ± 390[a]	4153 ± 766[a]	5139 ± 477[a]	5522 ± 170[a]

Notations [abc] are to compare means (horizontal comparison within category), different superscripts indicate a significant difference (*p*-value < 0.05).

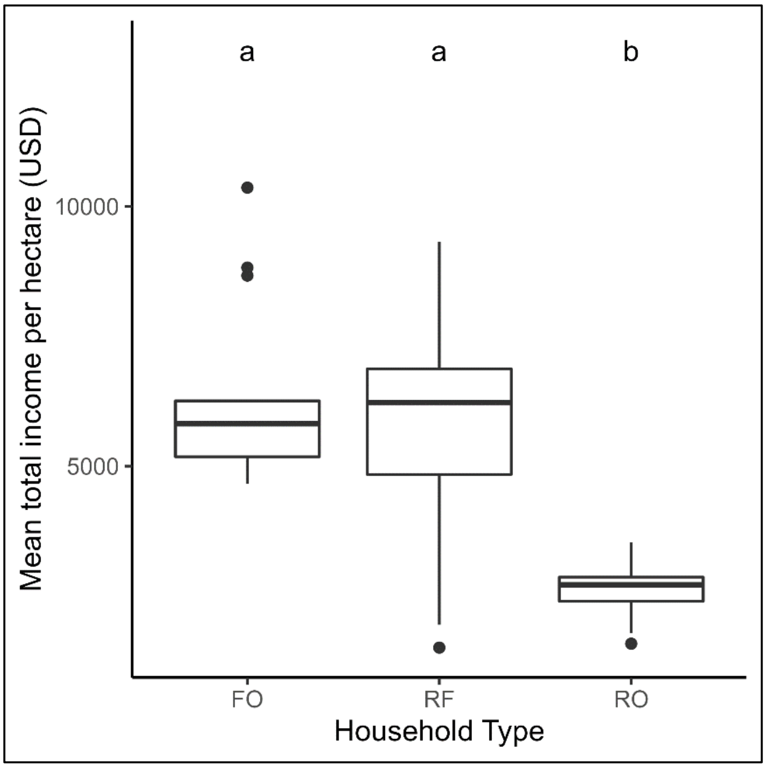


Figure 19. Total income (fish and rice) per hectare disaggregated by farm type. Notations [ab] are to compare means, different superscripts indicate a significant difference (*p*-value < 0.05).

5.3.4 Environmental Impacts

The environmental impacts for tilapia produced in FO and RF systems are presented in Table 32. RF farms performed best in all impact categories except abiotic depletion, abiotic depletion (fossil fuels) and marine aquatic ecotoxicity. From the contribution analyses (Figure 20 and Figure 21) it is clear fish feed have the greatest contribution for all impact categories for both RF and FO farms, contributing a minimum of 45% to each category at FO farms and a minimum of 33% at RF farms. Fertilisers contributed over 5% to all categories except water consumption at FO farms and water consumption and land use at RF farms, and chemicals were the next biggest contributor at over 5% for 10 and 11 out of 14 impact categories for FO and RF farms respectively. Rice seed contributed very little to the impacts for RF farms, however fish seed contributed between 3 and 42.5% in all categories at both FO and RF farms, with the highest contribution to terrestrial ecotoxicity, 39% and 42.5% for FO and RF farms, respectively.

Table 32. Life cycle impact assessment of 1 tonne tilapia production using economic allocation.

Impact category	**Unit**	**Fish-only**	**Rice-fish**
Water consumption	m3	267	205
Land use	m2a crop eq	4.78E3	4.17E3
Abiotic depletion	kg Sb eq	0.174	0.137
Abiotic depletion (fossil fuels)	MJ	1.2E4	1.25E4
Global warming (GWP100a)	kg CO2 eq	970	951
Ozone layer depletion	Kg CFC-11 eq	1.02E-4	1.02E-4
Human toxicity	kg 1,4-DB eq	990	957
Fresh water aquatic ecotox.	kg 1,4-DB eq	639	598
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.15E6	1.24E6
Terrestrial ecotoxicity	kg 1,4-DB eq	54.3	42.5
Photochemical oxidation	kg C2H4 eq	0.506	0.428
Acidification	kg SO2 eq	6.77	6.65
Eutrophication	kg PO4--- eq	5.54	4.52
GWP LUC	kg CO2 eq	424	292

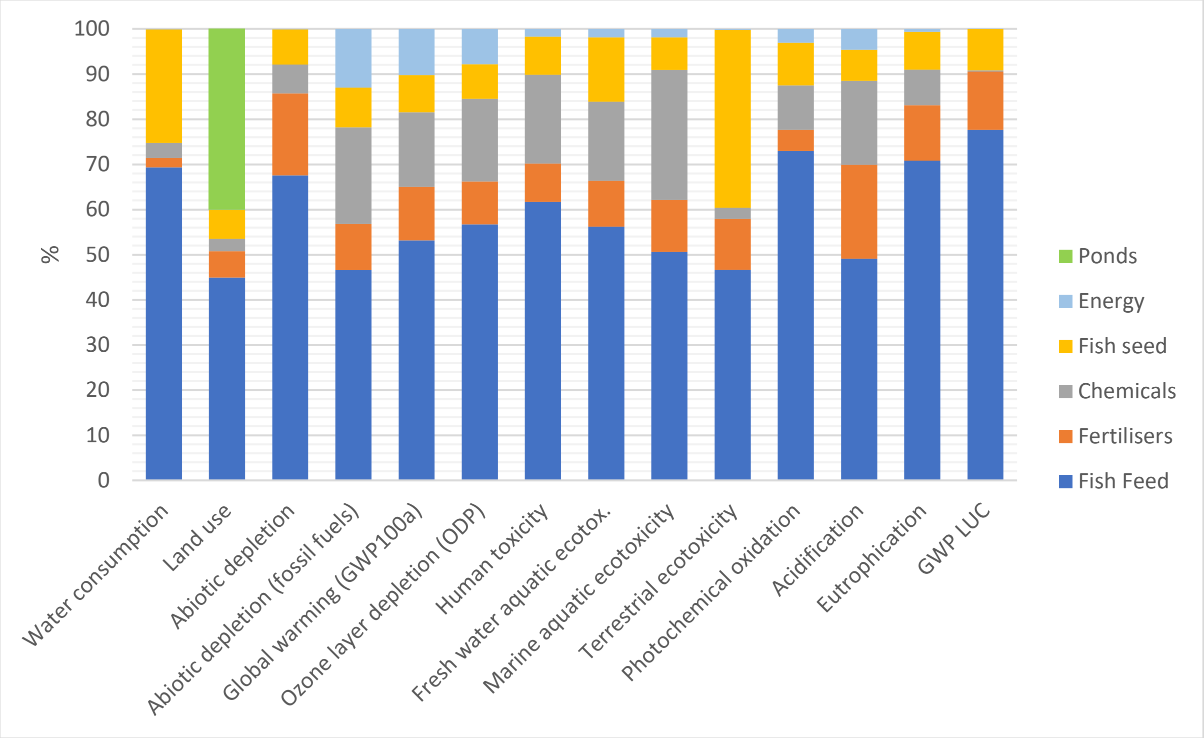


Figure 20. Average contribution analysis for fish-only plots for 1 tonne tilapia production.

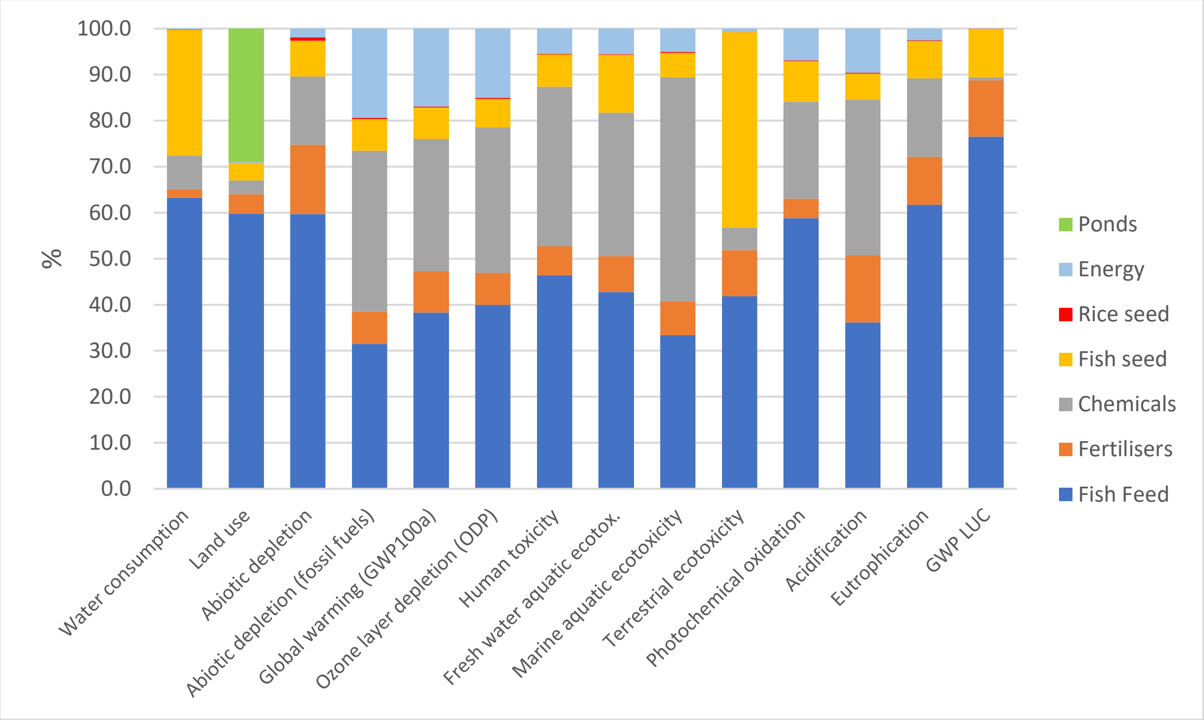


Figure 21. Contribution analysis for rice-fish plots for 1 tonne tilapia production.

Although tilapia was the focus of this study, all rice-fish and fish-only farms were polyculture systems so produced other species of fish alongside tilapia. The impacts of 1 tonne of mixed fish production were measured to evaluate the overall environmental performance (Table 33). Results show rice-fish farms perform better than fish-only farms for all impact categories.

Table 33. LCIA of 1 tonne average mixed fish production using economic allocation.

Impact category	Unit	Fish-only	Rice-fish
Water consumption	m3	276	164
Land use	m2a crop eq	5.55E3	4.24E3
Abiotic depletion	kg Sb eq	0.195	0.137
Abiotic depletion (fossil fuels)	MJ	1.38E4	1.22E4
Global warming (GWP100a)	kg CO2 eq	1.12E3	952
Ozone layer depletion (ODP)	kg CFC-11 eq	1.18E-4	1.03E-4
Human toxicity	kg 1,4-DB eq	1.12E3	999
Fresh water aquatic ecotox.	kg 1,4-DB eq	707	578
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.32E6	1.27E6
Terrestrial ecotoxicity	kg 1,4-DB eq	53.8	27.9
Photochemical oxidation	kg C2H4 eq	0.56	0.409
Acidification	kg SO2 eq	7.84	6.97
Eutrophication	kg PO4--- eq	6.2	4.67
GWP LUC	kg CO2 eq	468	273

The environmental impacts for 1 tonne of rice production at RO and RF farms are presented in Table 34. RO farms performed best in all impact categories. The use of fish feed at RF farms caused increased environmental impacts at these farms.

Table 34. Life cycle impact assessment of 1 tonne rice production using economic allocation using average production of farms.

Impact category	**Unit**	**Rice-only**	**Rice-fish**
Water consumption	m3	5.41	23.5
Land use	m2a crop eq	1090.8	1903.8
Abiotic depletion	kg Sb eq	0.007	0.018
Abiotic depletion (fossil fuels)	MJ	1790.36	1851.15
Global warming (GWP100a)	kg CO2 eq	114.4	138.9
Ozone layer depletion	Kg CFC-11 eq	1.26E-5	1.5E-5
Human toxicity	kg 1,4-DB eq	111.1	142.2
Fresh water aquatic ecotox.	kg 1,4-DB eq	64.2	84.9
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.77E5	1.83E5
Terrestrial ecotoxicity	kg 1,4-DB eq	1.3	4.8
Photochemical oxidation	kg C2H4 eq	0.032	0.054
Acidification	kg SO2 eq	0.8	1
Eutrophication	kg PO4--- eq	0.26	0.61
GWP LUC	kg CO2 eq	1.59	32.8

5.3.5 Nutritional Outcomes

The nutritional outcomes of rice-fish plots were compared to fish-only plots using nutrient nutritional quality assessment methodology outlined in section 2.2.7. The nutritional yields and potential nutrient adequacy are outlined in Table 35.

On average, FO farms had a higher PNA score compared to RF farms but there was no significant difference found. RF farms provided significantly more energy per hectare compared to FO farms due to the high energy content of rice. There were no significant differences found between the rest of the nutrients included in the nutritional performance assessment.

Table 35. Average nutritional yields for selected nutrients and PNA scores for fish-only and rice-fish systems.

System	Energy	Protein	Fat	Iron	Zinc	Calcium	Vit B12	Vit A	Iodine	Vit D	PNA
FO	3.4 ± 0.3^{a}	36.7 ± 2.6^{a}	2.6 ± 0.2^{a}	7.5 ± 0.4^{a}	7.9 ± 0.5^{a}	29.4 ± 2^{a}	149.5 ± 49^{a}	6.1 ± 2^{a}	5.6 ± 1^{a}	72.5 ± 10.3^{a}	5.46 ± 1.1^{a}
RF	9.7 ± 0.9^{b}	33.7 ± 3.1^{a}	2.7 ± 0.4^{a}	6.8 ± 0.7^{a}	9.6 ± 0.8^{a}	24.3 ± 2.5^{a}	91.6 ± 11.2^{a}	4.4 ± 1^{a}	4.4 ± 0.6^{a}	51.5 ± 17.5^{a}	4.06 ± 0.5^{a}

Notations ^{ab} are to compare means (comparison within individual nutrient), different superscripts indicate a significant difference (p-value < 0.05).

5.3.6 Processing Stage

5.3.6.1 Affordability

Tilapia is a relatively affordable fish species in Bangladesh with average prices ranging from 60 BDT/kg to 180 BDT/kg depending on fish size and quality, and market location. Using data collected at various markets across Rangpur, the affordability of each fish species found in the farms in this study have been assessed and are presented in Table 36. The affordability index outlined in Chapter 2 is used to calculate the cost of 1 portion of fish per hours worked, and the nutritional affordability (Table 37) is calculated as per the methodology outlined in Chapter 2. On average, tilapia is the cheapest fish at food fish markets and *majhari* tilapia is the fifth cheapest option. When assessing the affordability of nutrients of interest, *darkina* performs best followed by *majhari* tilapia, mrigal and tilapia. Both forms of tilapia perform better than all other large fish and SIS species on the list.

Table 36. Cost (BDT/100g and hours worked/100g) of each fish species found in the surveyed FO and RF farms.

Species	**Scientific name**	**Portion cost (BDT/100g)**	**Hours worked/ 100g**
tilapia	*Oreochromis niloticus*	12.9	0.36
bighead	*Hypophthalmichthys nobilis*	13.25	0.37
pangas	*Pangasianodon hypophthalmus*	13.65	0.38
mrigal	*Cirrhinus mrigala*	13.75	0.39
majhari tilapia	*Oreochromis niloticus*	13.8	0.39
silver carp	*Hypophthalmichthys molitrix*	13.9	0.39
grass carp	*Ctenopharyngodon idella*	14.36	0.40
common carp	*Cyprinus carpio*	14.4	0.40
sarputi	*Barbonymus gonionotus*	14.65	0.41
bata	*Labeo bata*	14.8	0.42
catla	*catla catla*	14.8	0.42
bata fingerling	*Labeo bata*	16	0.45
rui	*Labeo rohita*	16.3	0.46
kali bash	*Labeo calbasu*	17.325	0.49
puti	*Puntius ticto*	17.7	0.50
taki	*Channa punctatus*	19.03	0.53
darkina	*Esomus danricus*	20.1	0.56
ayere	*Sperata seenghala*	30.9	0.87
bele	*Glossogobius giuris*	32.75	0.92
mola	*Amblypharyngodon mola*	36.95	1.04
magur	*Clarias batrachus*	41	1.15
shol	*Channa striata*	41.7	1.17
chitol	*Chitala chitala*	42.35	1.19
shing	*Heteropneustes fossilis*	42.46	1.19
pabda	*Ompok pabda*	43.25	1.21
koi	*Anabas testudineus*	43.3	1.22
tengra	*Mystus vittatus*	44.4	1.25
snakehead	*Channa marulius*	75	2.11

Table 37. Cost per fish species to meet an average of one third of the daily RNIs for the selected nutrients of interest.

Species	Cost to meet average third of daily RNIs (BDT)
darkina	8.8
majhari tilapia	10.2
mrigal	10.3
tilapia	13.4
puti	14.8
sarputi	15.4
bata	20.0
common carp	21.3
mola	21.3
Rui	21.6
silver carp	21.6
bata fingerlings	21.7
catla	25.7
taki	28.7
bele	37.7
tengra	42.8
bighead	62.9
pangas	69.1
magur	71.2
shing	77.2
kali baus	84.1
koi	85.5
ayere	96.8
shol	213.7
grass carp	223.6
chitol	257.1
pabda	447.4
snakehead	478.7

* Note: there were no available data for iodine content of bata, no data for vitamin D or iodine content of chitol, no data for vitamin D content of pabda, and no vitamin A or vitamin B12 content data for grass carp.

5.3.7 Consumption Stage

5.3.7.1 Consumption Survey Results

Unlike the farm production results above, the consumption survey results have been separated into four farming household types: RF, FO, RO, and D-RF. This is because D-RF households were seen to have a higher land ownership and total household income.

Keeping D-RF households grouped with the RF households skewed the results, so they were separated since they are two distinct categories.

5.3.7.2 Household Food Insecurity Access Scale (HFIAS)

Results from the HFIAS survey showed no difference in the prevalence of household food insecurity between the four farming categories. All 66 households involved in the HFIAS survey scored 0 except one RF and one FO household which scored 1 and 5, respectively. The survey was performed during the dry season and over half of the survey participants explained that food insecurity is considered less significant in the area during the dry season but is an issue during the wet season. Most survey participants believed they would score higher in the HFIAS if the survey was taken during the wet season. However, a follow-up survey was beyond the scope of this study due to time and budget constraints.

5.3.7.3 Dietary Diversity

Household dietary diversity scores (HDDS), women dietary diversity scores (WDDS) and children dietary diversity scores (CDDS) did not differ significantly between the different types of households (Figure 22). Scores were disaggregated further by wealth category and there were still no significant differences found between categories.

5.3.7.4 Animal-Source Food Consumption

Table 38 shows the average amount of animal-source foods eaten by each person per household category in one week. As intrahousehold distribution data was not collected, it was assumed each household member ate equal amounts of each food item, however in reality this is not often the case. Fish consumption was statistically significantly higher than any other animal-source food for all household types.

On average, fish-only farmers consumed more fish per week compared to the other farmer types (Table 38), and wealthier farmers consumed more per week than those on lower incomes (Table 39). Figure 22 shows which groups of households significantly differ in terms of weekly fish consumption.

Table 38. Animal-source food consumption per person (kg week^{-1}) disaggregated by household type (mean ±SE).

HH Type	Fish (kg)	Beef (kg)	Chicken (kg)	Egg (no.)	Goat (kg)	Total ASF (kg)*
D-RF	0.85 ± 0.1	0.25 ± 0.19	0.29 ± 0.03	2.9 ± 0.04	0.33 ± 1.17	1.34 ± 0.12
Fish-only	1.04 ± 0.36	0.25 ± 0	0.23 ± 0.04	3.33 ± 0.93	0.5 ± 0	1.51 ± 0.45
Rice-fish	0.82 ± 0.07	0.19 ± 0.02	0.37 ± 0.06	3.5 ± 0.45	0.18 ± 0.04	1.19 ± 0.08
Rice-only	0.56 ± 0.09	0.23 ± 0.02	0.3 ± 0.06	2.68 ± 0.46	0	0.86 ± 0.1

*To calculate total ASF in kg, it was assumed each egg weighed 50g.

Table 39. Animal-source food consumption per person (kg week^{-1}) disaggregated by wealth category (mean ±SE).

Wealth Category	Fish (kg)	Beef (kg)	Chicken (kg)	Egg (No.)	Goat (kg)	Total ASF (kg)*
Low	0.62 ± 0.06	0.21 ± 0.03	0.26 ± 0.04	3.08 ± 0.46	0	0.98 ± 0.08
Middle	0.77 ± 0.06	0.2 ± 0.02	0.38 ± 0.04	2.99 ± 0.36	0.22 ± 0.04	1.14 ± 0.08
High	1.14 ± 0.2	0.17 ± 0	0.31 ± 0.06	4.04 ± 0.87	0.5 ± 0	1.6 ± 0.22

*To calculate total ASF in kg, it was assumed each egg weighed 50g.

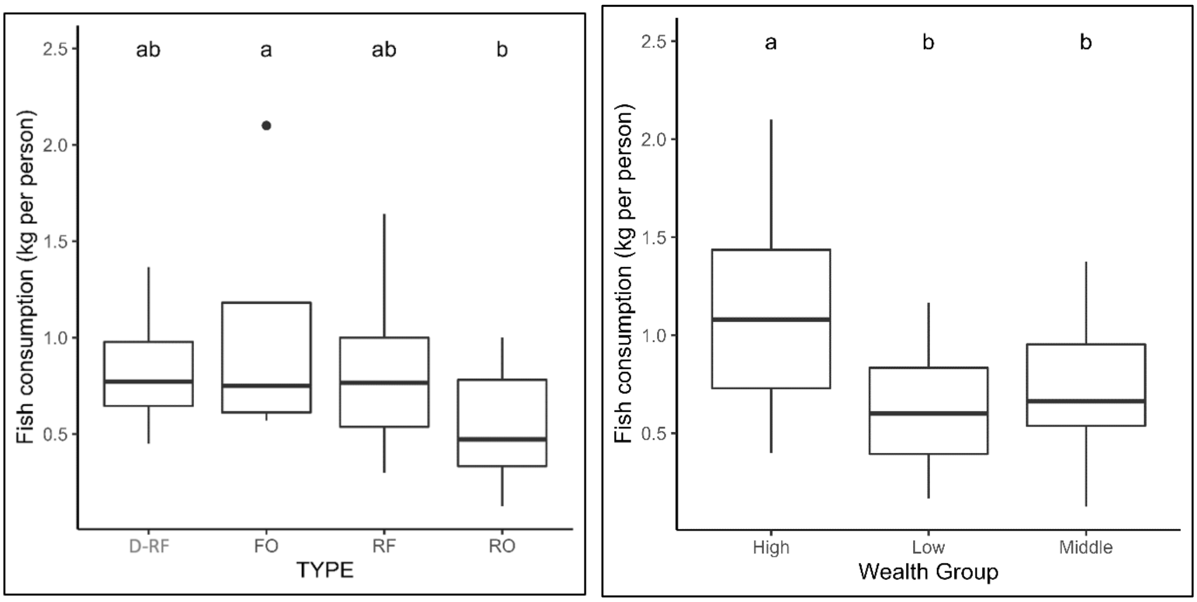


Figure 22. Mean weekly fish consumption rates (kg per person) disaggregated by household type and wealth category. Notations ^{ab} are to compare means (comparison within graph), different superscripts indicate a significant difference (*p*-value < 0.05).

All aqua farms produced tilapia with every farm retaining some tilapia production for home consumption except 2 farms. Of the 8 farms which produced fish fingerlings (all species excluding tilapia) for sale, only 2 consumed fingerlings from their own production, whereas 7 of the 12 farms which produced "*majhari* tilapia" (fish from fingerling size to 50g) ate a portion of their own *majhari* production.

From the 66 households involved in the consumption survey, only 7 survey participants claimed they did not consume the bones of tilapia. From the 59 households which claimed to consumed tilapia with bones, 73% said they would consume the bones of tilapia 10cm or smaller.

Table 40 shows the average volumes of fish production kept for household consumption. There were no significant differences found between the households or within wealth categories. On average, all households retained a higher percentage of SIS for home consumption and sold the majority (>80%) of their large fish.

Table 40. Percentage of total fish production, total large fish production, and total SIS production which was kept for home consumption.

Farming Household	Production kept for home consumption (%)	Large fish kept for home consumption (% of total production)	SIS kept for home consumption (% of total production)
D-RF	14.7 ± 2.3^{a}	12.9 ± 1.9^{a}	49.6 ± 10.4
Fish-only	16.11 ± 3.32^{a}	15.92 ± 3.3^{a}	19.12 ± 2.59
Rice-fish	14.8 ± 1.8^{a}	12.9 ± 1.6^{a}	31.3 ± 4.6

5.3.8 Nutrition Stage

Body Mass Index (BMI) calculations for each household type and wealth category did not differ significantly, even when controlling for sex of household member (Table 41).

5.4 Discussion

This study has assessed the performance of various stages of fish production systems in Northwest Bangladesh. Multiple dimensions of these systems have been evaluated and results have shown the performance of rice-fish and fish-only systems varies depending on the food system stage which is being assessed. RF systems out-performed FO systems in terms of environmental impacts from tilapia culture, however, FO systems had a higher nutritional quality. Farmland used to produce rice and fish together generated the highest USD per hectare on average followed by fish-only plots then rice-plots, however, farmers who produced fish and rice on separated plots were found to own the most land and therefore had the highest mean annual household incomes.

After separating farming households by farm type, they were further separated by wealth, as production and consumption rates are often affected by the wealth status of the household (Belton and Azad, 2012; Bogard et al., 2017b; Haque et al., 2014; Horn et al., 2021). Total fish yields at FO farms were significantly higher than RF farms, but there was no significant difference found between the level of inputs (feed and fertilisers) into FO and RF farms, even when controlling for wealth category. Therefore, it may be assumed fish yields are higher at FO farms since farm management solely revolved around fish production. Due to time and budget constraints, the sample size of this study was relatively small and may have impacted the statistical analysis. A follow-up survey would be worthwhile to confirm the reason behind FO farms achieving better yields with similar levels of inputs, and to clarify the reasons behind FO and RF farms performing similarly in terms of income from fish sales.

To assess the food and nutrition security dimension of the production stage of FO and RF systems, a nutritional quality score was calculated using nutritional yields for each farm. On average, FO farms had a higher nutritional quality score compared to RF farms but there were no significant differences found. At the consumption stage, farming households consumed between 12% - 20% of their own fish production and there were no significant differences found when assessing the food and nutrition security status. However, it should be noted that the dietary diversity and household food insecurity scores are likely to change over time, so follow-up surveys later in the year would be beneficial. Measuring the food and nutrition security using indicators at the production and consumption stages, especially when the household relies on the farm for a large proportion of their food, is important in defining the nutritional quality of the food system. Taking an integrated approach to food systems assessments reveals positive and negative impacts of the system and can help identify points for intervention (Ingram, 2011).

The results from this study show there are similarities in the food and nutrition security impacts of FO and RF systems but there are areas for improvement. For instance, FO farms produced higher yields and had a higher PNA score, without any significant difference in feed and fertiliser use, therefore improved farm management practices at RF farms could yield better results. Additionally, several essential micronutrients, which are known to have high levels of deficiency in Bangladesh, are more abundant in FO farms due to elevated levels of fish production. Incentivising RF farmers to adopt better fish rearing practices may improve yields and in turn the levels of these important nutrients in the food environment.

Results show tilapia produced in rice-fish farms have a lower environmental impact compared to tilapia produced in fish-only farms for 11 out of the 14 impact categories. From available data, 60% of the farmers involved in this study purchased tilapia from a hatchery or nursery in the current year, however, some farmers had the same stock for over 10 years, yet tilapia production rates were not affected by the year of stocking. Tilapia free-breeding in ponds is thought to negatively impact productivity due to genetic losses from inbreeding (Saura et al., 2017), however tilapia performance in both rice-fish and fish-only systems were similar regardless of the age of tilapia stock. Tilapia seed was found to contribute between 4% - 44% of the environmental impacts at FO and RF farms. These impacts are high from fish seeds due to the commercial feed use and use of hormone treatments to induce monosexuality in tilapia. Through using mixed sex tilapia and allowing free breeding to occur, it might be possible to reduce some environmental impacts without reducing productivity.

Affordability was used to measure the processing stage of the fish production systems. It was found that tilapia is the least expensive fish in general, but when taking nutrition into account, *darkina* is the most affordable. Tilapia and *majhari* tilapia provide the second and fourth most affordable nutrition to markets in Bangladesh. This is somewhat contradictory to current narratives in the food systems discourse which are calling for small indigenous fish species (SIS) to replace large fish species in food systems in Bangladesh (Bogard et al., 2017b; Castine et al., 2017; Shepon et al., 2020). Although research has shown the environmental and nutritional benefits of SIS, the affordability of these fish has often been overlooked. Recently, the prices of SIS, such as *mola,* have risen yet the price of tilapia has fluctuated little over the years. Although *mola* is a commonly consumed food item, tilapia is more readily available at markets and is less expensive. Consumers in Rangpur have indicated better availability and lower prices would encourage them to buy more fish (Rahman and Islam, 2020), therefore increasing *mola* production might be counterproductive in the fight against food and nutrition insecurity.

Using multiple indicators to assess the different dimension of a food system is important as policymakers require high-quality data to make evidence-based decisions. Many of the UNs Sustainable Development Goals are considered as guidelines in LMICs policy and programme strategies, and the indicators used throughout this study can be used to monitor and evaluate progress towards achieving these goals (Lele et al., 2016).

Chapter 6

A comparison of the combined environmental and nutritional performance of tilapia aquaculture systems in Bangladesh

6.1 Introduction

Food and nutrition insecurity and the environmental crisis are negatively impacting planetary and human health on a global scale (IPCC, 2023; United Nations, 2023). Driven by profit-maximisation, capitalist societies have led to the destruction of important ecosystems, alarming rates of anthropogenic pollution, hugely unequal societies, and the inequitable and unsustainable occupation of land and other resources. Profiteering within the global food system has played a part in these negative outcomes, for instance the agriculture industry is responsible for highest proportion of child labour (ILO, 2022), 78% and 21% of nitrous oxide and carbon dioxide emissions are produced by the global food system, respectively (Poore and Nemecek, 2018), and 3.1 billion people are still unable to afford a healthy, sustainable diet (FAO et al., 2022). For these reasons, food systems must be transformed, and environmental and nutritional performance assessments are crucial for guiding transitions.

An interdisciplinary approach should be taken when assessing the performance of a food system (Pounds et al., 2022) and indicators used in assessments should be multidimensional and system and context specific. Integrating nutrition into LCAs is a relatively new practice but there are already numerous efforts within the literature and there have already been published reviews of these efforts (Green et al., 2020; Hallström et al., 2018; McAuliffe et al., 2018; Saarinen et al., 2017). McLaren et al. (2021) have extensively discussed the available and appropriate methodologies and have called for further improvements in the way nutrition is integrated into LCAs. The authors note that although nLCAs offer a way to combine nutrition with LCA, it is important to remember that the nLCA results cannot offer a comprehensive enough picture of the situation to make fully informed decisions. For instance, there are many other societal and cultural factors about a food item or food production system which should be considered alongside the environmental and nutritional performance. Additionally, the use of nutrient metrics often only offers information on the nutritional value of individual food items whereas any decisions about food systems should be made in the context of the whole diet and the wider food environment.

The development of a nutrition metric is a very complex process, where relevant nutrients and non-nutrients should be considered, and weighting, capping and reference amounts need to be distinguished. Selecting a nutrition metric which is population/ dietary dependent is necessary when defining a nutritionally-based functional unit (Sonesson et al., 2019). The nutrition metric (PNA) used in this chapter has not been used in LCA before, however it's utility has been noted (Green et al., 2020).

Identifying production systems which can supply priority nutrients to populations deficient in those nutrients is an important step in addressing micronutrient deficiencies, especially in LMICs where food is less accessible (Beal and Ortenzi, 2022). Concentrating efforts in understanding the reasons behind nutrient deficiencies and addressing inadequate diets by identifying foods which are rich in priority nutrients is important in addressing these deficiencies (Beal et al., 2021). Therefore, the aim of this chapter was to compare the environmental and nutritional performance of Bangladeshi aquaculture systems and species and explore ways to enhance nutrient-rich food production while reducing environmental impacts.

The overall aim of this study was to present system-level impacts of different tilapia production systems across Bangladesh. The previous chapters have presented the nutritional quality and environmental performance of tilapia production in experimental systems, and rice-fish and fish-only systems. This chapter will build on the results of these assessments by expanding the impact analysis to other species produced within these systems and will also include poultry-cum-fish systems which were included in the tilapia nutrient composition analysis (Chapter 3). Additionally, the nutritional quality of the systems, which were evaluated in the previous chapters, will be integrated into the LCAS. The Potential Nutrient Adequacy (PNA) score for each system will be combined with the impact results, and the nutrient content and affordability of the fish produced in these systems will be combined with the relative climate change impact results.

6.2 Materials and Methods

6.2.1 Site Selection

The systems analysed in this chapter include the experimental systems discussed in Chapter 4, the fish-only ponds (*n*= 13) and the rice-fish plots (*n*= 30) outlined in Chapter 5, and the poultry-fish systems (*n*= 14) located in Noakhali which are described in Chapter 2.

Fish-only (FO), rice-fish (RF) and poultry-fish (PF) farms were visited in January 2022, and a structured questionnaire was used to collect LCI data for farm production for 2021. All these farms were fish polycultures and produced fish alongside various fruit and vegetables, rice, or broiler chickens. Table 41 shows the LCI data for an average of 1 tonne of mixed fish production at each farm type. Fertilisers include compost, cattle manure, poultry manure, lime, maize bran, rice bran, wheat bran, mustard oilcake, salt, urea, gypsum, and potash. Chemicals include rice pesticides, TSP, zeolite, rotenone, DAP, and oxygen tablets. The system boundary for PF farms is seen in Figure 23, and system boundaries for FO and RF farms can be seen in Chapter 5.

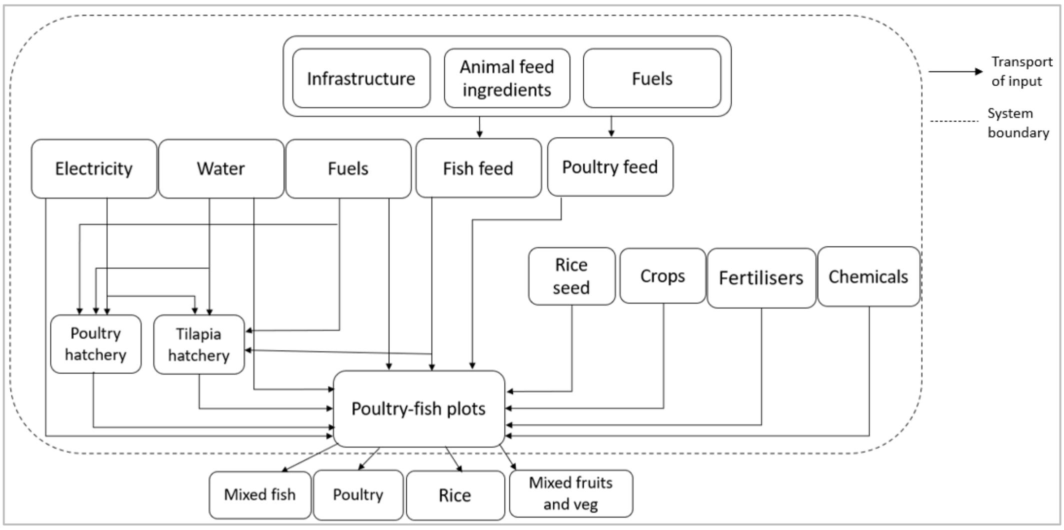


Figure 23. Schematic diagram of the system boundaries used for the LCA for the poultry-fish systems. A cradle to farm gate assessment was conducted.

Table 41. Unit process data for the different farming systems assessed in this study per tonne mixed fish (means ± se).

	Unit	Rice-Fish	Fish-Only	Poultry-Fish
Inputs				
Land	m2	3670.2 ± 261.1	2685.2 ± 146.8	1564.2 ± 184.4
Fish seed	kg	160.6 ± 35.6	157.3 ± 21.3	177.6 ± 50.3
Rice seed	kg	6.7 ± 1		1.5 ± 0.1
Chicks	kg			31.7 ± 6.8
Fertilisers	kg	5345.2 ± 1114.3	1668 ± 744.8	1036.6 ± 272.8
Chemicals	kg	144.2 ± 24.2	190.1 ± 10.9	94.4 ± 31.2
Commercial fish feed	kg	1658.5 ± 245.4	1367.9 ± 252.9	626.5 ± 192.4
Homemade fish feed	kg	579.8 ± 223.4	177 ± 0	36.6 ± 17.9
Poultry feed	kg			15499.8 ± 4782.2
Electricity	kWh	324.4 ± 53	232.8 ± 55.9	1511.8 ± 228.2
Diesel	kg	14.3 ± 2.5		2981.8 ± 765.4
Outputs				
Mixed fish	kg	1000	1000	1000
Large fish	kg	920.4 ± 18.3	951.1 ± 11.3	974.5 ± 11.1
SIS fish	kg	79.6 ± 18.3	48.86 ± 11.3	25.5 ± 11.1
Poultry	kg			8406.5 ± 1376.7
Rice	kg	2222.2 ± 295.6		536.4 ± 102.3
Fruit and Vegetables	kg	1670.2 ± 487.7	502.2 ± 93.4	946.7 ± 140.6

6.2.2 Life Cycle Assessments

6.2.2.1 Goal and Scope definition

The primary goal of the LCAs performed in this chapter was to compare the environmental impacts of fish production at FO, RF and PF units to evaluate the overall performance of each farming system. The system boundaries were set as cradle to farmgate, and economic allocation was used at farm production level and for all other multifunctional processes included in the assessment. Three functional units (FU) were used in this chapter to capture the impacts of the studied food systems. The first FU was ‘1 tonne of mixed fish production’ which directly translates to the reference flow, i.e. the environmental impacts were assessed against 1 tonne of food.

The second FU used was ‘1 hectare of farmland production’. This FU was then combined with a nutrition metric by dividing the impacts by the PNA for the total production of all crops on 1 hectare. In practice, this nutritional-FU (n-FU) tells us the climate impacts of producing enough crops to provide a PNA score of 1, which essentially translates to the fulfilment of 4.5 peoples yearly RNI of the selected macro- and micro-nutrients included in the PNA calculation This is because the PNA score is relative to the proportion of people in a given population who are nourished, and the given population is one Bangladeshi household.

The third functional unit was another n-FU which was used to integrate nutrition into the LCA. The reference flow for this n-FU relates to the number of kilograms of fish required to fulfil 33% weekly RNIs of selected priority nutrients for the average adult in Bangladesh.

6.2.2.2 Nutritional-Life Cycle Assessment (n-LCA)

Building on the LCAs in the previous chapters, a nutritional life cycle assessment was carried out for each of the focal systems. The below equation shows how the nutrition metric (PNA) was integrated with the environmental impact assessment, i.e. results for each impact category were divided by the PNA score.

$$\text{Nutritional environmental impact score} = \frac{Impact\ score}{PNA\ score} \qquad [4]$$

Environmental impacts were also measured against the affordability and nutritional quality of each species within the systems. The affordability of each species produced in RF, FO and PF systems was determined using the affordability index outlined in chapter 2. Market price data and unskilled workers wage data were collected then used to calculate the number of hours which should be worked afford 100g of each species. The nutritional affordability was then calculated using the equation set out in Chapter 2.

Nutritional affordability, or the Average Share of Priority Nutrients (ASPN), relates to the price for the portion size (g) of fish needed to provide an average of one third of the weekly recommended intake (RNI) values for the 7 priority micronutrients (iron, zinc, calcium, iodine, vitamin A, vitamin B12 and vitamin D).

To combine the nutritional affordability with the environmental impact analysis, the amount (kg) of fish required to fulfil one third of weekly RNIs was calculated and climate change impacts (kg CO2 equivalents) were calculated for that amount. The environmental and economic cost for the amount of fish which provides one third of weekly RNIs for priority nutrients were plotted together in a ranking exercise below.

6.3 Results

6.3.1 Nutritional Performance

Two PNA scores were calculated for the systems studied in this chapter, firstly a full system production PNA score which includes all food items produced within the system, secondly a PNA score for only fish production (Figure 24). The experimental systems scored significantly higher PNA scores due to high contents of vitamin D found in tilapia during the nutrient composition analysis outlined in Chapter 3. Mean PNA scores for RF farms were significantly lower than most other systems, and out with the experimental systems, PF farms performed best.

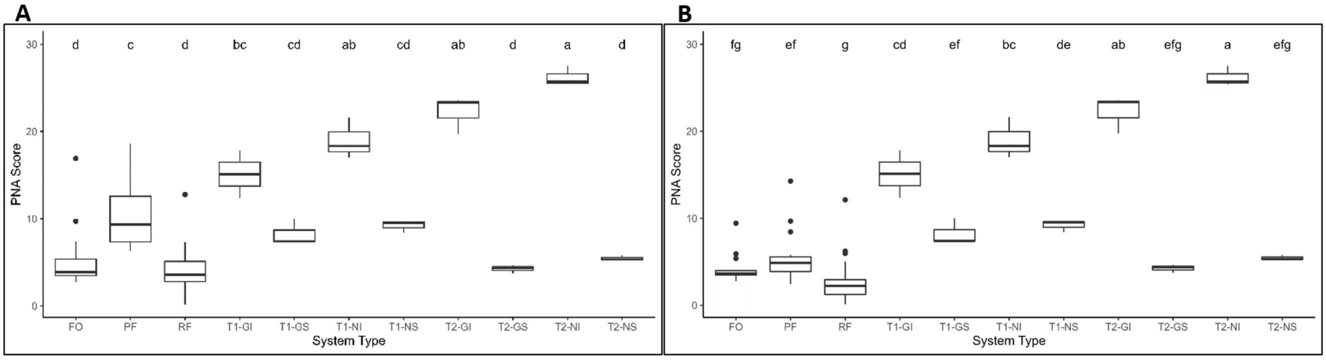


Figure 24. PNA scores for full production (A) and for fish production (B) at each system (boxplots show mean ± se). Columns with different superscripts above boxplot indicate significant differences ($p < 0.05$).

Assessing PNA at system-level allows comparison between the farms involved in this study. However, pond stocking rates across Bangladesh vary greatly and availability and affordability play a role in the species which farmers choose to stock. For this reason, and to compare nutritional quality between species, PNA scores were modelled for 1 tonne of each species found in this study (Table 42). The results are theoretical production volumes from 1 hectare of production, and it must be noted that producing 1 tonne of small indigenous fish species on 1 hectare of land may be unlikely. Nevertheless, these results allow the species to be ranked by nutritional quality. The top 3 PNA scores were small fish (*mola, darkina*, and *majhari* tilapia), followed by 3 large fish species including tilapia. As seen in chapter 3, tilapia nutrient contents varied between systems, so tilapia and majhari tilapia were separated by system type (FO and RF) for this analysis. *Majhari* tilapia produced in FO ponds had a higher PNA score compared to *majhari* produced in rice-fields, but large tilapia produced in rice-fields had higher PNA scores than tilapia from FO ponds.

Table 42. PNA scores for 1 tonne of production of commonly found species in aquaculture systems across Bangladesh. Nutrient contents for calculations were taken from literature sources (Annex 2) except tilapia where averages were taken from nutritional composition analysis results in chapter 3.

Species	**PNA**
mola	4.387
darkina	4.383
majhari tilapia (pond)	3.093
majhari tilapia (rice-fish)	2.675
sarputi	1.919
mrigal	1.726
tilapia (rice-fish)	1.686
puti	1.512
tilapia (pond)	1.244
tengra	0.930
bele	0.896
prawn	0.795
rui	0.678
channa	0.631
taki	0.631
shing	0.543
silver carp	0.499
common carp	0.473
Bata*	0.466
koi	0.463
catla	0.432
magur	0.279
pangas	0.171
ayere	0.164
bighead	0.144
Chitol*	0.132
shol	0.093
Pabda*	0.082
snakehead	0.080
grass carp*	0.028

*There were no available data for iodine content of bata, no data for vitamin D or iodine content of chitol, no data for vitamin D content of pabda, and no vitamin A or vitamin B12 content data for grass carp.

6.3.2 Life Cycle Assessment

6.3.2.1 Farming Systems

Life Cycle Assessments were performed for PF, FO and RF farms using two functional units, 1 tonne mixed fish and a score of 1 PNA as described in the methods section. Life Cycle Impact assessments for 1 tonne of mixed fish production at PF, FO and RF farms are presented in Table 43 and the contribution analysis in Figure 26.

Table 43. LCIA of the farming systems expressed as 1 tonne mixed fish production, using economic allocation.

Impact category	**Unit**	**1 tonne mixed fish**		
		PF	**FO**	**RF**
Water consumption	m3	780	276	164*
Land use	m2a crop eq	4.38E3	5.55E3	4.24E3*
Abiotic depletion	kg Sb eq	0.416	0.195	0.137*
Abiotic depletion (FF)	MJ	1.2E4*	1.38E4	1.22E4
Global warming	kg CO2 eq	968	1.12E3	952*
ODP	kg CFC-11 eq	1.04E-4	1.18E-4	1.03E-4*
Human toxicity	kg 1,4-DB eq	872*	1.12E3	999
Freshwater ecotox.	kg 1,4-DB eq	922	707	578*
Marine ecotoxicity	kg 1,4-DB eq	1.31E6	1.32E6	1.27E6*
Terrestrial ecotox.	kg 1,4-DB eq	87.5	53.8	27.9*
Photochemical ox.	kg C2H4 eq	0.558	0.56	0.409*
Acidification	kg SO2 eq	6.32*	7.84	6.97
Eutrophication	kg PO4--- eq	5.59	6.2	4.67*
GWP LUC	kg CO2 eq	1.04E3	468	273*

*Indicates lowest environmental impact in row.

Results of the environmental impact analysis per tonne mixed fish production shows RF farms had the lowest impact for 11 of the 14 impact categories, and PF farms were lowest for 3 impact categories. As seen from the contribution analysis in Figure 25, the overall impact is dominated by commercial fish and poultry feeds. At PF farms, commercials feeds contributed over 80% to every impact category, the only other notable impact hotspots were from electricity, which contributed 14%, 11%, 8% and 5% to abiotic depletion (FF), global warming, ozone depletion, and acidification respectively. At FO farms, fish feeds contributed over 39% to all impact categories, fertilisers contributed between 5% - 32% for all categories, fish seed contributed between 4% - 29%, and chemicals contributed between 0.07% - 21.5% to all impact categories. Similar to PF farms, electricity at FO farms contributed over 5% to abiotic depletion (FF), global warming, ozone depletion, and acidification. RF farms had a similar contribution trend to FO farms with feed contributing the most to all impact categories excluding land use, fertilisers having the second highest contributions and chemicals the third highest. Electricity at RF farms also contributed over 5% to abiotic depletion (FF), global warming, ozone depletion and acidification. The only other notable impact at RF farms was the use of diesel (fuel) which contributed 5% to ozone layer depletion.

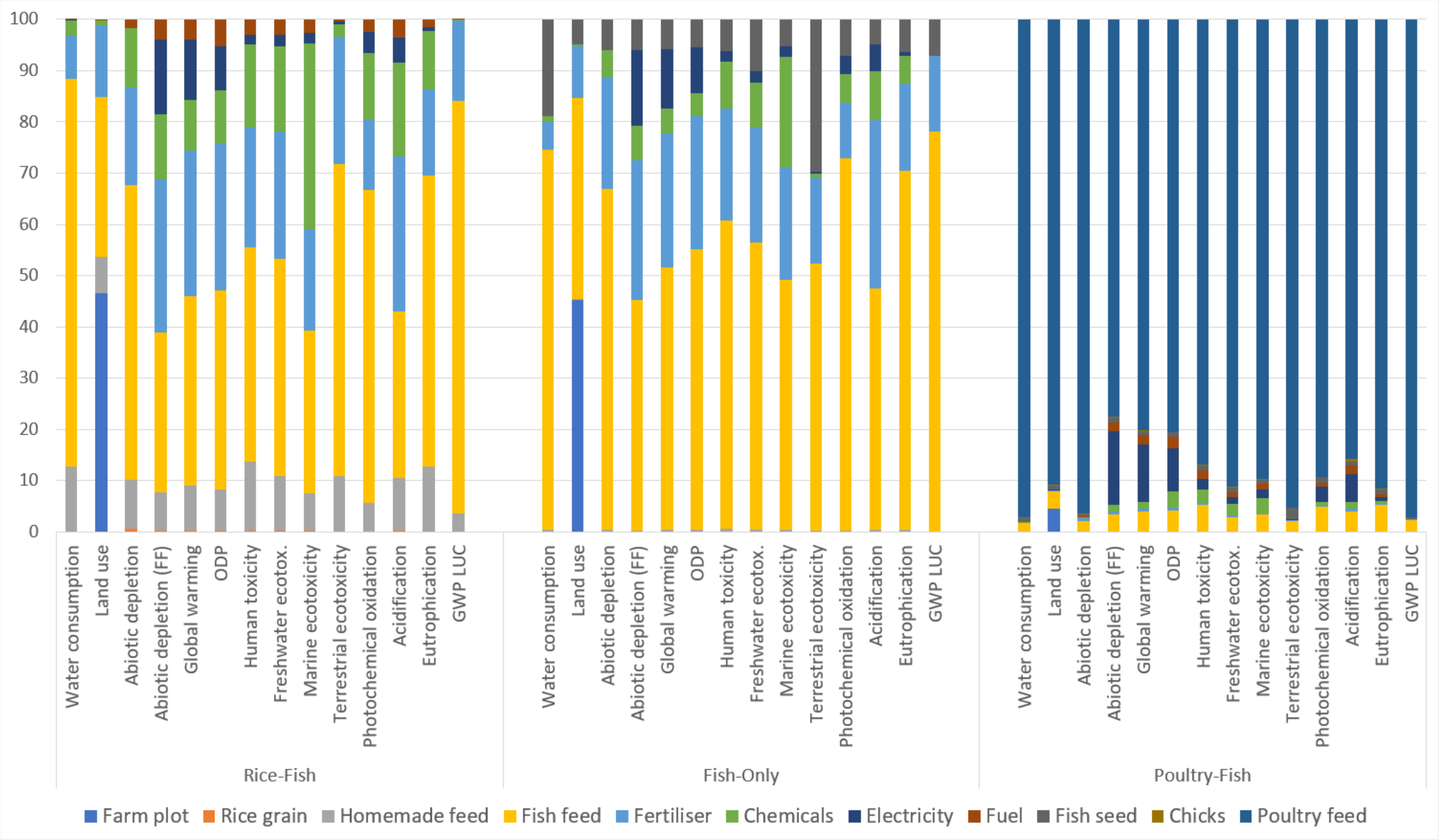


Figure 25. Contribution analysis to impact categories at farm for 1 tonne mixed fish production from RF, FO, and PF systems. Bars show the percentage of contribution.

Although PF farms use considerably less land, fish feed, fertilisers, and chemicals (Table 41) to produce 1 tonne of fish, they use considerably higher amounts of electricity and diesel, and use high levels of commercial poultry feeds. Since poultry encompasses the largest amount of production at these farms, birds are allocated the highest amount of impact resulting in environmental impact scores which look favourable for fish production at PF farms. However, when using 1 hectare as the reference unit and 1 PNA as the functional unit, the high use of energy and commercial feeds are clear. Table 44 presents the LCIA results for each system per hectare production, and per unit of PNA.

LCIA results for 1 hectare of production were divided by the PNA score for each system to integrate the nutritional quality into the environmental performance assessment. When PNA was integrated, the results changed so from FO farms performing best in 6 of the 13 categories, to performing best in 12 categories. PF farms performed worst for all impact categories before and after nutrition was integrated into the assessment.

Table 44. LCIA of different farming systems expressed as per hectare, and per PNA using 1 hectare as the reference flow (RF).

Impact category	**Unit**	**1 hectare**			**PNA**		
		PF	**FO**	**RF**	**PF**	**FO**	**RF**
Water consumption	m3	46988	1108	966.5	4432.8	201.5	235.7
Land use	m2a crop eq	264766.3	24198.3	65309.8	24978.0	4399.7	15929.2
Abiotic depletion	kg Sb eq	25	0.8	0.7	2.4	0.1	0.2
Abiotic depletion (FF)	MJ	712864.8	55790.1	61268.8	67251.4	10143.7	14943.6
Global warming	kg CO2 eq	57791	4499.1	4751.3	5452.0	818.0	1158.9
ODP	kg CFC-11 eq	0.00619	0.00047	0.00051	0.00058	0.00009	0.00012
Human toxicity	kg 1,4-DB eq	52244.3	4478.3	4949.6	4928.7	814.2	1207.2
Freshwater ecotox.	kg 1,4-DB eq	55383	2825.3	2986.1	5224.8	513.7	728.3
Terrestrial ecotox.	kg 1,4-DB eq	5250	216.1	191.4	495.3	39.3	46.7
Photochemical ox.	kg C2H4 eq	33.4	2.3	2.1	3.2	0.4	0.5
Acidification	kg SO2 eq	379	31.3	34.5	35.8	5.7	8.4
Eutrophication	kg PO4--- eq	334.8	24.8	23.3	31.6	4.5	5.7
GWP LUC	kg CO2 eq	62848.5	1875.4	1386.9	5929.1	341.0	338.3

Note: Total farm production PNA scores outlined in Table 18 in Chapter 3.

The relative environmental performance of each system before and after PNA scores were integrated are shown in Figure 26. The radar charts highlight the difference in performance between PF farms compared to FO and RF farms. PF farms had the highest PNA score due to the high fish yields and high poultry production which contributed to increased protein, energy, fat, and zinc (Chapter 3). The higher PNA score for PF farms mean that the LCIA results improved slightly and took up less area on radar chart B than in chart A, however FO and RF farms were still significantly better performers for all impact categories. As seen from the radar charts, FO farms improved more than RF farms when PNA was integrated due to FO farms having a high PNA score. FO farms had higher levels of protein, iron, calcium, vitamin B12, vitamin A, iodine and vitamin D compared to RF farms which explains the higher PNA score and therefore the improved environmental performance. The radar charts are unevenly distributed, with peaks exposing a problem category for FO and RF farms compared to PF farms, i.e., land use. Since PF farms have poultry sheds on pillars above the ponds, farm the fish intensively, and grow fruits and vegetables around the pond area, the land is used more efficiently than the extensive rice-fish farming systems or fish-only farms.

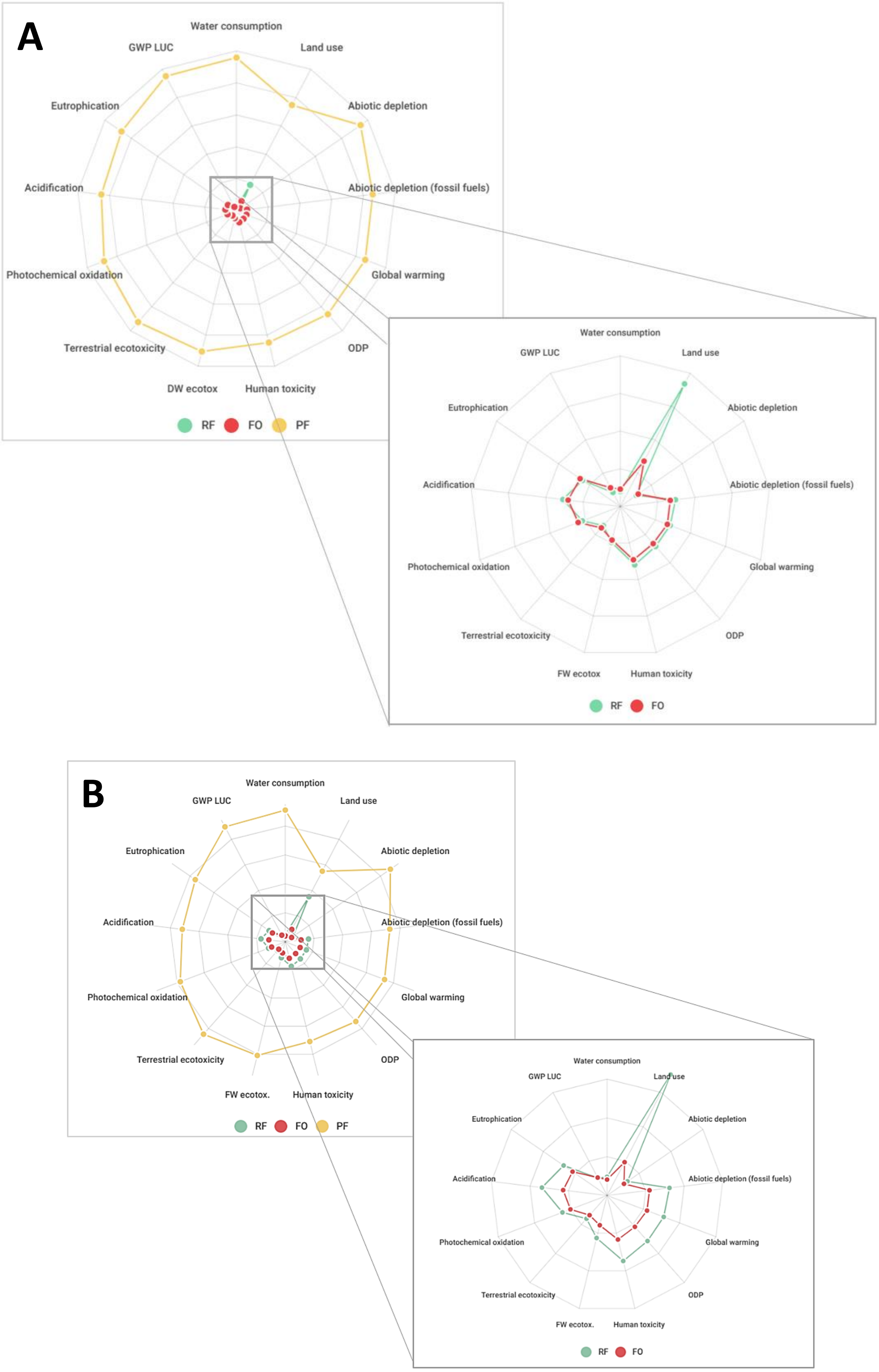


Figure 26. Radar charts showing the impact indicators as relative values for 1 hectare of farm production (A), and per unit PNA (B).

6.3.2.2 Experimental Systems

LCIA results for the experimental systems were also combined with the total farm production PNA scores and results are presented in Table 45. T1-GI performs best for 5 impact categories, T1-GS performed best for 4 categories, T2-NI for 3 categories, and T2-NS for 2 categories. T2-GS performed worst for 11 out of 13 categories but performed relatively better for GWP LUC and eutrophication compared to the other treatments. Soybean meal used in the commercial fish feed was a big contributor to GWP LUC and eutrophication, and since the semi-intensive systems were not fed commercial pellets, these systems performed better for GWP LUC and eutrophication. For similar reasons T2-NS performed best for GWP LUC and terrestrial ecotoxicity as no commercial pellets were fed, and since the fish were mixed sex, the hatchery did not use an in-feed hormone treatment which also has a significant contribution to terrestrial ecotoxicity.

Although T2-NI performed best for just 3 categories, the results for the majority of the other 10 categories were within close range to the best performing systems. This is due to T2-NI having the highest PNA score. While T2-NI had relatively higher inputs, integrating such a significantly higher PNA score meant the system still had a competitive environmental performance.

When comparing the results with the FO, and RF farming systems (excluding PF), the farming systems perform relatively similarly for all impact categories. However, in general, the farming systems perform better for water consumption and the experimental systems generally perform better for land use. However, this is due to the water consumption data at the farming systems not being as detailed as the data from the experimental systems. Water consumption at the experimental systems included water consumed at input stage, such as for feeds, and the evaporation from ponds, whereas for the farming systems only the consumed water for inputs were included in the LCIA. When comparing all farm and experimental systems, PF farms performed worst for all impact categories except water consumption, however this is likely again attributed to the inequalities in water use data.

Table 45. LCIA of the experimental farming systems expressed as unit PNA, i.e. 1 hectare of production divided by total farm production PNA score, using economic allocation.

Impact category	**Unit**	**T1-GI**	**T1-NI**	**T1-GS**	**T1-NS**	**T2-GI**	**T2-NI**	**T2-GS**	**T2-NS**
Water consumption	m3	2316.64	1940.61	3847.84	3548.72	1200.30	1055.19*	7604.1ˆ	3797.34
Land use	m2a crop eq	3406.96	3559.19	2219.69*	2514.88	3481.05	3308.67	4386.5ˆ	2998.87
Abiotic depletion	kg Sb eq	0.16*	0.17	0.16*	0.18	0.18	0.18	0.31ˆ	0.29
Abiotic depletion (FF)	MJ	9127.38	9596.23	13129.52	13746.51	9113.25	8915.17*	25946.4ˆ	18960.89
Global warming	kg CO2 eq	789.06*	841.33	893.35	957.06	828.76	806.06	1765.4ˆ	1286.39
ODP	kg CFC-11 eq	1.19E-4	1.18E-4	1.59E-4	1.59E-4	1.01E-4	9.7E-5*	3.14E-4ˆ	1.73E-4
Human toxicity	kg 1,4-DB eq	846.69*	928.47	872.82	940.56	956.72	921.58	1724.9ˆ	1192.55
Freshwater ecotox.	kg 1,4-DB eq	530.66*	584.25	537.89	611.67	560.25	544.82	1063ˆ	716.59
Terrestrial ecotoxicity	kg 1,4-DB eq	50.16	55.94	32.37	50.05	39.02	39.70	64ˆ	19.90*
PO	kg C2H4 eq	0.49	0.54	0.29*	0.35	0.58	0.56	0.6ˆ	0.36
Acidification	kg SO2 eq	4.90*	5.28	5.78	6.12	5.27	5.10	11.4ˆ	8.31
Eutrophication	kg PO4--- eq	5.04	5.64	2.37*	2.99	6.07ˆ	5.84	4.7	2.90
GWP LUC	kg CO2 eq	408.59	462.72	76.40	136.62	507.05ˆ	488.28	151	47.28*

Note: Total farm production PNA scores outlined in Table 17 in Chapter 3.
PO is photochemical oxidation, abiotic depletion (FF) is abiotic depletion fossil fuels.
*Indicates best score in row.
ˆ Indicates worst in row.

6.3.2.3 Species Level Performance Assessment

In addition to the system-level impacts described above, species-level impacts were evaluated. The top 20 species produced within the three farming systems were assessed using the number of kilograms of fish required to fulfil an average of 33% weekly RNIs of selected priority nutrients for the average adult in Bangladesh as the functional unit and using economic allocation to deal with the multifunctionality of the systems.

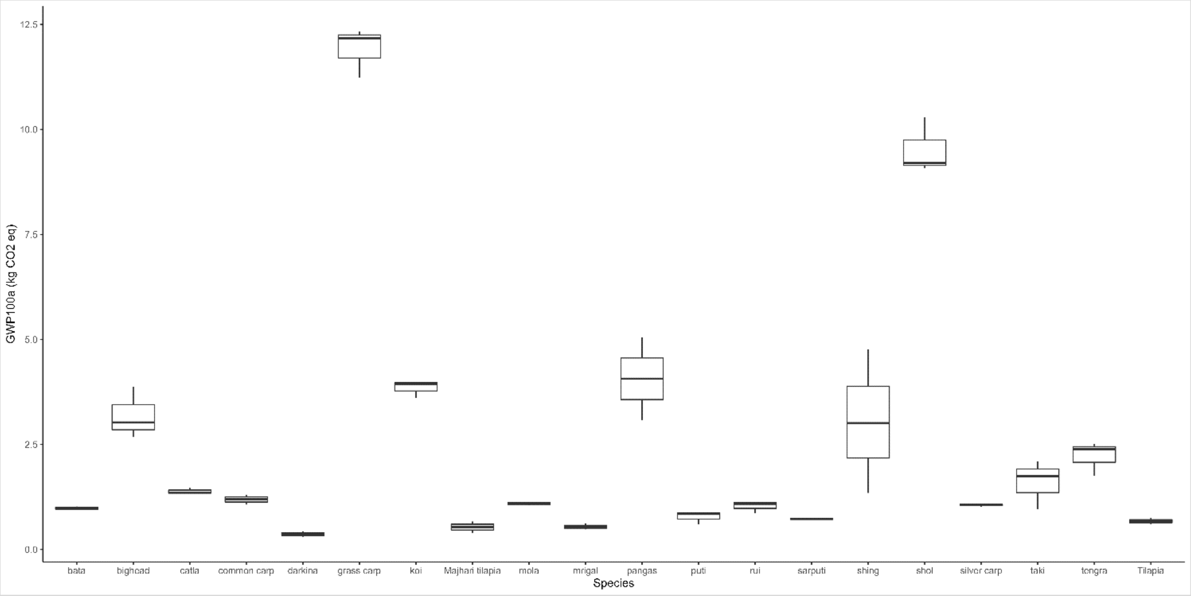


Figure 27. Global warming potential (CO2 eq) of producing enough fish to fulfil 33% of an adult's weekly RNIs for selected priority nutrients. Presented as means ± SE between systems (RF, FO, and PF). *Data for vitamin A and B12 was not available for grass carp and so the results for grass carp are likely to change when this data becomes available.

Figure 27 shows the global warming potential from producing enough kilograms of each species to fulfil an average of 33% weekly RNIs of the selected priority nutrients. The boxplots and whiskers show the mean and standard errors between system types. Global warming potential varies little for the majority of the 20 species with the exception of *bighead, grass carp, pangas, shing, shol*, and *taki*. For this reason, the ranking exercise in figure 6 has used the mean GWP results across the three systems, however the separated bubble charts for each system can be seen in Annex 1. Figure 29 shows the number of hours the average unskilled worker in Bangladesh must work to afford the amount (kg) of each species which fulfils an average of 33% of their weekly RNIs for selected priority nutrients (iron, zinc, calcium, iodine, vitamin A, vitamin B12 and vitamin D).
Although the vitamin A and vitamin B12 content of grass carp was unknown (and hence assumed 0 in the calculations), the species was still included in the analysis since it is an important farmed species in Bangladesh, and it serves as an example of how the environmental performance and affordability is impacted when nutrition is considered for a species with low nutritional value, albeit hypothetically low in this case.

As expected, there is a clear trend seen in Figure 28 which shows fish species which can fulfil an average of 33% of weekly RNIs for the priority nutrients with smaller portions have a lower environmental impact and therefore provide more affordable nutrition. Surprisingly, of the top 5 species ranked in Figure 29, three are large fish species and two are small fish, with *majhari* tilapia and tilapia in second and fourth place respectively. *Darkina* can provide an average of 33% of the weekly RNIs at the most affordable price and with the lowest global warming impact. Generally, species which require less kilograms to provide the necessary nutrients have the lowest impact and are most affordable, with some exceptions for example koi and *tengra*. Excluding *grass carp, shol* is the most expensive species in terms of nutritional affordability and has the highest environmental impact, this is due to the comparably low contents of iron, vitamin B12 and D, and the absence of detectable levels of vitamin A and iodine.

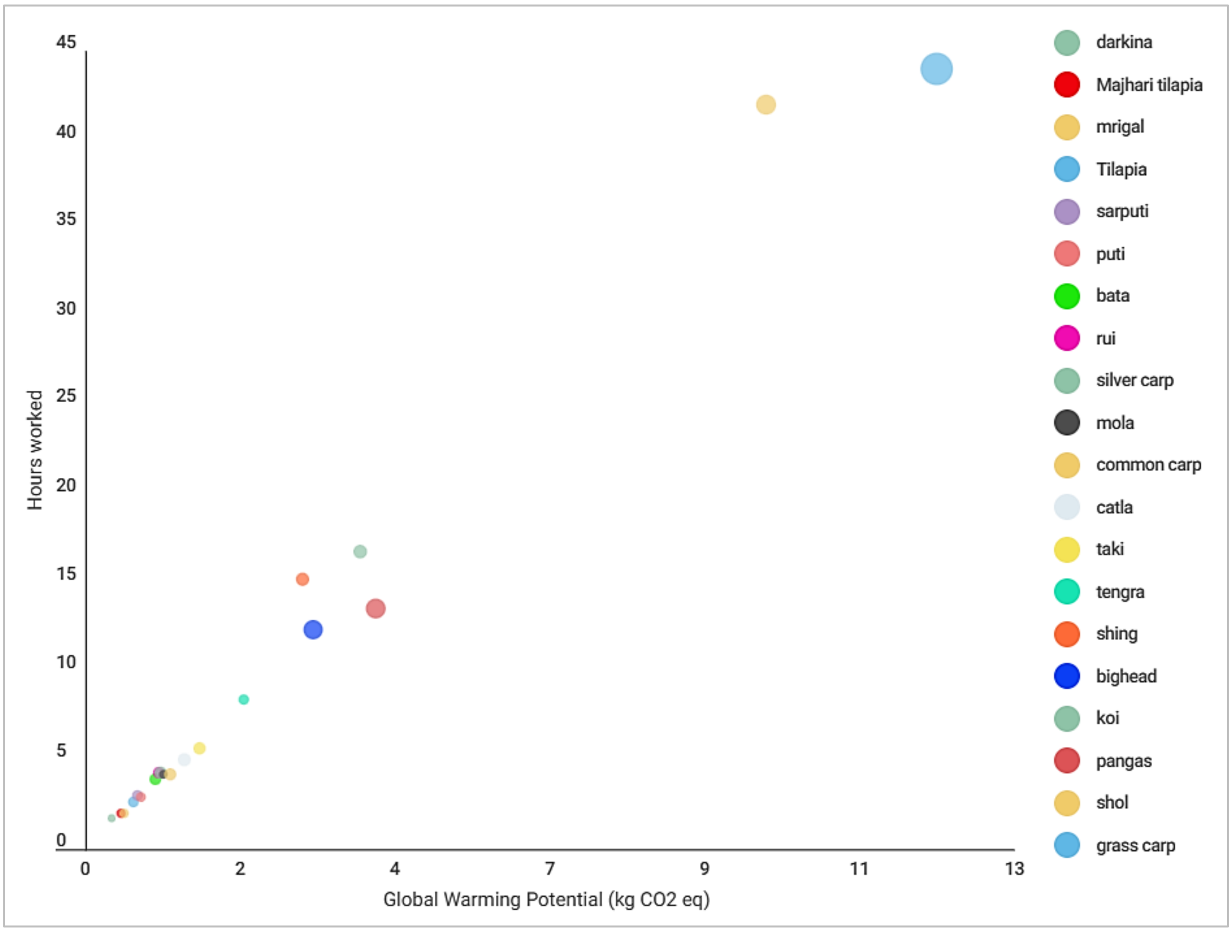


Figure 28. Mean nutritional affordability and mean environmental performance of various fish species in Bangladesh. Nutritional affordability is measured as the hours worked to earn the necessary amount of money to purchase the required kg of fish which fulfils 33% weekly RNIs of the selected priority nutrients for the average adult in Bangladesh. Mean environmental impact is measured as the global warming potential of producing the required kg to fulfil 33% weekly RNIs of the selected priority nutrients. Size of bubble represents the amount of kg required to fulfil the RNIs. Legend is in order from lowest to highest global warming potential.
* Note: there were no available data for iodine content of bata and no vitamin A or vitamin B12 content data for grass carp.

6.4 Discussion

Using a population specific and system-level nutrition metric has allowed the environmental and nutritional performances to be combined. Previous life cycle assessments of integrated aquaculture-agriculture systems have used various function units, such as unit area (Hu et al., 2021), kilocalorie of total farm output (Phong et al., 2011), kg of total farm production (Paramesh et al., 2019), 1 tonne fish production (Kluts et al., 2012) and nutrition density units (Xu et al., 2022). This study has assessed the environmental and nutritional performance of the focal systems studied throughout this thesis and results have shown nutritional quality influences the outcomes of life cycle assessments, i.e. environmental performance can vary when a nutrient quality index is combined.

From the results of the integrated LCIAs, it is evident that poultry-fish farms are poor performing systems compared to fishponds and rice-fish fields. The average feed conversion ratios for poultry in this study was 1.8 which is standard for broiler chickens and within the range of recent broiler chicken studies in Bangladesh (Islam et al., 2022; Rudra et al., 2018). Although the FCR was within the standard ranges it is clear from this study commercial feed use is an environmental hotspot. To overcome the issues related to animal production specific attention should be given to all types of animal feeds, especially fish and poultry. In recent years there has been progress made in this regard as alternative protein sources for animal feeds have been identified such as insect meal, microalgae, and single-cell proteins. However, farmers also need to play their part in feed management by adopting sustainable feeding practices, ensuring to use appropriate feeds, avoiding over-feeding and feed spoilage, and minimising waste.

Recently, there has been concerns regarding the food safety and public health issues surrounding poultry-fish farming. As the poultry faeces enter the fishponds, there is the risk of adverse changes to the pond environment which can impact fish health, and ultimately human health. For example, the high loads of heavy metals used in poultry feeds are often excreted and enter water bodies, resulting in heavy metal concentrations in the water which are above acceptable limits (Oyewale et al., 2019). Additionally, intestinal pathogens may pass from poultry to fish and then onto humans (Adeyemi et al., 2022). Although results favour the performance of PF systems, further research is required to fully understand the food safety aspect of these systems.

Although poultry-fish farms had a significantly higher nutritional quality, the environmental impact and various food safety concerns may result in this system appearing unfavourable. This study has shed light on the trade-offs between the environmental and nutritional dimensions of PF systems and demonstrated how these dimensions can be assessed in combination. Further assessments of poultry-fish systems are required to fully understand the social and economic impacts arising of such systems, and more research is required which examines human and animal health and welfare impacts of PF farming.

Adopting an appropriate functional unit is key to a representative life cycle assessment (Henriksson et al., 2012). The FU should describe the function of the product under question and should be interpretable. The use of appropriate functional units to integrate nutrition and affordability into life cycle assessments in this study have shown two species of small fish, *darkina*, and *majhari* tilapia, are alongside three large species, tilapia, *mrigal* and *sarputi* in the top 5 most affordable and sustainable sources of nutrition. These results have major policy-making implications as previous research has focussed on increasing *mola* production in Bangladesh as a way of addressing micronutrient deficiencies (Castine et al., 2017; Karim et al., 2017; Kongsbak et al., 2008), and although *mola* is the most nutritious fish as per results in Table 42, there are clearly more affordable sources of micronutrients which are significant to the Bangladeshi population. Attempts have been made to identify the fish production system in Bangladesh with the highest nutritional quality (Bogard et al., 2018) and lowest environmental impact (Shepon et al., 2020), yet the affordability of the aquatic systems have been overlooked. High food prices are known to be significant barriers in increasing fish consumption in Bangladesh (Rahman and Islam, 2020) so identifying affordable fish species and increasing availability and accessibility is an important step in addressing malnutrition in a country like Bangladesh where fish is an vital part of the diet. Tilapia has a negative reputation within the literature as it is seen as having a relatively low nutritional quality and high environmental impact (Hallström et al., 2019; Robinson et al., 2022a). However, addressing issues related to the use of secondary data, this study collected primary data from a variety of tilapia systems across Bangladesh and showed the nutrient content and farm production data was integral in accurately assessing the performance of tilapia production systems.

Future studies should consider using the results in this thesis, which have identified highly nutritious and affordable small and large fish species, alongside national production yield data to develop model production systems which limit the environmental impacts while maximising nutritional output. It is likely tilapia would play a role in such a system considering the nutritional affordability, high production yields and overall versatility of this species.

There are various policy implications from this research, mainly surrounding the promotion and management of fish production systems in Bangladesh. From the results there are clear environmental impact hotspots which should be addressed, primarily commercial feeds.

Feed companies and farmers should prioritise feed management strategies which limit environmental impacts, however until these strategies are enforced, private companies are unlikely to adopt them. Government intervention is required to set standards and monitor adherence to such standards. Additionally, the most and least affordable source of nutrition has been identified here and as such, organisations should aim to use these results when taking a nutrition-sensitive approach to food systems interventions. For example, when promoting small fish production in Bangladesh, *darkina* should be considered alongside *mola* since *darkina* provides significantly more affordable nutrition.

Chapter 7

Discussion

7.1 Introduction

The ultimate goal of this thesis was to assess the nutritional and environmental performance of tilapia production systems in Bangladesh. To do this, tilapia nutrient contents were analysed and described, and results have empirically shown tilapia composition is influenced by system type, seasonality, fish feed type and tilapia product form. The results in this thesis demonstrate tilapia is an affordable source is essential nutrients in Bangladesh, and the environmental performance of tilapia varies considerably depending on the systems in which the fish are raised. This is an important finding for policy and decision makers since tilapia is often regarded as a relatively poor performer in terms of nutritional quality and environmental sustainability (Crona et al., 2023; Gephart et al., 2021). Tilapia provides more affordable nutrition, with a lower environmental impact, than all other species assessed in chapter 6 except the local species *darkina*, which is a small indigenous species and *mrigal,* a widely cultured Indian Major carp. This chapter will summarise the main results of the thesis, discuss their relevance to the broader literature and policy implications, describe the strengths and weaknesses of this research, and make suggestions for future research.

7.2 Summary and Significance of Research

Nutritional-LCA methodology has received significant attention in the food systems discourse in recent years and this research has built upon previous work. However, this is the first time the Potential Nutrient Adequacy metric has been used as a nutritional functional unit for in-depth life cycle assessments of aquaculture and integrated agriculture-aquaculture systems. Additionally, this is the first time the environmental impacts of fish in Bangladesh have been assessed using a n-FU combined with affordability. This thesis helps advance the n-LCA literature and echoes the warnings of others that the choice of the functional unit for LCA can have significant impacts on the results (Bohnes and Laurent, 2019; Henriksson et al., 2012; Saarinen et al., 2017).

The outcomes of chapter 3 show that farming and harvesting methods significantly influence the nutritional profile of tilapia as some techniques encourage the harvesting of small tilapias. It is well-known juvenile tilapias are often consumed (Haque, 2007), and they are usually eaten whole excluding viscera and jaw/head. Bogard et al. (2015) recognised the nutrient content differences between adult and juvenile (*majhari*) tilapias there but there have not been any studies which assess the consumption rates or the differences in nutritional quality of the two product forms. The results of chapters 3, 4 and 5 addressed this as the nutritional differences between large and small tilapias were described in chapter 3, whereby juvenile tilapias contain significantly higher levels of calcium, iron, and zinc (chapter 3). In chapter 4 it was shown that the nutritional yields of systems producing various amounts of small and large tilapias varied considerably and was dependant on the farming intensity, and chapter 5 showed 89% of households involved in the survey confirmed they eat the bones of small tilapia, likely contributing to nutritional security.

An important finding in chapter 4 was the clear economic and nutritional benefits of producing tilapia under intensive conditions. Although it was demonstrated in chapter 4 that semi-intensive systems generate lower environmental impacts, the improved environmental performance of intensive systems was recognised when PNA was integrated into the assessment as the functional unit (chapter 6). The intensively managed experimental systems went from performing best in 2 of the environmental impact categories, to performing best in 8. Similarly, rice-fish (extensive farming system) and fish-only (considered semi-intensive/ intensive) systems in Northwest Bangladesh were assessed and results showed that tilapia produced in rice-fish (RF) systems performed better in terms of environmental impacts compared to in fish-only (FO) systems, however when the nutrition metric was integrated into the assessment (chapter 6), FO farms out-performed RF farms. RF and FO farming households were found to be food and nutrition secure, but it should be noted that many of the households that were involved in the study mentioned their food security struggles during the latter part of the year, suggesting seasonality plays a role in food and nutrition security for all households. Future food and nutrition security assessments should aim to survey households a minimum of twice per year to avoid such skewed results.

Results from chapters 4,5 and 6 show the environmental impacts from tilapia production are highly dependent on farm management techniques, mainly the intensity of farming. Results show the experimental systems farmed at a higher intensity have similar or, in some instances, improved environmental performance after combining nutrition with LCA (Chapter 6). Tilapia is one of the most affordable sources of essential micronutrients in Bangladesh (Chapter 6). These results indicate that sustainable intensification of tilapia aquaculture could improve access to affordable nutrition without negatively impacting the environment, contributing to three of the UN Sustainable Development Goals (United Nations, 2015), namely zero hunger (SDG 2), responsible consumption and production (SDG 12), and climate action (SDG 13). In the past, researchers have been criticised for taking a productionist perspective when applying SDG 2 to their studies (Blesh et al., 2019), whereas this thesis has identified a pathway to realising SDG 2 through a food systems lens and taking all stages of the food system into account, with a focus on local diets and population specific nutrition metrics.

Another significant finding from chapter 4 was the identification of productivity and profitability differences between GIFT and non-GIFT strains of tilapia. The GIFT fish performed similarly to the other non-GIFT strain in Trial 1, which is unsurprising since the are both genetically improved strains. However, the non-GIFT strain in Trial 2, which was a local strain, performed best in terms of productivity when compared to the other 3 strains used throughout the two trials. This is somewhat contradictory to results found elsewhere in the literature which show GIFT and other improved strains to be better than local or unimproved strains in Bangladesh. These results in this chapter have important policy implications. Genetic improvement programs need to be well-informed and, through showcasing these performance differences, it is clear further information is required for future tilapia genetic improvement programs. Although GIFT was seen to have a comparable FCR to the other strains, future-proofing the use of GIFT in Bangladesh will depend on many factors, such as supporting the adoption of the most up-to-date generation of GIFT by farmers and further investigations into the types of farming systems GIFT are being produced and tailoring GIFT to the needs of those farms.

Increasing the availability and affordability of nutritious foods across Bangladesh is a recognised impact pathway for addressing various issues with the Bangladeshi food system

(GAIN, 2020). Since this thesis has demonstrated tilapia is an affordable source of nutrition, increasing funding aimed at the sustainable intensification of tilapia production is an action which can contribute to this impact pathway by improving access to nutrient-rich fish. Sustainable intensification describes a targeted approach designed to increase production while improving the environmental sustainability of the production system (FAO, 2017). There are various ways tilapia production systems can be sustainably intensified, for example, diversifying production, appropriately integrating aquaculture and agriculture, increasing the availability, affordability and adoption of high-quality, fast-growing tilapia seed, and improving overall farm management including water, feed, and fertiliser management (FAO, 2013). Sustainable intensification is seen as a way of improving production with existing resources, however this approach does not always address other issues existing within the food system (Cook et al., 2015) such as unequal access to food and nutrition, food waste and losses, and the ongoing monopoly of agro-businesses within the global food system. Food system transformations are required at every level, from smallholder farms to multinational companies, with the latter expected to shoulder the biggest burdens.

Results from this thesis show farm management is highly linked to the environmental performance since feed and fertiliser use were key hotspots for the majority of impact categories. Improving feed management strategies and production techniques is therefore crucial in reducing the environmental impacts of fish farms in Bangladesh. Knowledge sharing, farmer training programmes, and governmental policies are therefore key strategies in achieving sustainable food systems in Bangladesh. Additionally, feed manufacturers should take targeted approaches to reduce the environmental impacts of fish and poultry feed production. To drive this, policies should be implemented which push feed manufacturers towards sustainably certified, ethically sourced, and nutritious feed ingredients, and which encourage businesses to invest in the exploration of alternative protein sources for animal feeds in Bangladesh.

Tilapia can fulfil an average of one third of recommended nutrient intakes for 7 essential micronutrients at least cost to the consumer and lower environmental impacts than 80% of the other 19 cultured species which were assessed (chapter 6). Therefore, it is clear tilapia is one of the key species contributing to sustainable food and nutrition security in Bangladesh.

According to the law of demand, the low market price is a contributing factor to the success of tilapia (Nicholson and Snyder, 2012). This economic theory states that product price and product quantity flow in opposite directions, in other words, when a product has a low price there is high demand and supply, but if the product has a high price, there is low demand. This may explain why tilapia has maintained a low price and a high demand for a long period of time compared to other fish products in Bangladeshi markets. *Mola*, which is shown to be more nutrient-rich than tilapia (Table 43), is high in price and has significantly lower production values. Although *mola* is a commonly consumed fish, there has been little improvements made within the *mola* aquaculture sector. Researchers have promoted *mola* as a way of addressing malnutrition in Bangladesh for many years (Castine et al., 2017; Kongsbak et al., 2008; Roos et al., 2007b; Thilsted and Wahab, 2014), and effort has been made to understand the optimal conditions for *mola* culture (Ali et al., 2016; Karim et al., 2017). The biology, distribution, breeding and rearing requirements have been defined (Rajts and Shelley, 2020) and the profitability of *mola* produced in polycultures has been recognised (Karim et al., 2017), however there has not been any scaling up of mola farming as yet. Improvements in *mola* aquaculture may lead to increased availability of *mola* in markets, and possibly lower market prices once supply/demand is high enough. Alternatively, *darkina* is another small indigenous fish species which provides similar levels of nutrition at lower cost. *Darkina* is the most affordable source of nutrition (Table 43) and has the lowest environmental impact compared to all other 19 species assessed in chapter 6 (Figure 27). For this reason, and since *mola* is not yet an affordable species, *darkina* should also be considered for promotion in Bangladesh. Upon realising the very high levels of vitamin A in *mola*, many organisations, including WorldFish which are a highly influential institution in Bangladesh, began promoting *mola* and invested into the development of *mola* aquaculture. Now *darkina* has been highlighted in this study as an affordable, nutritious, and sustainable species which is commonly consumed, similar investment should be applied to the research, and possible development of *darkina* culture and marketing. Additionally, *mrigal* was found to be a sustainable and affordable source of nutrition too and emphasising mrigal culture alongside darkina, tilapia and several other nutrient-rich, affordable species could transform pond polyculture. Further research should be conducted to identify the combination of species which can provide the highest nutritional quality with the lowest environmental impact.

Multiple dimensions of the food and nutrition system were analysed throughout this study and the trade-offs between the nutritional, environmental and socio-economic impacts of fish production systems were assessed. Fish species which have the lowest environmental impact and highest nutritional quality, and which are also the most affordable, have been identified however there are many other factors which influence farming decisions and food consumption behaviours. The results in chapter 5 showed the differences between farm incomes at rice-fish, fish-only and mono-rice farms, with mono-rice farms generating the lowest incomes. Although adopting rice-fish culture in rice paddies may improve the farm profitability and nutritional quality, there are other considerations smallholder farmers take into account such as the time and investments needed for fish culture and access to markets. Promotion of rice-fish co-culture, whether it is alternate or concurrent co-culture should address the adoption constraints for poorer farmers. Similarly, poultry-fish co-culture could be another avenue for sustainable intensification of tilapia production systems in Bangladesh as fish production was high in these systems, however there are various environmental and food safety concerns surrounding poultry-fish farming which requires more investigation before these systems are truly sustainable. Further research is urgently required to identify the barriers, opportunities, and environmental and health concerns of integrated agriculture-aquaculture systems in Bangladesh if sustainable intensification is to be made possible.

Fish production and consumption values have increased steadily over the years and food and nutrition security have slowly progressed, however the food system in Bangladesh still fails to deliver the essential micronutrients required to overcome the issues of malnutrition. Studies have suggested aquaculture does not provide enough essential micronutrients to overcome documented nutritional deficiencies when moving from wild-caught fish consumption to farmed fish consumption (Bogard et al., 2017a), but utilising the results in this study could help identify appropriate strategies which can deliver high levels of essential nutrients in an affordable and sustainable way. For example, one nutrition-sensitive strategy could be to stock hatchery dependent, nutritious fish like *mriga*l alongside SIS such as *mola* and *darkina* into systems where tilapia free-breed, or in areas where tilapia are self-recruiting into ponds during flooding.

7.3 Strengths and Limitations

Although this study has put a major emphasis on using rigorous, primary data collected during field visits, a limitation of this study lies within the use of secondary data on population specific nutrient deficiencies. The ICDDR,B are a highly-reputable institution and most data used to identify nutrients of significance within the Bangladeshi population have come from studies and reports by the ICDDR,B. Additionally, it is generally well-understood which nutrients are deficient in certain populations, however documenting deficiency levels at gender, age and wealth group would be highly beneficial for food and nutrition security studies. These data are difficult to collect, and often require specific medical training for biomarker sampling. This was out of the scope of this study, but investments are needed to collect biomarker data on micronutrient levels for all population types.

The strengths of this research lie in the collection of high-quality data which has allowed a detailed analysis of the nutritional and environmental performance of fish production systems across Bangladesh. Secondary data taken from quality resources such as Henriksson et al. (2014) and Bogard et al. (2015) alongside large amounts of primary data collected during fieldwork exercises has enabled complex calculations which offer a new insights into the nutritional affordability and environmental performance of various fish species produced under varying conditions. Recently published, similar studies (Robinson et al., 2022a; Shepon et al., 2021) utilise the same high quality literature however no other studies have collected primary nutrient content, LCI and market price data.

One of the major issues with life cycle assessment is the use of secondary data and the uncertainties which arise from this practice. Data collection is a major part of any LCA and obtaining high quality, primary and secondary data is important for understanding environmental impacts of food producers. By collecting data from experimental systems which were run in triplicate, whilst collecting data from numerous farms allowed more emphasis to be place on inter- and intra-farm variations. Being able to compare farms, and trials, provides a more rigorous method of comparing LCIAs compared to using single data points or ranges estimated derived from Monte Carlo analyses (McAuliffe, 2018).

Through using LCA methodology, ecological functional trait metrics and food and nutrition indicators, this study has identified fish species which have low environmental impacts, high nutritional quality and which are affordable. The methodologies used and results in this thesis bridge the gap between two fields of research which are indisputably linked and offer an essential evaluation of important food systems in Bangladesh.

Although this study aimed to use the most relevant nutrition metric to the population of interest, non-nutrients were disregarded in the analysis. The reason behind this is because the life cycle assessment functional unit should define the function of the product, which is to provide nutrition to humans and non-nutrients were not considered to be the primary function. However, when addressing malnutrition in Bangladesh, where obesity is on the rise, careful consideration of the non-nutrient content should be given to the foods which are being promoted as nutritious.

Although the focus of this thesis was on tilapia and nutrient content of different tilapias were assessed appropriately, large parts of this thesis were dependent on book values for nutritional compositions of other species. The values taken from the literature were mainly from one high quality source which analysed fish within Bangladesh (Bogard et al., 2015), which should be the case, however it is clear from this study that nutrient contents vary under different conditions and obtaining high quality, real-time data would benefit nutritional performance assessments.

7.4 Future Research

As seen from this study, rigorous, up-to-date data is critical in food system assessments. Currently, fish nutrient composition data is lacking within the literature as is accurate edible yield data for fish species consumed in different ways across different cultures. Nutrient content and edible yields play a huge role in determining the nutritional value of a food source so future research should aim to determine and analyse these important traits.

The methodology used in this thesis aimed to give a holistic sustainability evaluation using interdisciplinary research methods. Further work identifying appropriate indicators and metrics for use in these types of evaluations would be beneficial for future assessments. Ecological trait indicators and/or other environmental impact categories may offer new insights which have not yet been discussed in the current literature.

For future LCAs, higher quality data which is representative of different regions and life cycle stages is beneficial. More data is required on the post-farmgate side of the life cycle, i.e. processing, retailing, consumption and food loss and waste. Improving the background data for LCAs is a constant requirement and research aiming to contribute to this would be welcomed.

Finally, future undertakings of n-LCAs should utilise both old and new indicators as this is a novel field of study. Trialling new methodologies and disseminating n-LCA results will help overcome the current issues surrounding methodology and will enhance the field of research.

7.5 Concluding Remarks

This thesis provides important insights into Life Cycle Assessments methodology and the current state-of-art of tilapia farming systems across Bangladesh. Moreover, the framing of the results within the broader food systems literature shows the complexity of food systems assessments. It is clear from the literature that alternative methods for assessing food systems are needed, and Life Cycle Assessment should be considered as a one of the tools to be used. Interdisciplinary research is required which combines the best methods for assessment will enhance food system performance assessments, for example Life Cycle Assessments can be performed alongside value chain assessments, complex computer-based food system models or remotely sensed environmental data linked with population health.

Looking forward, assessments which consider the whole food environment are urgently required. Although food systems assessments at farm and sub-national level are lacking within the literature, it is imperative that large agro-businesses, which hold power over small- and medium- enterprises and smallholders, are included within the assessments. Farm-level interventions which aim to improve the environmental sustainability and nutritional quality of food systems will be better equipped to meet their targets if policies are in place which hold those in power to account.

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Annex 1. Nutrient content for all fish, crop and bird species involved in the nutritional quality analysis for this research.

Species	Scientific name	Type	epc	energy_kj	protein_g	fat_g	iron_mg	zinc_mg	calcium_mg	vb12_ug	vatotal_ugrae	VitD_ug	Iodine_ug	Data sources
tilapia (pond)	Oreochromis niloticus	large fish	0.83	390	18.6	1.4	1.02	0.82	35	2.48	0.82	32.65	1.97	Own data
tilapia (rice-fish)	Oreochromis niloticus	large fish	0.83	390	18.3	1.1	2.78	0.89	90	2.48	0.62	32.65	2.5	Own data
rui	Labeo rohita	large fish	0.83	422	18.2	3.0	0.98	1.00	51	5.05	13	2.11	20	(Bogard et al., 2015; Mohanty et al., 2016)
catla	*catla catla*	large fish	0.83	267	14.9	0.7	0.83	1.10	210	1.30	22	1.49	18	(Bogard et al., 2015; Mohanty et al., 2016)
mrigal	Cirrhinus mrigala	large fish	0.83	363	18.9	1.1	2.50	1.50	960	5.57	15	3.8	15	(Bogard et al., 2015; Mohanty et al., 2016)
grass carp	*Ctenopharyngodon idella*	large fish	0.83	341	15.2	1.1	0.46	0.91	54	nd	nd	0.04	0	(Bogard et al., 2015; Golgolipour et al., 2019)
bighead	Hypophthalmichthys nobilis	large fish	0.83	400	17.7	1.1	4.70	0.30	218	0.00	16	0	0	(Bogard et al., 2015)
mola	Amblypharyngodon mola	SIS	0.867	445	17	4.5	5.70	3.20	853	7.98	2503	2.5	25	(Bogard et al., 2015)
tengra	Mystus vittatus	SIS	0.867	428	15.1	4.6	4.00	3.10	1093	1.80	8	0.19	28	(Bogard et al., 2015)
magur	Clarias batrachus	SIS	0.867	326	16.5	1.3	1.20	0.74	59	2.40	8	0	22	(Bogard et al., 2015)
channa	Channa punctatus	SIS	0.867	306	18.3	0.6	1.80	1.50	766	0.80	66	0	18	(Bogard et al., 2015)
bata	Labeo bata	large fish	0.867	446	16.6	4.7	1.20	0.94	493	0.20	4	8.76	nd	(Bogard et al., 2015; INFS, 2013)
silver carp	Hypophthalmichthys molitrix	large fish	0.83	435	17.2	4.1	4.40	1.40	903	0.55	0	0.24	0	(Bogard et al., 2015)
common carp	Cyprinus carpio	large fish	0.83	381	16.4	2.9	1.10	2.20	37	0.55	2	6.6	13	(Bogard et al., 2015; INFS, 2013)
sarputi	Barbonymus gonionotus	large fish	0.83	466	18.4	4.4	1.60	1.80	270	1.107	8	23	38	(Bogard et al., 2015)
majhari tilapia (pond)	Oreochromis niloticus	SIS	0.867	412	16.44	3.03	4.46	1.77	1249	2.96	2.78	24.9	16.69	Own data
majhari tilapia (rice-fish)	*Oreochromis niloticus*	SIS	0.867	412	15.9	3.0	6.30	1.58	1333	2.96	1.07	24.9	7.12	Own data
ayere	Sperata seenghala	large fish	0.77	400	16.2	1.3	0.97	0.372	81.7	0.2	10.9	1.8	18.11	(Mohanty et al., 2012)
darkina	Esomus danricus	SIS	0.867	384	15.5	3.2	12	4	891	12.5	660	6.31	81	(Bogard et al., 2015)

puti	Puntius ticto	SIS	0.867	385	15.4	3.4	3.40	3.80	1480	3.38	8	0.995	19	(Bogard et al., 2015)
shol	Channa striata	large fish	0.83	310	18.7	0.3	0.41	0.73	96	0.594	0	0.18	0	(Bogard et al., 2015)
taki	Channa punctatus	SIS	0.867	306	18.3	0.6	1.8	1.5	766	0.8	66.3	0	18	(Bogard et al., 2015)
koi	Anabas testudineus	SIS	0.867	737	15.5	12.8	0.87	0.6	85	1.18	149.22	1.19	0	(Bogard et al., 2015)
bele	Glossogobius giuris	SIS	0.867	292	16.6	0.4	2.3	2.1	790	1.1	8.29	1.6	25	(Bogard et al., 2015)
pabda	Ompok pabda	SIS	0.867	619	16.2	9.5	0.46	0.9	91	0	0	nd	7	(Bogard et al., 2015)
pangas	Pangasianodon hypophthalmus	large fish	0.83	925	16	17.7	0.69	0.65	8.6	0.756	16.58	0.12	0	(Bogard et al., 2015)
snakehead	Channa marulius	large fish	0.83	286	17.1	0.3	0.43	0.6	9.3	0.27	0	0.42	14	(Bogard et al., 2015)
prawn	Macrobrachium malcolmsoni	shellfish	0.8	364	15.7	2.2	13	3.3	1200	0	0		120	(Bogard et al., 2015)
chitol	Chitala chitala	large fish	0.83	405	17.8	2.8	1.6	0.61	104	0.25	30	nd	nd	(INFS, 2013)
shing	Heteropneustes fossilis	SIS	0.867	374	19.1	1.9	2.2	1.1	60	6.372	16.58	0	0	(Bogard et al., 2015)
rice	Oryza sativa	-	1	560	2.8	0.4	0.08	0.4	14	0	0	0	0	(McCance and Widdowson, 2021)
banana	Musa paradisiaca	-	0.74	400	1.3	0.8	0.3	0.24	11	2	3	0	2	(INFS, 2013; McCance and Widdowson, 2021)
eggplant	Solanum melongena	-	0.9	64	0.9	0.4	0.3	0.2	10	0	12	0	1	(INFS, 2013; McCance and Widdowson, 2021)
malta	Citrus sinensis	-	0.67	208	0.2	0.1	0.1	0.07	31	0	11	0	1	(INFS, 2013; McCance and Widdowson, 2021)
papaya	Carica papaya	-	0.66	125	0.8	0.1	0.6	0.22	15	0	1	0	0	(INFS, 2013; McCance and Widdowson, 2021)
pumpkin	Cucurbita pepo	-	0.79	77	1.4	0.3	0.7	0.11	52	0	369	0	0	(INFS, 2013; McCance and Widdowson, 2021)
bean	Phaseolus coccineus	-	0.91	122	2.4	0.1	0.9	0.37	70	0	19	0	2	(INFS, 2013; McCance and Widdowson, 2021)
cowpea	Vigna unguiculata	-	0.9	160	3	0.4	0.5	1.01	54	0	8	0	0	(INFS, 2013; McCance and Widdowson, 2021)
ladies finger	Abelmoschus esculentus	-	0.84	164	2.1	0.2	0.9	0.34	93	85	19	0	0	(INFS, 2013; McCance and Widdowson, 2021)

lufa	Luffa aegyptiaca	-	0.94	102	0.9	0.2	0.6	0.5	19	3	0	0	0	(INFS, 2013; McCance and Widdowson, 2021)
chilli	Capsicum frutescens	-	0.91	189	2.8	0.1	1.6	1.97	22	29	10	0	0	(INFS, 2013; McCance and Widdowson, 2021)
melon	Cucumis melo L	-	0.9	73	0.3	0.2	0.2	0.06	17	0	105	0	2	(INFS, 2013; McCance and Widdowson, 2021)
lychee	Litchi chinensis	-	0.68	259	1.4	0.5	0.5	0.27	11	0	0	0	0	(INFS, 2013; McCance and Widdowson, 2021)
mango (langra)	Mangifera indica	-	0.69	348	0.8	0.4	0.2	0.3	0.2	73	25	0	0	(INFS, 2013; McCance and Widdowson, 2021)
lemon	Citrus limon	-	0.76	234	0.8	1	0.3	0.07	65	1	4	0	0	(INFS, 2013; McCance and Widdowson, 2021)
tomato	Solanum lycopersicum L.	-	1	66	1.1	0.2	0.2	0.41	13	0	9	0	2	(INFS, 2013; McCance and Widdowson, 2021)
raddish	Raphanus sativus	-	0.99	74	0.09	0.1	0.4	0.38	24	0	0	0	0	(INFS, 2013; McCance and Widdowson, 2021)
cucumber	Cucumis sativus	-	0.83	72	0.8	0.1	0.6	0.17	13	0	4	0	3	(INFS, 2013; McCance and Widdowson, 2021)
cauliflower	Brassica oleracea	-	0.45	113	2.6	0.3	0.8	0.41	33	0	1	0	0	(INFS, 2013; McCance and Widdowson, 2021)
chicken	gallus gallus domesticus	-	0.61	457	22.3	2.1	0.7	1.2	6	0	11	0.1	6	(INFS, 2013; McCance and Widdowson, 2021; Murawska et al., 2018)

*nd- no data available

Annex 2. Bubble charts showing the mean nutritional affordability and mean environmental performance of various fish species in Bangladesh for each system type. A- poultry-fish, B- fish-only, C- rice-fish.

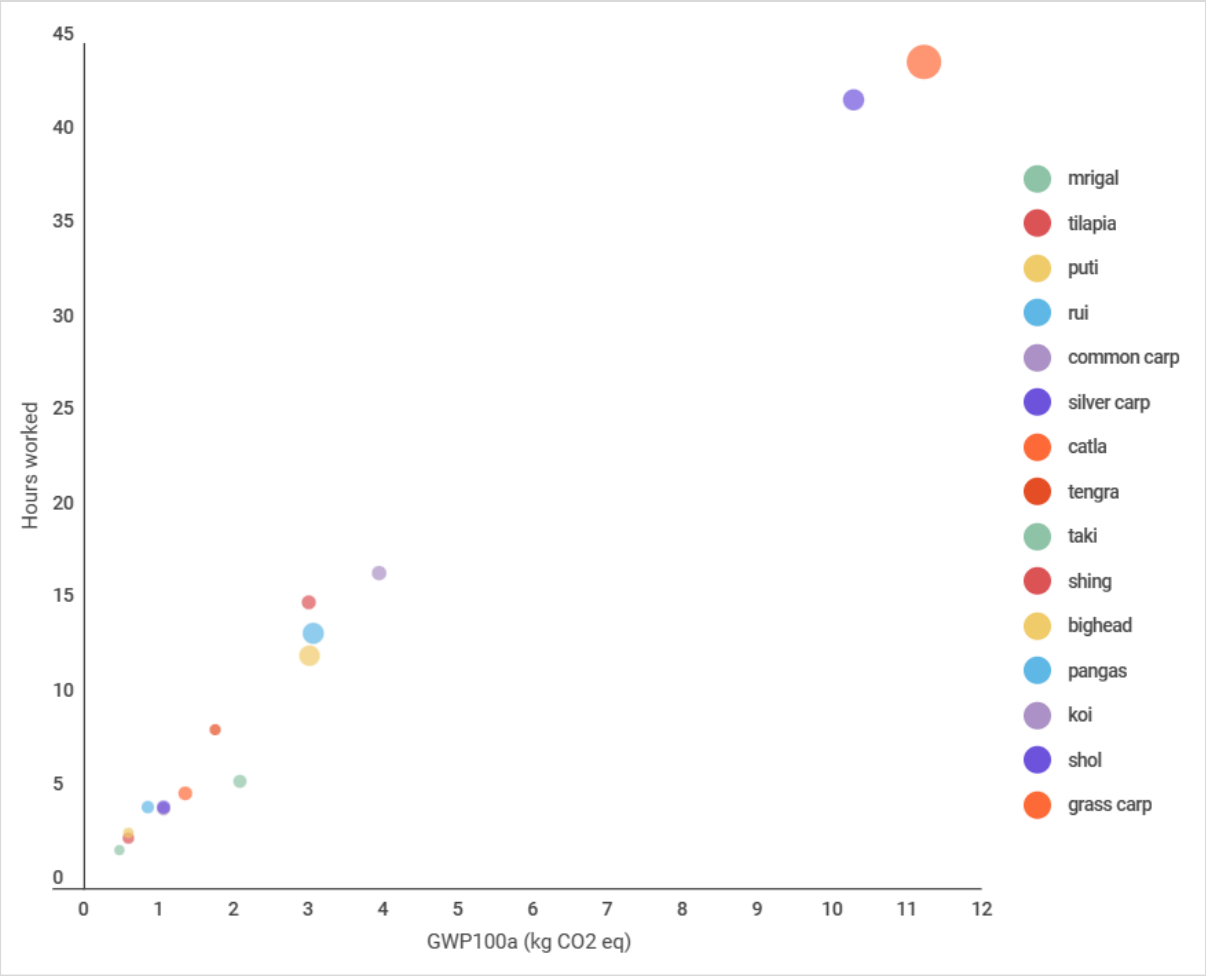

Figure A. Mean nutritional affordability and environmental performance of various fish species in poultry-fish systems. Nutritional affordability is measured as the hours worked to earn the necessary amount of money to purchase the required kg of fish which fulfils 33% weekly RNIs of the selected priority nutrients for the average adult in Bangladesh. Mean environmental impact is measured as the global warming potential of producing the required kg to fulfil 33% weekly RNIs of the selected priority nutrients. Size of bubble represents the amount of kg required to fulfil the RNIs. Legend is in order from lowest to highest global warming potential.
* Note: there were no available data for iodine content of bata and no vitamin A or vitamin B12 content data for grass carp.

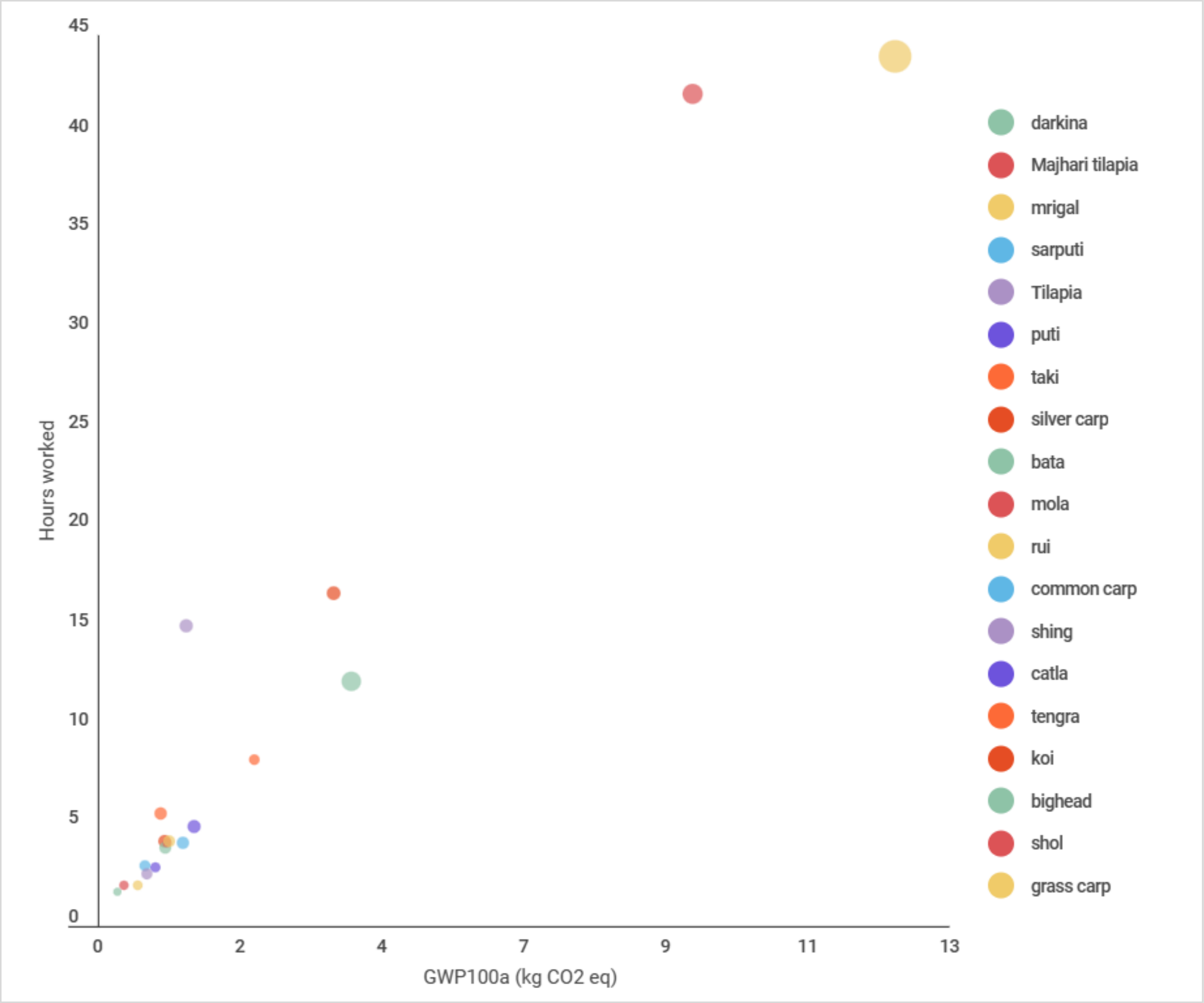

Figure B. Mean nutritional affordability and environmental performance of various fish species in fish-only systems. Nutritional affordability is measured as the hours worked to earn the necessary amount of money to purchase the required kg of fish which fulfils 33% weekly RNIs of the selected priority nutrients for the average adult in Bangladesh. Mean environmental impact is measured as the global warming potential of producing the required kg to fulfil 33% weekly RNIs of the selected priority nutrients. Size of bubble represents the amount of kg required to fulfil the RNIs. Legend is in order from lowest to highest global warming potential.

* Note: there were no available data for iodine content of bata and no vitamin A or vitamin B12 content data for grass carp.

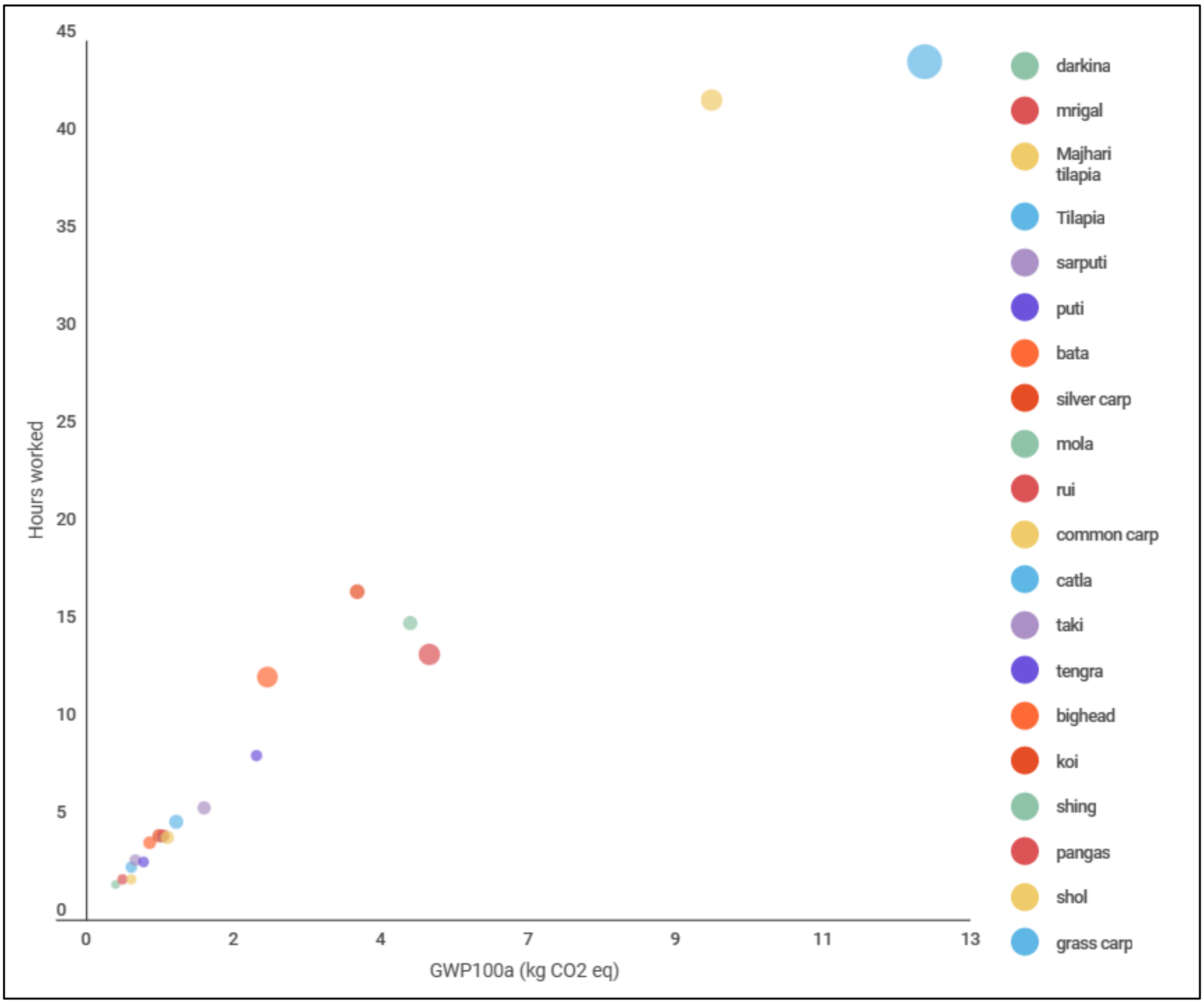

Figure C. Mean nutritional affordability and environmental performance of various fish species in rice-fish systems. Nutritional affordability is measured as the hours worked to earn the necessary amount of money to purchase the required kg of fish which fulfils 33% weekly RNIs of the selected priority nutrients for the average adult in Bangladesh. Mean environmental impact is measured as the global warming potential of producing the required kg to fulfil 33% weekly RNIs of the selected priority nutrients. Size of bubble represents the amount of kg required to fulfil the RNIs. Legend is in order from lowest to highest global warming potential.

* Note: there were no available data for iodine content of bata and no vitamin A or vitamin B12 content data for grass carp.

Annex 3. Example of household survey performed with farming households to collect food behaviours and tilapia consumption behaviours.

Note for enumerator: The survey questions are only to be asked to household member who is responsible for the daily cooking. If the person responsible is unavailable, then continue this survey with the household head or his/her nominated person.

Survey year: Jan 2022	**Survey period: Past 1 Month**		
Respondent identification			
1. Household type (Poultry-fish /Fish-only /Poultry- only)			
2. Household ID			
3. Household head name			
4. Respondent's Full Name			
Respondents phone number			
5. Respondent's husband Name			
6. Division		7. District	
8. Upazila		9. Village	
10. Union/Ward		11. GPS location	

Respondent background				
12. Relationship with household head		13. Age (years)		
14. Education level		15. Marital status		

	Name	**Age**	**Gender (M / F)**	**Relationship to HH head**	**Height (m)**	**Weight (kg)**
16. Details of members present in the household in the last week.	A.					
	B.					
	C.					
	D.					
	E.					
	F.					
	G.					
	H.					
	I.					
	J.					
	K.					
	L.					

	M.					
	N.					

17. Number of members of guest present in the HH in the last week		18. Number of days guest were present in the HH in the last week	

19. Consumption of animal protein in the household in last week (07 SEVEN days)

Food items	**Total quantity consumed (kg)**	**How many days**	**How many meals**	**Source of quantity consumed**			**Unit price (BDT/kg/Liter)**
				Own production	**Market**	**Gift**	
Fish (kg), list all species- identify large fish or fingerling sized							
Tilapia (>50g)							
Small tilapia (<50g)							
Dried fish (kg)							
Chicken meat (kg)							
Cow meat (kg)							
Goat meat (kg)							
Duck meat (kg)							
Other meat (kg)							
Egg (no.)							
Milk (ltr.)							

Note for enumerator: The survey questions are only to be asked to household member who is responsible for the daily cooking. If the person responsible is unavailable, then continue this survey with the household head or his/her nominated person.

Survey year: Jan 2022	**Survey period: Past 1 Month**
Respondent identification	
1. Household type (Poultry-fish /Fish-only /Poultry- only)	
2. Household ID	
3. Household head name	
4. Respondent's Full Name	
Respondents phone number	
5. Respondent's husband Name	

6. Division		7. District	
8. Upazila		9. Village	
10. Union/Ward		11. GPS location	

20. Consumption of other food items in the household in last week (07 SEVEN days)

Food items	**Total quantity consumed (kg)**	**How many days**	**How many meals**	**Unit price (BDT/Kg)**
Rice				
Wheat				
Other cereals				
Leafy vegetable				
Non-leafy vegetable				
Potato				
Condiment & spices				
Pulses				
Fruits				
Edible oils				
Sugar & Molasses				
Salt				

21. Expenditure on non-food items in Bangladesh Taka (BDT) in last 1 (ONE) month

Items	**Expenditure (BDT)**	**Items**	**Expenditure (BDT)**
Education		Savings and loan repayment	
Clothing & footwear		Transport costs/fuel for vehicle	
Housing and house repair		Electricity Bill	
Furniture and home appliances		Mobile Bill	
Health problem (e.g. General medicine, doctor fee, hospital cost)		Festival (Eid, puja, new year, etc.)	
Social program (funeral, wedding, mela, picnic etc.)		Others (specify)	

Respondent background

12. Relationship with household head		13. Age (years)	
14. Education level		15. Marital status	

Members present in the household in the last week

Fish Sourcing and Consumption

22. Do you consume small fish whole, including bones? If yes, please specify fish species	☐ No ☐ Yes, please specify which species:

23. If yes, how many days per week do you consume small fish?	
24. How much small fish are eaten per week? (kg)	
25. Where do you source your small fish and large fish? Please select as many as applicable.	☐ Own ponds- how do you catch them? ☐ Neighbours ponds ☐ Fish fingerling market ☐ Fish market ☐ Trader ☐ other, please specify:
26. Are there any months in the year small fish are unavailable? If yes, which months?	☐ Jan ☐ Feb ☐ Mar ☐ Apr ☐ May ☐ Jun ☐ Jul ☐ Aug ☐ Sep ☐ Oct ☐ Nov ☐ Dec
27. Do you consume tilapia?	☐ No ☐ Yes
28. What sizes of tilapia do you usually consume?	☐ <10cm ☐ 10cm – 15cm ☐ >15cm
29. Do you ever consume tilapia whole (including bones)? If so, what is the maximum size of tilapia that would be consumed whole? (cm)	☐ No ☐ Yes ________cm / _______g
30. If yes to above question, where do you source your small tilapias? Please select as many as applicable.	☐ Own ponds- how do you catch them? ☐ Neighbours ponds ☐ Fish fingerling market ☐ Fish market ☐ Trader ☐ other, please specify:

31. If tilapia is consumed whole, how is the fish prepared? List stages i.e. washing, de-scaling, viscera removal ect.	Step 1. 2. 3. 4. 5. 6. 7. 8.
32. What do you do with discarded (non-eaten) fish parts?	☐ Trash ☐ Feed to terrestrial animals ☐ Feed to fish ☐ Other, please specify:
33. If you eat tilapia whole (including bones), how much 'whole tilapia' is consumed each week? (kg)	
34. Are there any months in the year small tilapias are unavailable? If yes, which months?	☐ Jan ☐ Feb ☐ Mar ☐ Apr ☐ May ☐ Jun ☐ Jul ☐ Aug ☐ Sep ☐ Oct ☐ Nov ☐ Dec
35. Does your household consume larger tilapias? If yes, how much 'large tilapia' is consumed per week? (kg)	☐ No ☐ Yes __________________kg
36. How is 'large tilapia' fish distributed in the household? i.e. who receives the head, tail, middle part? Or is there 1 medium tilapia fish per household member?	☐ Head- ☐ Middle- ☐ Tail-
37. Does the size of tilapia consumed depend on the time of year? If so, please explain when small and large tilapias are usually consumed.	☐ No ☐ Yes, please explain:
38. What is the preferred size of tilapia for consumption? (g/cm)	_________g OR ________cm

39. Do you ever gift fish from your own ponds (if applicable)? If so, what species and size, and who do you gift to?	☐ No ☐ Yes, please specify: Species Size (cm) Recipient
40. How much fish do you gift per month? (kg)	
41. Do you ever use fish from your own ponds as payment for goods or services?	☐ No ☐ Yes, please specify:
42. If yes, what species and size of fish do you use as payment, and which services are they used to pay for? This may include paying day labourers/ fish harvesting teams	Species Size (cm) Service
43. How much fish do you use to pay for goods/services per year? (kg)	

Housing Facilities	
44. Area of household (decimal)	
45. Source of drinking water	☐ Tubewell ☐ Filter ☐ Rainwater ☐ Pond
46. Food storing facilities	☐ Refrigerator ☐ Covered/ sealed containers ☐ In a cupboard ☐ Open on shelf
47. Is stored food reheated? i.e. leftover rice/ curry If so, how is it reheated?	☐ Not reheated ☐ Reheated in frying pan/pot ☐ Reheated in other way, please specify:

48. Cleaning of cooking utensils	☐ No cleaning necessary ☐ Washed with water ☐ Washed with water and soap
49. When does hand washing occur	☐ Before preparing food ☐ Before serving food ☐ Before eating
Enumerator to make observations and check appropriate boxes in next 3 questions.	
50. House type	☐ Building ☐ Semi-building ☐ Tin-shed ☐ Tin-bamboo ☐ Tin-mud
51. Toilet facilities	☐ Offset ☐ Direct pit ☐ Open
52. Stove	☐ Commercial (bondhu chula) ☐ Improved ☐ Traditional

Household Food Insecurity Access Scale (HFIAS). Questions about your household's food supply in the last 1 (ONE) month	
53. In the past four weeks, did you worry that your household would not have enough food?	☐ No (skip next Q) ☐ Yes
54. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks)

	☐ Often (More than ten times in the past four weeks)
55. In the past four weeks, were you or any household member not able to eat the kinds of food you preferred because of lack resources?	☐ No (skip next Q) ☐ Yes
56. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
57. In the past four weeks, did you or any household member have to eat a limited variety of food due to lack of resources?	☐ No (skip next Q) ☐ Yes
58. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
59. In the past four weeks, did you or any household member have to eat some food that you really did not want to eat but due to lack of resources to you could not obtain other types of food?	☐ No (skip next Q) ☐ Yes
60. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
61. In the past four weeks, did you or any household member have to eat a smaller meal than you felt you needed because there was not enough food?	☐ No (skip next Q) ☐ Yes

62. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
63. In the past four weeks, did you or any other household member have to eat fewer meals in a day because there was not enough food?	☐ No (skip next Q) ☐ Yes
64. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
65. In the past four weeks, was there ever no food to eat of any kind in your household because of lack of resources to get food?	☐ No (skip next Q) ☐ Yes
66. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)
67. In the past four weeks, did you or any household member go to sleep at night hungry because there was not enough food?	☐ No (skip next Q) ☐ Yes
68. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)

69. In the past four weeks, did you or any household member go a whole day and night without eating anything because there was not enough food?	☐ No (skip next Q) ☐ Yes
70. How often did this happen?	☐ Rarely (Once or twice in the past four weeks) ☐ Sometimes (Three to ten times in the past four weeks) ☐ Often (More than ten times in the past four weeks)

71. HOUSEHOLD DIETARY DIVERSITY

"Now I would like to ask you about the types of food that you or anyone else in your household ate yesterday during the day and at night."

Note for enumerators: Please ask the respondent about the food and drinks that household members ate or drank yesterday during the day and night. Ask about each meal, what was eaten between each meal, and what was eaten before breakfast and at any time during the night. Write down all the food items and drinks in a separate sheet (e.g. record sheet at the end of the survey module). When composite dishes are mentioned, ask for the list of ingredients. When the respondent has finished, probe for food groups not mentioned. When the respondent recall is complete, fill in the food groups of the table below based on the information of your notes. If foods are used in small amount (less than 15g) for seasoning include them under condiments food group. Insert ONE (1) if anyone in the household ate the food. Insert a ZERO (0) if no one in the household ate the food.

Household Dietary Diversity Score (HDDS) module

Variable ID	Food group	Examples	Response
S1	CEREALS	Rice, wheat, corn, or any other grains or food made from these(roti, flour, flattened rice/chira, puffed rice, rice pudding, bread, noodles, other products containing cereals)	
S2	WHITE ROOTS, TUBERS, AND PLANTAINS	Potatoes, sweet potatoes, red potatoes, turnip, radish, taro, taro root, yam and other foods made from roots.	
S3	VITAMIN A RICH VEGETABLES AND TUBERS	Pumpkin and carrot	
S3a	ORANGE COLOURED SWEET POTATO	Orange colored sweet potato	
S4	DARK GREEN LEAFY VEGETABLES/ SPINACH , RED AMARANTH	Spinach, sweet potato leaves, amaranth, red amaranth, stem amaranth, other different kinds of amaranth/spinach.	
S5	OTHER VEGETABLES	Tomato, onion, eggplant, garlic, green chilies, mushrooms, cauliflower, cabbage, kohlrabi, bottle gourd, palwal, snake gourd, bitter gourd etc.	
S6	VITAMIN-A RICH FRUITS	Ripe mango, ripe papaya, fruit juice from these	
S7	OTHER FRUITS	Bananas, jackfruit, oranges, apples, melon, lemon, guava, olives, hog plum and other fruits	
S8	ORGAN MEAT	Liver, kidney, heart, or other organ meat or blood-based food	

S9	FLESH MEAT	Chicken, beef, goat, duck, lamb, duck, pork or other meat.	
S10	EGGS	Egg from chicken, duck, or other birds.	
S11	LARGE AND MEDIUM FISH AND SEAFOOD	Rui mach, shrimp, prawn, dried fish, crab, shellfish, big dried fish	
S11a	SMALL FISH	Small fish including tilapia <50g or 10cm (Choto mach, mola, dhela), small dried fish	
S11b	DRIED FISH	Any type of dried fermented fish, shutki like loitta, kechki, chingri, vetki, rupchanda, cheapa etc, lonailish, shidal	
S12	LEGUMES, NUTS AND SEEDS	Dal, lentils, peanuts, peas, broad beans seeds, cowpeas, nuts, or other foods made from these	
S13	MILK AND MILK PRODUCTS	Milk, yoghurt, cheese, other milk products	
S14	OILS AND FATS	Vegetable oil, corn oil, ghee, animal fat, margarine or other oil/fat added to food or used for cooking	
S15	SWEETS	Mishti, Sugar, sugar cane, honey, sweetened soda, sugary drinks, chocolate, candies, biscuits, cakes	
S16	SPICES, CONDIMENTS AND BEVERAGES	Spices (chili powder, other spices), condiments (hot sauce, coriander etc.), coffee, tea	

DIETARY DIVERSITY OF WOMEN AND YOUNG CHILDREN

Now I would like to ask about the types of foods that women and young children of your household ate yesterday during the day and at night. To be asked to 1 woman and 1 child per household (6 months – 12 years of age)**.** If the respondent has a child of 6-24 months of age, select this child. If there are multiple, select one child randomly. If there are no children 6-24 months of age, then select any child from the household (does not need to be the child of the respondents).

72. Individual Dietary Diversity Score (IDDS) module – Women

Note for Enumerators: Check the food items that you listed in your record sheet for identifying household dietary diversity. Ask the respondent – what food items she has eaten from the list. Insert ONE (1) if the women member ate the food item. Insert a ZERO (0) if she did not eat the food item.

Variable ID	**Food group**	**Examples**	**Response of women**
S1	CEREALS	Rice, wheat, corn, or any other grains or food made from these(roti, flour, flattened rice/chira, puffed rice, rice pudding, bread, noodles, other products containing cereals)	
S2	WHITE ROOTS, TUBERS, AND PLANTAINS	Potatoes, sweet potatoes, red potatoes, turnip, radish, taro, taro root, yam and other foods made from roots.	
S3	VITAMIN A RICH VEGETABLES AND TUBERS	Pumpkin and carrot	

S3a	ORANGE COLORED SWEET POTATO	Orange colored sweet potato	
S4	DARK GREEN LEAFY VEGETABLES WITH RED AMARANTH	Spinach, sweet potato leaves, amaranth, red amaranth, stem amaranth, other different kinds of amaranth/spinach.	
S5	OTHER VEGETABLES	Tomato, onion, eggplant, garlic, green chilies, mushrooms, cauliflower, cabbage, kohlrabi, bottle gourd, palwal, snake gourd, bitter gourd etc.	
S6	VITAMIN-A RICH FRUITS	Ripe mango, ripe papaya, fruit juice from these	
S7	OTHER FRUITS	Bananas, jackfruit, oranges, apples, melon, lemon, guava, olives, hog plum and other fruits.	
S8	ORGAN MEAT	Liver, kidney, heart, or other organ meat or blood-based food.	
S9	FLESH MEAT	Chicken, beef, goat, duck, lamb, duck, pork or other meat	
S10	EGGS	Egg from chicken, duck, or other birds.	
S11	LARGE AND MEDIUM FISH AND SEAFOOD	Rui mach, shrimp, prawn, dried fish, crab, shellfish, big dried fish	
S11a	SMALL FISH	Small fish including tilapia <50g or 10cm (Choto mach, mola, dhela), small dried fish	
S11b	DRIED FISH	Any type of dried fermented fish, shutki like loitta, kechki, chingri, vetki, rupchanda, cheapa etc, lonailish, shidal	
S12	LEGUMES, NUTS AND SEEDS	Dal, lentils, peanuts, peas, broad beans seeds, cowpeas, nuts, or other foods made from these	
S13	MILK AND MILK PRODUCTS	Milk, yoghurt, cheese, other milk products	
S14	OILS AND FATS	Vegetable oil, corn oil, ghee, animal fat, margarine or other oil/fat added to food or used for cooking	
S15	SWEETS	Mishti, Sugar, sugar cane, honey, sweetened soda, sugary drinks, chocolate, candies, biscuits, cakes	
S16	SPICES, CONDIMENTS AND BEVERAGES	Spices (chili powder, other spices), condiments (hot sauce, coriander etc.), coffee, tea.	

73. Individual Dietary Diversity Score (IDDS) module – child (<12 YEARS)

Name of the child	**Age**	**Gender**	**Relationship with household head**	**Name of mother**

Note for Enumerators: Check the food items that you listed in your record sheet for identifying household dietary diversity. Ask the mother – what food items the child has eaten from the list. Insert ONE (1) if the child ate the food item. Insert a ZERO (0) if the child did not eat the food item.

Variable ID	**Food group**	**Examples**	**Response for young child**
S1	Breast milk	Breastfeeding	
S1a	CEREALS	Rice, wheat, corn, or any other grains or food made from these(roti, flour, flattened rice/chira, puffed rice, rice pudding, bread, noodles, other products containing cereals)	
S2	WHITE ROOTS, TUBERS, AND PLANTAINS	Potatoes, sweet potatoes, red potatoes, turnip, radish, taro, taro root, yam and other foods made from roots.	
S3	VITAMIN A RICH VEGETABLES AND TUBERS	Pumpkin and carrot.	
S3a	ORANGE COLOURED SWEET POTATO	Orange colored sweet potato.	
S4	DARK GREEN LEAFY VEGETABLES WITH RED AMARANTH	Spinach, sweet potato leaves, amaranth, red amaranth, stem amaranth, other different kinds of amaranth/spinach.	
S5	OTHER VEGETABLES	Tomato, onion, eggplant, garlic, green chilies, mushrooms, cauliflower, cabbage, kohlrabi, bottle gourd, palwal, snake gourd, bitter gourd etc.	
S6	VITAMIN-A RICH FRUITS	Ripe mango, ripe papaya, fruit juice from these.	
S7	OTHER FRUITS	Bananas, jackfruit, oranges, apples, melon, lemon, guava, olives, hog plum and other fruits.	
S8	ORGAN MEAT	Liver, kidney, heart, or other organ meat or blood-based food.	

S9	FLESH MEAT	Chicken, beef, goat, duck, lamb, duck, pork or other meat	
S10	EGGS	Egg from chicken, duck, or other birds.	
S11	LARGE AND MEDIUM FISH AND SEAFOOD	Rui mach, shrimp, prawn, dried fish, crab, shellfish, big dried fish	
S11a	SMALL FISH	Small fish including tilapia <50g or 10cm (Choto mach, mola, dhela), small dried fish	
S11b	DRIED FISH	Any type of dried fermented fish, shutki like loitta, kechki, chingri, vetki, rupchanda, cheapa etc, lonailish, shidal	
S12	LEGUMES, NUTS AND SEEDS	Dal, lentils, peanuts, peas, broad beans seeds, cowpeas, nuts, or other foods made from these.	
S13	MILK AND MILK PRODUCTS	Milk, yoghurt, cheese, other milk products	
S14	OILS AND FATS	Vegetable oil, corn oil, ghee, animal fat, margarine or other oil/fat added to food or used for cooking	
S15	SWEETS	Mishti, Sugar, sugar cane, honey, sweetened soda, sugary drinks, chocolate, candies, biscuits, cakes	
S16	SPICES, CONDIMENTS AND BEVERAGES	Spices (chili powder, other spices), condiments (hot sauce, coriander etc.), coffee, tea.	

Nutrition knowledge and attitude of the household members with regards to fish

Question	**Code**	**Response**
74. Which types of fish do you consider the most nutritious?		NA
75. Why is this fish species more nutritious?	Fish provide more vitamins-1 Fish are rich in iron-2 Fish are rich in calcium-3 Fish are rich in vitamin A -4 Fish are rich in protein-5 Eating fish is good for health-6	

	Eating fish aids in foetus growth -7 Eating fish is good for eyesight-8 Don't know-9 Other (specify)	
76. Small fish species such as mola, should be eaten whole with bone, head and eyes	True -1 False-2	
77. Do you think eating small tilapia is as nutritious as eating mola?	Yes- 1 No-2	
78. During pregnancy, should a woman's fish consumption change or remain the same during this time?	Increase – 1 stay the same -2 Decrease -3 Don't know -4	
79. During lactation, should a woman's fish consumption change or remain the same during this time?	Increase – 1 stay the same -2 Decrease -3 Don't know -4	
80. Why is consuming fish important for pregnant women?	Fish provide more vitamins-1 Fish are rich in iron-2 Fish are rich in calcium-3 Fish are rich in vitamin A - 4 Fish are rich in protein-5 Eating fish is good for health-6 Eating fish aids in fetus growth -7 Eating fish is good for eyesight-8 Don't know-9 Other (specify)	
81. Why is consuming fish important for lactating women?	Fish provide more vitamins-1 Fish are rich in iron-2 Fish are rich in calcium-3 Fish are rich in vitamin A - 4 Fish are rich in protein-5 Eating fish is good for health-6 Eating fish aids in fetus growth -7 Eating fish is good for eyesight-8 Don't know-9 Other (specify)- 10	
82. At what age should babies start eating foods in addition to breastmilk?	At one month- 1 At two months- 2 At six months- 3 Don’t know- 4 Other, specify- 5	
83. Why is consuming fish important for young children?	Fish provide more vitamins-1	

Note for ENUMERATOR: RECORD FOODS EATEN ON A SEPARATE PAGE. WHEN THE RESPONDENT RECALL IS COMPLETE, FILL IN THE FOOD GROUPS TABLE BELOW BASED ON THE INFORMATION RECORDED. FOR ANY FOOD GROUPS NOT MENTIONED, ASK THE RESPONDENT IF A FOOD ITEM FROM THIS GROUP WAS CONSUMED. IF FOODS ARE USED IN SMALL AMOUNTS (LESS THAN 15g) FOR SEASONING INCLUDE THEM UNDER CONDIMENTS FOOD GROUP.

	Fish are rich in iron-2 Fish are rich in calcium-3 Fish are rich in vitamin A - 4 Fish are rich in protein-5 Eating fish is good for health-6 Eating fish aids in fetus growth -7 Eating fish is good for eyesight-8 Don't know-9 Other (specify)- 10	
84. How good do you think it is to eat a lot of different kinds of foods than eating only a few kinds of foods	Not good – 1 Not sure -2 Good-3	
85. How much do you like the taste of small fish	Dislike -1 Neutral -2 Like -3	
86. Would you eat more small tilapia with head/eyes if they were as nutritious as mola?	Yes- 1 No- 2	
87. How difficult is it for you to prepare meals with small fish (with whole with bone, head and eyes)?	Not difficult -1 So-so -2 Difficult – 3	
88. How confident do you feel in preparing meals with small fish (with whole with bone, head and eyes)?	Not confident -1 Ok/so-so -2 Confident -3	
89. Do you think it is healthier to eat fish, meat, or eggs during pregnancy	Fish – 1 Meat -2 Eggs -3	

Example of the Record Sheet for Your Notes

Breakfast	Morning Snacks	Lunch	Afternoon Snacks	Dinner	Late night snacks

Annex 4. Example of survey used to collect LCA data from farms.

Module A: Farm Information

Survey year: Jan 2022	**Production Year: 2020-2021**				
Farmer Identification					
1. Farm Name (if applicable)					
2. Farmer type (poultry-fish, fish-only, poultry-only)					
3. Farmer ID					
4. Farmer’s Full Name					
Respondents phone number					
5. Farmer’s wife/husband Name					
6. Division		7. District			
8. Upazila		9. Village			
10. Union		11. GPS location			
Basic information of the farmer					
12. Age (years)		13. Gender			
14. Marital status		15. Religion			
16. Education level		17. Main occupation			
18. What is your relationship to the household head?					
19. How many years of experience you have in farming?		20. How many years of experience you have in fish farming? (if applicable)			
21. Have you received any training on farming?		22. Are you the member of any associations in relation to farming or business?			
23. If yes, please mention the name of association					
Demographic information of the household					
24. Household size (no.)		Male		Female	
25. Main income source of the household		26. Secondary income source of the household			
27. Household members involvement in farming activities		Male		Female	
28.Household members with salaried or casual job		Male		Female	
29. Land owned by the household (Decimal)		30. Homestead land of HH (dec)			
31. Leased /rented/mortgaged land of HH (decimal)					
Basic information of farming in the last production year					
32. Number of plots used for fish-only farming		Total area (decimal)			
33. Number of plots used for poultry-only farming		Total area (decimal)			

34. Number of plots used for poultry-fish farming		Total area (decimal)	
35. Number of plots owned		Area (decimal)	
36. Number of plots leased		Area (decimal)	
37. Did you use dike for dike cropping? If yes, name all crops:		38. Amount of each crop grown (kg) on your dike:	
39. Source of vegetable seed		40. Income from dike cropping (BDT)	
41. Operating costs of dike cropping (BDT)		42. How much is eaten by household of each crop (kg)	

43. Cropping Calendar

Monthly cropping activities for each farm unit described in above section.

Crop	Crop being farmed- **C,** Partial Harvest- **PH,** Full crop harvesting- **H,** Fallow period- **F**											
	Jan	*Feb.*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Fish												
Layer chicken												
Broiler chicken												
Dyke crops												
Boro												
Amon												
Irri												

Module B: Fish Production

Farm Plot Information					
Plot	44. Technology used (poultry-fish plot / fishpond)	45. Depth of pond (m)	46. Area of pond without dyke (dec)	47. Area of dyke (dec)	48. Area of poultry shed (if applicable) (dec)

A					
B					
C					
D					
E					
F					
G					

Information of fish stocking Plot A

49. Species name	50. Average size of fish stocked (g)	51. Amount stocked (Number)	52. Total stocked weight (Kg)	53. Unit price of fish species (BDT/Kg)	54. Source of fingerling / fry

Information of harvesting

Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested	57. Total Production (kg)	58.Sold (Kg)	59. Household consumption (kg)	60. Restocking (Kg)	61.Gifted to neighbors (kg)	62.Selling price (BDT/Kg)
Plot A								

Plot B

Information of fish stocking

49. Species name	50. Average size of fish stocked (g)	51. Amount stocked (Number)	52. Total stocked weight (Kg)	53. Unit price of fish species (BDT/Kg)	54. Source of fingerling / fry

Information of harvesting

Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested	57. Total Production (kg)	58.Sold (Kg)	59. Household consumption (kg)	Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested

Plot C

Information of fish stocking

49. Species name	50. Average size of fish stocked (g)	51. Amount stocked (Number)	52. Total stocked weight (Kg)	53. Unit price of fish species (BDT/Kg)	54. Source of fingerling / fry

Information of harvesting

Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested	57. Total Production (kg)	58.Sold (Kg)	59. Household consumption (kg)	Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested

Plot D

Information of fish stocking

49. Species name	50. Average size of fish stocked (g)	51. Amount stocked (Number)	52. Total stocked weight (Kg)	53. Unit price of fish species (BDT/Kg)	54. Source of fingerling / fry

Information of harvesting

Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested	57. Total Production (kg)	58.Sold (Kg)	59. Household consumption (kg)	Species name	55. Average weight of harvested fish (g)	56. No. of fish harvested

Information of other inputs			
57. Input type and brand	**58. Amount of input used for each plot (Kg)**	**59. Unit price (BDT/Kg)**	**60. Total cost (BDT/kg)**
A. Urea	Plot A B C D		
B. TSP	Plot A B C D		
C. Limestone	Plot A B C D		
D. Potash	Plot A B C D		
E. Cow manure (dry/wet)	Plot A B C D		
F. Rotenone	Plot A B C D		
G. Salt	A B C D		
H. Geolight	A B C D		
I.	A B C D		

Information of feed used			
61. Feed type	**62.Company name (If formulated feed)**	**63. Amount of feed used (Kg)**	**64. Unit price (BDT/Kg)**
A. Commercial powder feed (kg)	Plot A B C D		
B. Commercial starter feed (kg)	Plot A B C D		
C. Commercial grower feed (kg)	Plot A B C D		
D. Commercial finisher feed (kg)	Plot A B C D		
E. Homemade (kg)-please specify type and amount of ingredients used to make feed.	Plot A B C D		
F. Rice bran (kg)	Plot A B C D		
G. Mustard oilcake (kg)	Plot A B C D		

Energy use			
65. Input	**66. Amount used**	**67. Unit price (BDT/Kg) if applicable**	**68. Total cost (BDT/kg)**
A. Diesel (L)- total used last year for pumps/machinery			
B. Electricity (kWh)- total used last year for pumps/machinery			

Information of labour use for fish plots						
Activities	Family labour		Hired labour			
	Male	Female	Male		Female	
	Man-day	Man-day	Man-day	BDT/man-day	Man-day	BDT/man-day
69. Daily aquaculture practices						
70. Fish harvesting						
71. Daily poultry practices						

Fixed costs of fish farming in the last production year			
72. Annual household income (BDT)		73. Annual household income from fish farming in (BDT)	
74. Fish farming – (%)		75. poultry farming income- (%)	
76. Other farming (except fish/ poultry) - (%)		77. Non-farm income - (%)	
78. Land tax (BDT)		79. Lease value (BDT) - Annual	
80. Total yearly outgoings on fish farming loans (BDT)		81. Duration of cash loan (months)	
82. Any other farming expenses (nets/ machines etc) (BDT/month)			

Other information of the last production year			
83. Did you face any shocks in production in this reporting year? i.e. mortalities	☐ Yes ☐ No	84. If yes, what types of shock you faced in the last production season?	
85. What was the effect of this shock?		86. How did you mitigate the effect?	
87. Financial loss in fish farming due to shock (BDT)			
88. If mortality event was experienced, how much fish was lost in total per species?			
89. How were the mortalities disposed?			

Module C: Water Management

Water management is important in terms of nutrient flows between neighbouring plots and farms. Please collect below data for entire farm over one year.

Water Management	
90. Main water source	
91. Secondary water source	
92. Do you pump water into or out of your farm plots?	☐ Yes - ☐ No -
93. If YES, please describe the pathway of water supply and discharge. Examples: • Pumped in from neighbouring farm tilapia pond/ tubewell/ own PF plot • Pumped out into potato field/ own tilapia pond/ canal Enumerator should add comments on when water is required throughout the year:	Water is pumped into plot A from:__________ ____ Water is pumped out of plot A into:__________ ____ Water is pumped into plot B from:__________ ____ Water is pumped out of plot B into:__________ ____ Water is pumped into plot C from:__________ ____ Water is pumped out of plot C into:__________ ____ Water is pumped into plot D from:__________ ____ Water is pumped out of plot D into:__________ ____

94. How often do you add water into each plot throughout the cycle?	**A** ________ times per week ________ times per month **B** ________ times per week ________ times per month **C** ________ times per week ________ times per month **D** ________ times per week ________ times per month
95. How much water did you add each time? (litres) If litres are unknown, ask how long water is pumped water into each plot and mention the hours and the type of pump used below:	A _________ litres / hours B _________ litres / hours C _________ litres / hours D _________ litres / hours

96. Did you empty the water out of the pond at the end of the cycle?	☐ Yes ☐ No
97. If yes, estimate how much water was discharged at the end of the cycle for each plot? i.e. the area and depth	A __________ litres OR Area________ decimal Depth ________ metres B __________ litres OR Area________ decimal Depth ________ metres C__________ litres OR Area________ decimal Depth ________ metres D __________ litres OR Area________ decimal Depth ________ metres
98. How often and how much drinking water is topped up in chicken shed	_______days per week _______litres per top-up
99. Source of drinking water for poultry	

100. Sediment removal frequency and fate, list for each plot	

Module D: Poultry Production

Inputs		Amount	BDT/unit
101. Land	A. Area of poultry shed (decimal)		
	B. Area of poultry nursery (decimal)		
	C. Days in nursery		
102. Seed	A. Number of chicks per cycle		
	B. Number of cycles in year		
	C. Stocking weight of chicks (g)		
	C. Source of chicks		
103. Chemical inputs	A. Vaccines used, specify:		
	B. In-feed treatments (kg), specify treatment/medicine brand name:		
104. Feeds	A. Pre-starter (kg)		
	B. Starter (kg)		
	C. Grower (kg)		
	D. Other feed (kg), specify:		
105. Utilities	A. Electricity use (kWh)		
	B. Diesel used (kg)		
	C. Drinking water (litres)		
	D. Bedding type and amount (kg)		
106. Mortalities	A. Number of mortalities per cycle		
	B. Fate of mortalities		
107. Harvest	A. Days from stocking to harvest		
	B. Number harvested and farm gate price		
	C. Weight harvested (kg)		
108. Outputs	A. Solid waste per bird (kg)		
	B. Waste feed (kg)		

Production of Rice (for year 2020-2021)

Inputs		Primary data	
		Boro	Aman
118. Land	A. Area of rice paddy (decimal)		
	B. Area of rice nursery (decimal)		
	C. Days in nursery		
119. Seed	A. Amount of seed (kg)		
	B. Type of seed (own collection/market hybrid)		
120. Fertilizer-Total used for entire cycle and all plots	A. Urea (Kg)		
	B. TSP (Kg)		
	C. Limestone (kg)		
	D. Gypsum (kg)		
	E. Cowdung (kg)		
	F. Compost (kg)		
	G. DAP (kg)		
	H. Sulphur (kg)		
	I. Others, specify:		
	J. Comments		
121. Pesticide-Total used for entire cycle and all plots	A. Carbofuran (kg)		
	B. Microthiol sulphur (kg)		
	C. Protaf, tilt (kg)		
	D. Diazon (kg)		
	E.		
	F.		
	F		
	F. Comments: indicate frequency of spraying rice		
122. Tilling	A. Diesel in Tractor (kg)		
	B. Diesel in power tiller (kg)		
	C. Lubricating oil (kg)		
123. Irrigation	A. Electricity (kWh)		
	B. Diesel (kg)		
	C. Comments Indicate frequency of irrigation, pump used		
124. Harvest	A. Type of harvest- i.e. by hand?		
	B. Days from planting to harvest		
	C. Diesel (kg)		
125. Threshing	A. Type of threshing		
	B. Diesel (kg)		
126. Labour	A. Quantity (Labour day)		
	B. Cost per day		
127. Outputs	A. Rice (kg), dry mass		
	B. Straw (kg)		
	C. Rice farmgate price (BDT/kg)		