AN ASSESSMENT OF SUITABLITY OF IR 2793-80-1 AND BASMATI 370 RICE VARIETIES IN INTERGRATED RICE-FISH FARMING IN BUNYALA IRRIGATION SCHEME, BUSIA COUNTY, KENYA

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF THE AWARD OF DEGREE OF MASTER OF SCIENCE (PLANT ECOLOGY) IN THE SCHOOL OF PURE AND APPLIED SCIENCES OF KENYATTA UNIVERSITY

OCTOBER 2025

DECLARATION

This thesis is my original work and has not been presented for award of a degree in any other university or for any other award.

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DEDICATION

I dedicate this work to my loving parents; the late Mr. David Juma Muchemi and Jane Nyambura Juma, my wife Jane Muthoni Muchemi, my daughters Caroline Nyambura Muchemi and Mercy Wanjeri Muchemi, my sons David Juma Muchemi and Tony Gichuki Muchemi and my precious brothers, sisters, nieces and nephews, not forgetting my parents in-law and family.

ACKNOWLEDGEMENTS

First, am very grateful to my caring parents, the late David Juma Muchemi and Jane Nyambura Juma for their support both morally, spiritually and financially all along. Secondly, I appreciate my wife Jane Muthoni for her patience, love encouragement and moral support. My two daughters; Carolyne Nyambura and Mercy Wanjeri and my precious sons; David Juma and Tony Gichuki. My appreciation goes to my siblings; Julius Njuguna, Joseph Wahome, Dr, John Kibe Juma, Naomi Juma, Florence Wambui, Wangari, Nduta Juma and family of my late brother Moses Ndungu for their support.

I am greatly indebted to my two supervisors; Dr. Francis W. Kariuki and Prof. Benson M. Mwangi who always spared time to assist me in the course of my research project. I also acknowledge the support I got from the Department of Plant Sciences and its technical staff. I also thank Mr. Francis Ouma and Mr. Peter Olonda for allowing me to carry out this research in their farms.

ABSTRACT

Rice and fish are major food and nutritional security, employment and income sources in Kenya. Rice is third most important staple food while fish is considered as a poor man`s rich food in proteins, Omega-3 fatty acids and mineral nutrients. Both crops are produced under intensive monoculture system which has constrained their sustainable production leading to huge deficits. To bridge the production gap, the current intensive monoculture production mode needs to be transformed into an ecological intensification system through integrated rice-fish farming. The aim of this study was to assess suitability of Basmati 370 (B) and IR 2793 (IR) rice varieties for integrated rice-fish farming in Bunyala Irrigation Scheme. The two rice varieties were grown in 2 blocks in separate plots of the same size with and without Nile tilapia (*Oreochromis niloticus* L.) fish. Each was replicated twice in each block in a complete random block design. The plots with fish were modified by constructing fish refugia in the periphery, each of an area of 52 m^2 and a depth of 1m. In rice–fish cultures no feeds and agrochemicals were used. Selected water physico-chemical parameters (dissolved oxygen, pH, temperature, electrical conductivity) were monitored *in situ* weekly at 0900 and 1600hrs. Alkalinity and Nitrates (NO_3-N) were determined through titration and calorimetric methods respectively. Fish and rice growth and yield indices were measured monthly for a period of 226 days. After harvesting at 120 and 135 DAT for IR and B respectively, Basmati, and integrated IR and B plots were irrigated again to produce ratoons as a second rice crop and allow fish to mature. Data on water physico-chemical parameters and fish and rice growth and yield indices collected were subjected to ANOVA and significantly different means of the treatments were separated using Tukey`s test at 5 % probability. Except total alkalinity, the selected water physico-chemical parameters were within suitable range for rice and fish growth. IR rice variety produced significantly ($p \geq 0.05$) higher rice yield in both rice monoculture and rice-fish cultures at 4616 ± 313.53 and 4136 ± 183.83 kg ha^{-1} respectively. Basmati yielded 3944 ± 327.90 and 3656 ± 192 kg ha^{-1} under monoculture and integrated culture respectively. The net income was significantly ($p \leq 0.05$) higher in Basmati fish culture (121887.824 ± 8763.3) followed by Basmati monoculture (88491.633 ± 14150.96) and then IR fish culture (61568.131 ± 7061.3) while the lowest was IR monoculture (40835.387 ± 8361.8). The two integrated rice fish cultures did not differ significantly ($p \geq 0.05$) in fish yields. Fish recovery rate was below 50% which was attributed to predation and poaching by humans. The higher net income from integrated rice-fish cultures than from rice monocultures could be attributed to lower production cost due to savings from the agrochemicals costs and the additional income from fish sales. Higher income from integrated rice-fish cultures is an indication that both IR and B rice varieties are suitable for integrated rice-fish farming and could be used as an incentive for adoption of integrated type of farming.

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ABBREVIATIONS AND ACRONYMS

AGRA	Alliance for a Green Revolution in Africa
ANOVA	Analysis of Variance
ARC	Africa Rice Centre
BIS	Bunyala Rice Irrigation Scheme
CIAT	International Center for Tropical Agriculture
CSA	Climate-Smart Agriculture
DAS	Days After Sowing
DAT	Days After Transplanting
EIL	Economic Injury Level
FAO	Food and Agriculture Organization
FFE & PP	Fish Farming Enterprise and Productivity Programme
GDP	Gross Domestic Product
GES	Gross Economic Sale
GHG	Greenhouse Gas
GHGE	Greenhouse Gas Emissions
GOK	Government of Kenya
ha	Hectare
hrs	Hours
IAA	Integrated agriculture-aquaculture
IPCC	Intergovernmental Panel on Climate Change Climate Change
IPM	Integrated Pest Management
IRRI	International Rice Research Institute
KMFRI	Kenya Marine and Fisheries Research Institute
KES	Kenya Shilling
KNBS	Kenya National Bureau of Statistics
MIS	Mwea Irrigation Scheme
MOA	Ministry of Agriculture of Kenya
MT	Metric Tonne
NEI	Net Economic Income
NIA	National Irrigation Authority
NRDS	National Rice Development Strategy
OM	Organic Matter
RFS	Rice Fish Systems
SGR	Specific Growth Rate
SI	Sustainable Intensification
SSA	Sub-Saharan Africa

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Worldwide, agriculture is the largest user of freshwater (both green and blue water) accounting for approximately 70% of freshwater withdrawals (Gleick *et al.,* 2014). Rice cultivation is the heaviest single consumer of freshwater, using between 34 and 43% of the global irrigation water which accounts for World's total freshwater withdrawal of between 24 and 30% (Surendran *et al.*, 2021). Irrigated systems predominate in Asia and rain-fed rice in Africa (Seck *et al.*, 2021). Over 90% of the global rice production comes from continuously flooded ricefields which can be a habitat for a variety of aquatic species and also provide an opportunity for their farming (Mishra *et al.*, 2014).

Unsustainable agricultural water use practices and climate change have resulted in waterscarcity in areas where irrigation is required and may in future limit the potential for expanding irrigation land area (FAO, 2011). Climate change is already exacerbating the world water crisis by intensifying water demand through prolonged droughts and in combination with more frequent and severe weather extremes impacting negatively irrigated crops production (DeNicola *et al.,* 2015). Currently, the challenge is how irrigation water use efficiency and productivity can be improved to close water supply and demand gaps in the agricultural sector to increase food production with limited water resources (Minzhong and Shaozhong, 2022).

Rice and fish are major contributors to food and nutrition security, household income, and livelihood opportunities for many people (Islam *et al.*, 2016). Even though most Kenyans in rural areas consume small amounts of rice, it constitutes a significant diet for a majority of those living in urban areas (MOA, 2009). Annual rice consumption is approximated at 949,000metric tons (KNBS, 2019) against a local production of 180,000 metric tons in 2020 and consumption is expected to reach 1, 292, 000 tons by 2030 (NRDS, 2020). To bridge the rice production demand gap, the country relies on imports (Watanabe *et al.,* 2021) which account for nearly 90% of the consumption (KNBS, 2019). Additionally, the annual rice consumption is increasing at a rate of 12% which is higher than 1% of maize, the main staple food and 4% for wheat (KNBS, 2020) will further widen the gap between local production and consumption. Overall, if traditional farming systems remain (status quo remains), Kenya's rice production will continue to be low because of being constrained by factors that include lack of suitable land, inadequate water and inefficient production systems.

On the other hand, fisheries sector in Kenya contributes significantly to the country`s socio-economic development despite performing below its potential (Republic of Kenya, 2019). Fish is an important source of inexpensive animal protein for food and nutritional security and its production can lead to food security and poverty reduction. Fish production from capture fisheries has declined over the past decades due to the decline in the Lake Victoria fishery (Kimani *et al.,* 2018a). The decline is partly explained by dwindling stocks of the Nile perch species, proliferation of invasive aquatic species especially water hyacinth due to increased nutrients from runoff, pollution in addition to overfishing and use of illegal fishing gear among other factors (Kimani *et al.*, 2018b). Also, because of depressed performance by pond-based aquaculture production, the industry has not been able to achieve its potential fully (KNBS, 2018).

Both rice and fish imports come at a huge cost to the economy and sometimes to human health. To meet the increasing rice and fish demand and generate some income, the area under cultivation as well as yield per unit of production area need to increase. However, there is limited opportunity to increase the rice planted area and further crop intensification is limited various environmental factors. This implies that land suitable for rice production is not expanding and water has become a resource under pressure. Therefore, it is hard to imagine an improvement being wrought without radical changes in the ways in which ricefields and irrigation water are used especially considering that water and land carrying capacities has not been fully utilized.

Since currently rice production is highly inefficient in terms of water and land use (Mallareddy *et al.*, 2023), a shift in practices towards water-saving technologies is required. Moreover, since freshwater availability for agriculture is becoming increasingly scarce, especially in inefficient irrigated rice production, greater water use efficiency is required. A fundamental rethinking of rice systems strategies to improve efficiency and productivity of water in irrigation systems need to be explored. Such strategies need to shift focus to producing a large amount of foods using available agricultural land with reduced water demand by improving both water use efficiency and water productivity. This requires redesigning the current intensive monoculture dominated cropping systems to maintain rice production without negatively impacting the environment (Brook *et al.*, 2023; Buzhdygan and Petermann, 2023). One such a redesign is the ecological intensification that involves enhancing ecosystem services to either substitute synthetic inputs in sustaining/improving yields (Kleijn *et al.,* 2019; MacLaren *et al.*, 2022) on one hand, or to substitute external inputs to minimize the negative environmental impacts of production (Wood *et al.,* 2015; Damgaard and Weiner, 2021). Integrated agriculture-aquaculture (IAA) systems are a form of ecological intensification that uses agro-diversity to increase agricultural yield and sustainability. Integrated rice fish farming is the most widely practiced type of aquaculture-crop integration system worldwide (Hasimuna *et al.*, 2023).

Since about 80% of rice in Kenya is grown under continuous flooding (Ndiiri *et al.*, 2017), the rice fields can contribute to water use efficiency and aquaculture production if it is integrated with aquaculture. Integrated rice fish farming in Kenya is still in the initial research stages and if the ricefields are to be exploited for rice and aquaculture production, there is need to identify rice varieties suitable for rice-fish farming and assess if fish in rice field ecosystem affect rice yield and productivity.

1.2 Statement of the Problem

Rice is ranked third after maize and wheat as most important staple food and constitutes a significantly a larger part of Kenya`s urban population diet (Short, 2012). Fish is a source of amino acids, essential omega-3 fatty acids and micronutrients (Beveridge *et al.*, 2013). Despite the increasing demand for both rice and fish, rice yields and capture fisheries have been declining. The average rice yield in Kenya is about 2.8 t ha^{-1}

compared to 10 t ha^{-1}, the global potential (MOA, 2009). For Kenya to meet rice and fish demand; there is need for suitable systems that can increase rice and fish production sustainably through efficient utilization of farm resources without significant increase in inputs. Integrated rice cum fish farming provides a strategy to increase rice and fish production by efficiently utilizing land and water (Islam *et al.*, 2016). Since rice-fish farming is site specific, it is essential to identify rice varieties and fish species that are well adapted to local conditions.

Adoption of integrated rice-fish farming will therefore require identification of the rice varieties and fish species suitable for rice-fish farming and determine rice and fish yields under integrated rice fish cultures. The system is in its nascent stage in Kenya. On-farm trials of integrated rice fish farming have been carried out in West Kano Irrigation (Rasowo, 2008) and Mwea Irrigation Scheme (Wambugu, 2022). This study was aimed at providing information on rice-fish culture in terms of suitable rice varieties for integrated rice Nile tilapia (*Oreochromis niloticus* L.) fish farming in Bunyala irrigation scheme where notwithstanding the benefits associated with integrated rice fish farming, rice monoculture is the dominant mode of rice production.

1.3 Justification of the study

In most irrigation schemes including Bunyala, farmers grow only one rice crop per year which takes a maximum of 4 months; hence the use of water and land resources are not optimized. Integrated rice-fish production can optimize resource utilization through the complementary use of land and water (Annie *et al.*, 2019) by simultaneously producing one and two fish and rice crops respectively when using rationing rice varieties.

Integrated rice fish can enhance rice yields by while also generating substantial quantities of fish, thus diversifying farmers' income and mitigating economic risk (Dubois *et al.*, 2021). Additional benefits include improved soil health due to reduced use of agrochemicals as fish fertilizes the rice fields and keeps weeds and rice pests to levels below the threshold for the application of pesticides. As opposed to the seasonal nature of monoculture rice production, integrated rice-fish farming can provide year-round income and employment. The findings of this study are anticipated to stimulate more research interest and encourage the adoption of integrated rice fish farming.

1.4 Research questions

a) Is water quality in rice fish cultures suitable for Nile tilapia (*Oreochromis niloticus* L.) fish growth?

b) Are Basmati 370 and IR 2793-80-1 rice varieties suitable for integrated rice- Nile tilapia fish farming?

c) Does integrating Nile tilapia fish into rice fields affect rice yield?

d) What is the net income from rice monocultures and integrated rice-Nile tilapia fish culture systems?

1.5 Null Hypotheses

i. Water quality in integrated rice-fish cultures is not suitable for Nile tilapia (*Oreochromis niloticus* L.) fish growth.

ii. Basmati 370 and IR 2793-80-1 rice varieties are not suitable for integrated rice-Nile tilapia fish farming.

iii. There is no significant ($p \geq 0.05$) difference in growth and yield of rice varieties between rice monocultures and integrated rice-Nile tilapia fish farming.

iv. There is no significant ($p \geq 0.05$) difference in net income between rice monocultures and integrated rice-Nile tilapia fish farming.

1.6 General objective

To investigate the suitability of Basmati 370 and IR 2793-80-1 rice varieties for integrated rice- Nile tilapia fish farming and the characteristics of selected physico-chemical parameters of water in Basmati 370 rice cultures in Busia County, Kenya.

1.6.1 Specific objectives

i. To determine physico-chemical parameters of water in Basmati 370 and IR 2793-80-1 rice monocultures and integrated rice-Nile tilapia fish culture.
ii. To determine the growth and yield of Basmati 370 and IR 2793-80-1 rice varieties in rice monoculture and integrated rice-Nile tilapia fish culture.
iii. To examine the growth and yield of Nile tilapia in integrated rice-fish culture.
iv. To quantify the net income from Basmati 370 and IR 2793-80-1 rice monocultures and integrated rice-Nile tilapia fish culture.

1.7 Significance of the study

The study provides an agroecological approach to farmers to use efficiently resources to improve food security and sustainability by increasing productivity on the same land, increase income, and reduce reliance on agrochemicals. The approach also provides an opportunity for livelihood diversification to diminish the risks associated with monoculture farming and for a resilient agricultural model to mitigate climate change.

CHAPTER TWO

LITERATURE REVIEW

2.1 Global Rice Output

Rice belongs to *Oryza* genus and Poaceae family, comprising 22 species of great magnitude economicallyb (Brar and Singh, 2011). Globally, high yielding African rice, *Oryza glaberrima* (Steudel) and the Asian *Oryza sativa* (L.) are the most commonly grown rice species (Manful and Graham-Acquaah, 2016). These species are suited to diverse conditions of climate where both can be cultivated in dry as well as in flooded environment at higher or lower altitudes.

Rice is an agricultural commodity that has third- highest production worldwide after sugarcane and maize (FAO, 2019) and is world's second most important crop as cereal after corn. It is the most widely consumed as staple food by over half of global population with more than 3.5 billion people depending on it to obtain up to two-thirds of their daily calories intake (Mosleh *et al.*, 2015; Wang *et al.,* 2017). Since some of the sugarcane and maize are utilized for other purposes rather than for human consumption, rice is the most vital agricultural food crop for human nutrition cum calories uptake (Naomi and Lewis, 2019). According to FAO (2015), in the year 2014, the world harvested 741.3 million tons of paddy rice with China and India contributing about half of the production. Globally, approximately 75% of the paddy rice is produced from 85 to 90 million ha of lowland areas (IRRI, Africa Rice and CIAT, 2010). The area of land under paddy rice constitutes 29% of the overall production of cereal crops globally with Africa standing for roughly 10 to 13% (Tsuboi, 2005; Onyango, 2006).

In Africa, about 800 million inhabitants rely on rice not only for food but also for their livelihoods (Africa Rice Centre, 2009). Rice emerges as the fifth most vital cereal as far as the cultivated acreage is concerned and the fourth production wise in sub-Saharan Africa (SSA) (Rodenburg and Demont, 2009). Even though rice output in SSA has increased considerably in the past 50 years, its consumption has surpassed domestic output leading to shortfalls (FAO, 2012; IRRI, 2012). With only limited foreign resources to sustain increased levels of imports, this dependence on rice imports causes serious economic and social strains. To improve the balance of trade and contribute to the rice farmers` well-being, production deficits need to be addressed through increased on-farm rice production (DeVries, 2008).

2.2 Rice production in Kenya

Rice as a cereal is major food crop in Kenya, placed third behind wheat and maize (NRDS, 2020) and its cultivation remains a great concern because of its positive impact on farmer’s livelihood (Atera *et al.,* 2018). In recent years, particularly in urban areas, per capita rice consumption has rapidly increased far more than any other cereal crop (Ndirangu and Oyange, 2019). Kenya rice production was estimated at 229,064 tons during the 2022/2023 season, accounting for 25% of the apparent consumption and this led to an increase in imports at 75.0% (KNBS, 2024). With the projected population increase and changes in consumption habits, the gap between production and consumption will continue to widen (Atera *et al.*, 2011). Despite the rising demand, rice production in Kenya has been declining (KNBS, 2018). This has been increasing the gap between production and demand and making the country been reliant on imports from international Asian markets (Gitau *et al.,* 2011; Watanabe *et al.,* 2021) with attendant implications for national food security. Increasing domestic rice production is an important strategy to bridge the gap between local production and the volume of consumption and in improving national food security (Muhunyu, 2012**)**. An integrated set of recommended crops, soil, water, pests and weed management practices have been proposed as important strategies to bridge the yield gap (Senthilkumar *et al.,* 2018).

Although soils are suitable for rice cultivation (Kihoro *et al.,* 2013), the potential to increase rice production, the sector has only recorded modest improvements in the last few years particularly in terms of yield and aggregate production (Ntiritu, 2014). In Kenya, rice yields do not surpass 5 t ha^{-1} which is considerably lower than the potential of close to 10 t ha^{-1} (MOA, 2009) and actually, between the year 2005 and 2009, the average rice output in Kenya was about 2.5 t ha^{-1} (Onyango, 2014). The lower rice grain output has been caused by a variety of factors that include soil degradation due to overuse of inorganic fertilizers and pesticides, continuous mono-cropping and use of inefficient production techniques (Nelson *et al.,* 2019). Other causes of decline in the unit rice yield recorded over the years are nutrient deficiencies (N, P) due to nutrient mining through crop harvest without applying sufficient quantities of manure and over-dependence on inorganic fertilizers (Billards, 2014). A lower yield potential of rice variety, weed buildup, pests and diseases also contribute to declining rice yield. Rice farmers are also faced with high costs of farm inputs (agrochemicals and machine power) and high incidence of waterborne diseases especially malaria and bilharzia that reduces a farmer`s productivity within the households in the irrigation schemes (NRDS, 2020). The changing climate is expected to aggravate the abiotic and biotic constraints, further limiting rice production (Balasubramanian *et al.,* 2007). With rice production declining and the demand rising, there is need to address the constraints to increase production for Kenya to meet its growing rice demand.

In response to declining rice production and increasing demand, the government of Kenya has been engaged in rehabilitation and horizontal expansion of the existing rice irrigation schemes (Atera *et al.,* 2018) even though there already exist challenges of water scarcity in the present rice irrigation schemes (Nyamai *et al.,* 2012). Muema *et al.* (2018) also found that in Kenya**,** there is inefficient water use and lower productivity in public rice irrigation schemes and concluded that the performance of Bunyala, Ahero and West Kano irrigation schemes is poor and unsustainable. Thus, the increases in rice yield could be achieved by ecological intensification through improvement of the productivity of water and rice in the existing schemes rather than to horizontal expansion of irrigated areas and considering the limited water resources and suitable land available (Nyamai *et al.,* 2012). On the other hand, intensification of rice production which requires high inputs application in form of synthetic agrochemicals, use of high yielding rice varieties and mechanization is not feasible for peasant farmers who are poorly resourced. The increased reliance on fertilizers and pesticides has had negative outcomes in terms of human health and environmental sustainability. In addition, agricultural intensification has socio-economic and environmental limits beyond which they may not be sustainable. Investments in technologies that increase water-use efficiency to achieve increase in water productivity (Kilemo, 2022) might have higher pay-off than investments in new irrigation schemes (Cai and Rosegrant, 2003). Kenya therefore, needs to invest in efficient rice production innovations that improve water-use efficiency and productivity. One innovation within the ricefields is the integration of rice cultivation with aquaculture/livestock production to maximize resource use efficiency. Integrated rice-aquaculture involves stocking paddy fields with aquatic species in order to obtain two crops and in case of using rice varieties that produce ratoons; an additional rice crop is obtained. This contributes to households' food and nutritional security and in case of rice crop failure; a farmer has a fall back in form fish yield from the rice field. In case of integrated rice fish cultures, fish excreta provide organic fertilizer (Roy and Sathoria, 2022), and promotes rice growth by fish movement which turns over and loosen the soil (Inayat *et al.*, 2023) and also fish predates on weeds and rice pests, all of which saves a farmer the costs of using fertilizers, herbicides and pesticides considerably (Fahad *et al.*, 2021).

About 95% of rice production in Kenya is mainly done by smallholder farmers under irrigation and 5% in rain-fed farms (Siwar *et al.*, 2014). Although there is an estimated production potential for irrigated rice of up to 1.3 million ha in Kenya (Gitau *et al.*, 2011), the average area that was under paddy rice cultivation nationally (2016–2020) was said to be 27,793 ha (FAO, FAOSTAT, 2022). These areas under rice irrigation have enormous potential for increasing both rice and aquaculture production through integration of aquaculture instead of relying on earthen fish ponds that are not only expensive to construct but also require high inputs in form of fish feed (Munguti *et al.*, 2014). Although this integration strategy has been used for thousands of years by Asian farmers, in Africa it is still marginally practiced (Rasowo *et al.*, 2008).

Integrated, rice fish farming in Kenya is still in its nascent stage as only a few on-farm researches have been undertaken. There is therefore knowledge gap on agronomic practices of integrated rice fish farming as well as economic feasibly, socioeconomic benefits, suitable fish species and rice varieties among other information required for adoption of the technology.

2.3 Global Fisheries and Aquaculture Production

Fisheries and aquaculture play an important role in providing food, opportunities for income and employment, foreign exchange earnings and contributing to livelihood improvement and poverty reduction of the rural poor (FAO, 2016). A small-scale fishery employs more than 90% of the people engaged in fisheries; majority being found in poorer countries of the world (Cochrane *et al.,* 2011).

Aquaculture provides a sustainable transition in over-exploited and overcapitalized capture fisheries to improve contributions to food security and poverty reduction. With an estimated 16.7×10^6 hm^2 area of pond aquaculture in 2011 around the world, freshwater aquaculture contributes significantly to inland fisheries production (Jescovitch, 2014). To achieve high yields, intensive culture characterized by high fish stocking density and high input of pelleted fish feeds has been used extensively in pond aquaculture (Bosma and Verdegem, 2011; Li *et al.,* 2011). Also, despite aquaculture sector creating employment alongside food products, it has been censured strongly for its negative environmental impacts as it discharges organic matter (OM) and nutrient-rich wastes into the environment (Bergheim *et al.,* 2019). Pond nutrient budgets shows that only 23.0% to 46.5% of the nitrogen and phosphorus in the feed is utilized by fish (Zhang *et al.,* 2018) with the remainder being either retained in the pond or released into the neighbouring water bodies leading to pollution of soils, water bodies and the environment. There has therefore been increasing calls for sustainable aquaculture systems to ensure environmental sustainability. Integrating fish with rice could be a viable technology to mitigate eutrophication since it enhances nutrients use efficiency thus reducing their release into the environment (Saikia *et al.,* 2015; Xie *et al.,* 2011).

2.4 Fisheries and Aquaculture Production in Kenya

The fisheries sub-sector in Kenya plays an important role in the national economy as an important source of food, nutritional security and employment creation opportunities. On average, fisheries sector contributes about 0.5% to the Gross Domestic Product (GDP) and provides direct employment positions to more than 500,000 people on top of supporting another more than 2 million people indirectly working as fishers, traders, processors, suppliers and merchants of fishing accessories and their dependents (KMFRI, 2017).

Most of the fishery's production in Kenya is from inland capture fisheries with comprising of more than 90% of inland capture fishery landing from Lake Victoria (Kimani *et al.,* 2018a). There has been a decline in fish production from the traditional capture fisheries from Lake Victoria and other lakes and an increasing demand for fish, particularly among the health-conscious people which has activated a surge in Kenya's yearly fish demand deficit (Odende *et al.,* 2022). Already a significant gap does exist between the projected production and fish demand that is anticipated to reach 553,000 MT by 2030 (Obiero *et al.,* 2019; Munguti *et al.,* 2021). This would make worse the already existing low average per capita fish intake of less than 5 kg person^{-1} year^{-1} in Kenya which is below the FAO recommended average of 20 kg person^{-1} year^{-1} (Ogello and Munguti, 2016) and can lead to high prices of fish yet fish is considered to be a `rich food for poor people. High prices not are desirable since fish is considered as one of the most accessible and affordable source of animal protein, providing key macro and micronutrients that are needed for human physical and mental development.

With the stagnating production and unsustainable nature of capture fisheries, the deficit can be bridged through aquaculture (FAO, 2020). However, despite being taunted as a panacea for household food security and poverty reduction, aquaculture has lost momentum and its performance in Kenya has remained dismal and today, the country imports fish. Further, aqua farming production by smallholder farmer's experiences performance gaps (Henriksson *et al.*, 2021) as the production from pond-based aquaculture has been registering low performance (KNBS, 2020). The decline has been attributed several constraints that include lack of efficient and economically affordable fish feeds, limited varieties of culture fish species, low quality seed fish, poor feed management skills, and high cost of aquaculture operations among other factors (Obiero *et al.,* 2019) which prompted some farmers abandoning their fish ponds that had been established under the Fish Farming Enterprise and Productivity Programme (FFE & PP).

The global food systems debate increasingly recognizes aquatic foods due to the higher-ranking of quality protein from fish for human consumption and nutrition (FAO, 2021). The urge to feed the inevitable ever increasing world population and address the corresponding increasing demand for fish production exerts immense pressure on the natural resources and therefore challenging sustainability of aquaculture development, marine and inland fisheries (FAO and World Vision, 2021). The widening gap between per capita production and demand can be bridged through refocusing aquaculture development strategies on other production systems. Also, the increasing scarcity of numerous inputs for aquaculture production (freshwater, land, energy, and feeds) and associated negative aquaculture impacts environmentally, there is need for low-cost intensification that is sustainable (SI), largely defined as "using less to producing more" (Henriksson *et al.*, 2018) in order to improve productivity of aquaculture and reduce negative impacts on environment (Waite *et al.*, 2014).

Integrated agriculture–aquaculture (IAA) systems, a form of sustainable intensification has been suggested as a strategy to reverse the declining performance of intensive aquaculture with rice cum fish farming being among most popular integrated agriculture–aquaculture systems (Nayak *et al.*, 2018). IAA links aquaculture with other agricultural farming systems either through direct integration or using off-farm by-products as inputs into aquaculture systems through indirect integration. It has successfully been implemented primarily in South Asia and southern China, where both rice farming and aquaculture are highly developed (Aditya *et al.*, 2010). Integrated rice–fish farming efficiently utilizes production spaces, similar to integrated multi-trophic aquaculture to produce grain and animal protein simultaneously, generating additional income for farmers and reducing the negative impacts of agriculture on the environment (Kibria and Haque, 2018). Integrated rice-fish systems entail culturing various fish species inside paddy fields for sale and/or domestic consumption. Rural communities in low and middle income countries across Asia depend on rice field fisheries as important source of nutrition security, food and livelihoods (Freed *et al.*, 2020).

2.5 Integrated Rice-Fish System

Green Revolution based agricultural intensification in agriculture and aquaculture relied upon intensified monoculture to increase rice and fish production which has come with huge unintended but harmful consequences on environment, agriculture and human health. There is evidence that agricultural intensification has not only failed to raise productivity, incomes and food security (Wise, 2020) but has also contributed to the unsustainable expansion of farming onto new lands. From an environmental perspective, agricultural intensification has vastly increased the ecological, energy and petrochemical costs of food production, raising concerns that industrial agriculture is contributing towards overstepping planetary biophysical boundaries (Campbell *et al.*, 2017; Rockström *et al.*, 2017). Further, according to Ray (2022), agricultural intensification has also been accelerating susceptibility of agricultural systems` to climate change hence threatening food production systems.

Monoculture cropping and use of synthetic fertilizers have been identified as the main drivers of soil acidification, soil infertility and biodiversity loss, which increase vulnerability to climate shocks and pest attacks. An assessment of the impact of the current Alliance for a Green Revolution in Africa (AGRA) concludes that Africa is on a pathway of over dependence on external inputs of fossil-fuel-based fertilizers and agrochemicals, worsening crop and diet diversity and recommends a to shift towards low-input sustainable farming under the banner of agro-ecology (Wise, 2020). Agro-ecological approaches that support biodiversity and utilize natural processes to grow multiple food crops in the same field, use bio-fertilizers and apply biocontrol methods are essential to transform current food systems to be sustainable with sound ecological outcomes (Freed *et al*., 2020). Because IAA requires limited resources to provide a sustainable method for climate change adaptation, mitigation and livelihoods, Anschell and Salamanca (2021) have termed it as a Climate-Smart Land Use for adaptation to Climate Change, Livelihoods and Mitigation.

Although rice is a victim of climate change, its production is also majorly a source of Greenhouse Gas Emissions (GHGE), mainly methane (CH_4) and nitrous oxide (N_2O) on account of anoxic environment in flooded rice field conditions and nitrogen-based fertilizer usage (Mboyerwa *et al.*, 2022). With increasing demand for rice, intensification may further accelerate CH_4 and N_2O emissions to the atmosphere (Gagnon *et al.*, 2011). Technologies that concurrently increase irrigation water use efficiency and productivity and reduce greenhouse gas (GHG) emissions from rice paddies without altering the grain yield need to be explored.

Integrated agriculture–aquaculture (IAA) has been suggested as an alternative to intensive monoculture cropping, because of its lower impacts on the environment and the positive impacts on rural livelihoods (Berg *et al.*, 2017). Apart from its potential ecological benefits, IAA can also become an effective climate change adaptation strategy by building households' resilience through livelihoods and income diversification, and producing more food using the scarce water more efficiently and productively. Integrated systems minimize waste and boost productivity by utilizing by-products formed by crops, fish systems and livestock and other waste being used as inputs for other subsystems. This too reduces farmers' dependence on inorganic fertilizer and other agro-industrial items especially commercial agrochemicals besides formulated feeds in pellet forms. Improving water-use efficiency through integrating rice production and aquaculture minimizes competition for other resources and water and offers additional food sources and income, a small buffer against climate variability (Miao, 2010). IAA utilizes the concept of circularity in integrated agricultural systems that minimize energy and materials use and reduce environmental impacts and create new business opportunities (Padilla-Rivera *et al.*, 2020). In addition, these low-cost forms of aquaculture can maximize bioproductivity by reducing waste of matter and energy from rice field ecosystem. The systems harvest and transform weeds, bacteria, phytoplankton, zooplankton, snails, and benthos that directly or indirectly compete with rice for nutrients and solar energy and effectively convert them into harvestable biomass in form of fish which otherwise represent a large portion of energy a farmer would have lost.

Rice cum fish culture farming has also been recognized as a strategy in integrated pest management (IPM) (Ahmed and Luong-Van, 2009). Fish in rice-fish farming functions as tool within system of IPM that makes rice production not only sustainable but also environmentally friendly while at the same time accruing monetary benefits as well as nutritional value. Rice-fish integration at the farm level, reduces fish feed requirements, use of agrochemicals in the farm, fish control human vector-borne diseases, among them malaria and schistosomiasis and also keep weeds and rice pests to threshold levels where the use of herbicides and pesticides is not economically justified. Fish manure serves as fertilizer improving soil fertility by boosting the availability of phosphorus and nitrogen (Ahmed *et al.,* 2011; Ahmed and Garnett, 2011) and feeds on disease vectors, insect pests and weeds thus reducing the need for agrochemicals (Xie *et al.,* 2011; Berg *et al.,* 2012). Various studies have advanced the idea that Integrated Rice-Fish Farming Systems (IRFFS) are eco-friendly and uses scarce land and water resources optimally resulting in diversification of farm production and household nutrition (Ahmed and Garnett, 2011; Ahmed *et al*., 2011).

In Egypt the potential of rearing fish within rice fields as an integrated system has increased, attracting the attention of many rice farmers in recent years (FAO, 2017). Agriculture and aquaculture Integration can contribute to reducing food insecurity, poverty, and malnutrition through provision of higher value nutritional foods, job creation and income (Omofunmi *et al.,* 2017). In Kenya, rice-fish culture has had little impact as it is still in nascent/formative stages of development but nevertheless, some farmers have embraced it using mainly cow and chicken manure for pond fertilization, leading to recorded impressive noticeable performance in certain areas (Ogello and Opiyo, 2011; Ogello *et al.,* 2013). However, this low-intensity system with its enormous potential has been an overlooked asset for the past and present aquaculture development even though, through its biophysical and socioeconomic benefits, it has immense potential to address income instability, food and nutritional insecurity, unemployment, and poverty of farmers (Ogello *et al.,* 2013).

2.5.1 Types of Integrated Rice-Fish Farming systems

Two types of rice cum fish farming integration based on the source of fish; culture and capture have been recognized. For the capture rice-fish system, wild fish enter the rice fields through irrigation canals, floods and reproduce in inundated rice fields and canals. It is practiced by trapping/catching fish in feeder/drain canals. In contrast, in the rice and aquaculture culture system, fish is deliberately stocked in the rice fields. Rice fish integration in rice farms is broadly classified into three 1) alternate (sequential/rotational) farming, 2) integrated (synchronous/concurrent) farming and 3) relay farming.

2.5.1.1 Alternate/rice-aquaculture rotation farming

In this system, fish and rice are cultured rotationally; fish species are stocked after harvesting rice in inundated fields while having rice stubbles. The water level is shallow in the case of rice, whereas for fish species, water depth is raised. The residues of pesticides used for rice production are expected to degrade during the interval between the harvesting of rice and subsequent stocking of fish. The rice straws in the water facilitate the growth of microorganisms that provide natural food for aquatic cultured species. The water and soil get enriched with natural fertilizer by the decomposition of stubbles for utilization by the next cycle of rice cultivation thereby improving rice yield. According to Reddy and Kishori (2019), the only limitation in alternate farming is about 20–60% loss of aquatic species due to piscivorous birds like herons and cormorants but besides this, sequential rice-aquaculture farming has many advantages such as (i) no limitation for depth of water neither in rice cultivation nor in aquatic species culture, (ii) maintenance of adequate water levels provides sufficient dissolved oxygen and water temperature, (iii) rice stubble decomposition facilitates microbial food for aquatic species and fertilizer for the next cycle of rice for improved production, (iv) useful for mono and polyculture of aquatic species and (v) reduced attack of insect pest on rice fields due to interruption in their life cycle in rotation farming.

2.5.1.2 Integrated system/ Synchronous/concurrent farming

In this integrated system, rice and fish are grown together concurrently in same field and are then harvested together cum harvesting time. The importance of rice-aquatic farming method synchronously is that production of aquaculture protein is realized with no extra cost; fertilizes ricefields from excretes of cultured aquatic species apart from enrichment of minerals (digging activity), destroying the weeds, and utilization of excess aquatic feeds by the rice plant. This is likely to increase rice yield compared to the conventional methods.

2.5.1.3 Relay farming

In relay farming, aquatic species and rice are usually started together similar to synchronous farming, but cultured aquatic species remain unharvested when rice crop is harvested and are allowed to grow to maturity. This farming system is more profitable if aquatic species are cultured with a rice variety that produces a ratoon to give a second rice crop. Relay farming needs extended period for aquaculture to mature. During harvesting of rice, the growing fish are transferred to refugia connected to the rice paddy field followed by restocking them back in the rice field after filling them up with water to allow further growth. Relay farming provides high amount of aquatic protein with high yield of rice crop within a short duration.

2.5.2.1 Net income return and yields in Integrated Rice-Fish System

Production in monocultures intensive agricultural systems usually requires a high input of agrochemicals, while rice–fish culture, in contrast, exploits benefits of synergies between the species to reduce chemical inputs thus maintaining higher stable crop output. Although culturing fish minimizes the land area available for cultivating rice, greater rice yield, extra income from sales of fish together with savings on agrochemicals (pesticides and fertilizer) lead to higher returns than from rice monoculture. The profit margins might be above 400% higher for rice farmers integrating higher-value aquatic species (FAO, 2016). In Bangladesh, farmers earned approximately 3 times greater profits from the rice cum fish culture compared to monoculture (Rahman *et al*., 2012). Thus, any loss of rice output is compensated by the higher extra income from the cultured fish as well as lower agrochemical cost under a rice cum fish system, hence the cost of fish introduction into a rice fields benefits outweigh the costs.

In terms of yields, where fish are kept in only a small area (“fish refugia”), fish yields are usually relatively low, and rice yield is not affected (Xie *et al.*, 2011; Ren *et al.*, 2014). Rice yields decrease with increasing fish refugia areas while increasing fish yield in intensive rice–fish systems but rice yield is not reduced if not more than 10% of the field area is used as a refugia (Hu *et al.*, 2016). Therefore, the current irrigated rice monoculture cropping system can be improved by introducing aquatic species into the system (Xie *et al.*, 2011).

2.5.2.2 Socioeconomic Benefits of Integrated Rice-Fish System

Due to high poverty levels in most irrigation schemes in Kenya, farmers are yet to achieve food self-sufficiency and nutrient deficiency mainly due to the insufficient consumption of animal protein attributed to high cost and a limited supply of protein sources rampant. Although the importance of fish culture in rice fields is socio-economically divergent, its contribution in addressing the shortfall of protein obtained from animals in rice growing areas is well-documented. Apart from being an efficient use of water, land and labour resources, rice cum fish culture is a basis of cheap, fresh animal protein. Studies have also shown that rice fish integration can reduce the need for external inputs inform of agrochemicals (Noorhosseini and Radjabi, 2010; Ahmed and Garnett, 2011) because fish increases soil fertility by improving the availability of phosphorus and nitrogen through feacal matter (Ahmed *et al.*, 2011; Ahmed and Garnett, 2011) and reduces insect pests and weeds (Ahmed and Garnett, 2011). The reduced use of agrochemicals lowers the production cost and therefore increases net income return to farmers in addition to that from sale of fish.

Rice-fish farming also can also improve nutrition particularly for low-income households in irrigation schemes through diversification of the usual monotonous rice diet. According to Rahman *et al*. (2012), the rice cum fish culture increases fish consumption and provides greater returns and employment opportunities than that of the rice monoculture. During field surveys in Malaysia, it was observed that rice fish culture farmer`s households usually consumed small sized fish instead of selling them in the market, making fish consumption to contribute in the nutrition (Rahman *et al.*, 2016) with small fish being a vital source of minerals, vitamins, and micronutrients, which are critical factors for the health and well-being. In Bangladesh, Ahmed and Luong-Van (2009) observed that concurrent rice fish farmers had a significantly greater portion of fresh fish in their diet compared to the rotational rice fish farmers. Thus, the switch from rice monoculture to integrated rice cum fish culture farming is not only merely a change in cropping system but also a switch to a more balanced diet (Ahmed *et al.,* 2011).

Although several laws and law-enforcing regulatory agencies exists to check the standard of food (like fish) and quality, the fish value chain, especially in the urban areas, is still adulterated (especially by the traders) through the use of different poisonous chemicals (like formalin) to preserve the fish fresh (Rahman, 2013; Uddin *et al.*, 2011). Awareness for this has resulted in a growing informative tendency in the consumers' preference for fresh live fish over the farmed fish under intensive aquaculture system resulting to very high price of green/organic food products than those produced under intensive monoculture systems. Rice-fish farming ecosystem can become a vital source of green and organic rice cum aquatic products to match the increasing consumer demand and preferences for organically produced agro-products. Rice-fish system has not only the potential of fulfilling consumers demand but can also become incentive stimulant for rice and fish monoculture farmers to change to an environmentally friendly ecosystem production systems due to higher income from organically produced rice and aquatic products and also a system for addressing adulteration of fish and the resultant health risks related to it.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

This study was carried out at Bunyala rice irrigation scheme (BIS) situated in Bundalangi sub-county in Busia County at coordinates 0.4347° N, 34.2422° E. The Bunyala Irrigation Scheme (BIS) is located on the Eastern side of Lake Victoria at central coordinates 34°03.658´E 00°05.797´N (Fig. 1).

The scheme specializes in growing of mainly IR 2793-80-1 rice variety where each farmer is allowed to cultivate 1.6 ha of irrigated rice in four fields, each measuring 0.4 ha. Rice is grown through continuous flooding using water drawn from river Nzoia. In 2018, the scheme irrigated 1734 acres out of the gazetted 1,880 acres with 1,394 farming households, National Irrigation Board (NIA, 2023) and over 2,500 acres in 2022 (NIA, 2022). In early 2024, the Bunyala Irrigation Scheme in Busia County was reported to have 3,246 acres under cultivation, National Irrigation Authority (NIA, 2025).

The scheme is an alluvial flood plain that is almost flat. The altitude ranges between 1135-1200 m above sea level with mean temperature range of 22.7-22.3^{0}C. Annual rainfall averages 900-1100 mm and is binomial with most of it falling in the first season (400-480 mm) months. The long rains occur between March and May while the short rains fall between October and December. Bunyala constitutes flood plain of poorly drained alluvial sediments made up of deep, gray- brown to very dark grey, mottled, very firm, saline and sodic, cracking clay soils (Jaetzold *et al.*, 2005).

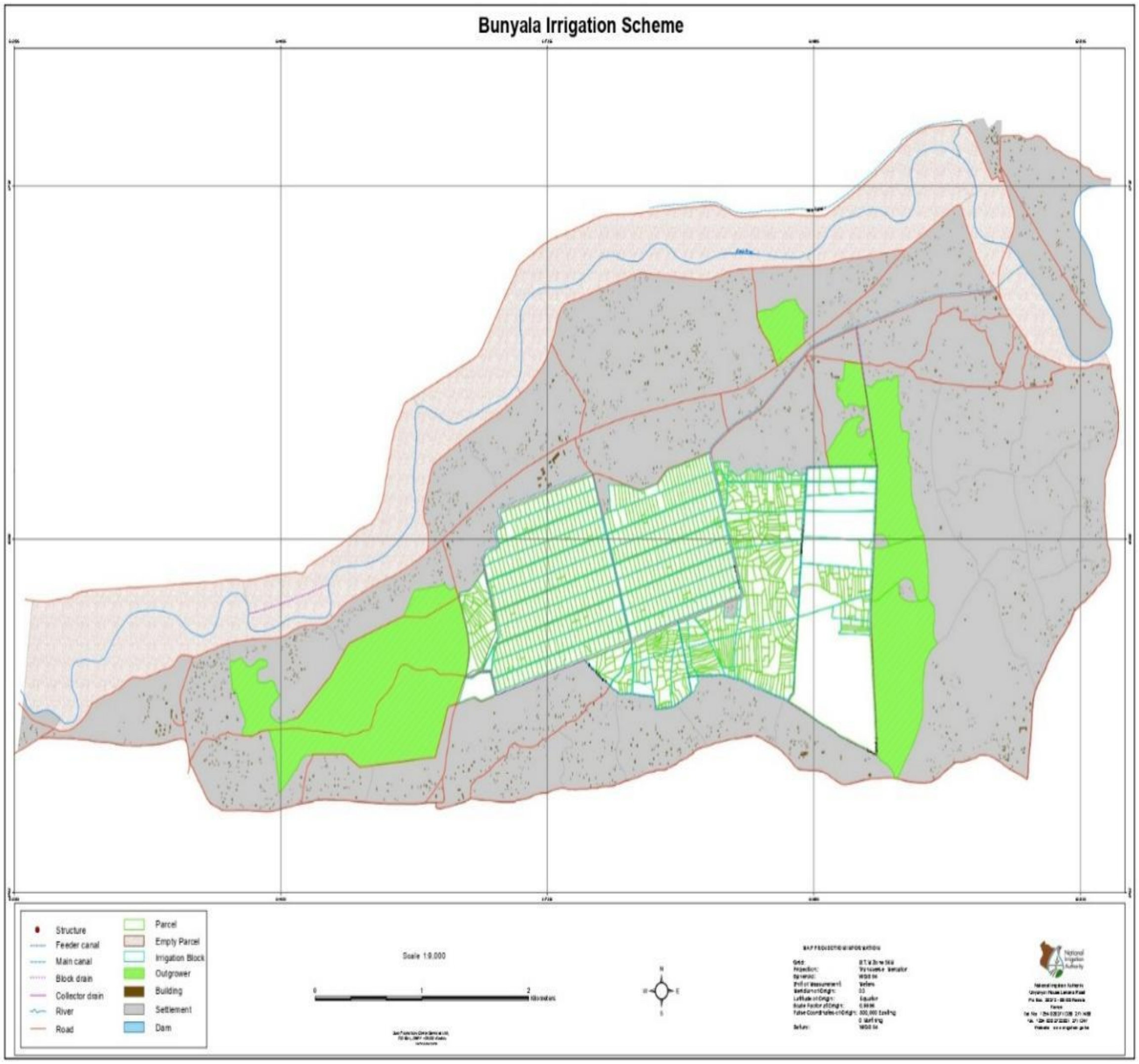

Figure 1 Map of Bunyala Irrigation Scheme (BIS)

3.2 The type of Integrated Rice-Fish Farming system used in the study

The relay rice fish farming system was used where two 2 rice varieties, IR 2793-80-1 and Basmati 370 and Nile tilapia (*Oreochromis niloticus* L.) of mixed sex were grown simultaneously in the same field. Nile tilapia is a fast-growing fish species, contracts fewer diseases, mature quickly, grow in a wide environment and has omnivorous-herbivorous feeding habits, offering an opportunity for biological weed and rice stem pest control. Basmati 370 rice variety was introduced in this study from Mwea Irrigation Scheme, it is aromatic, produces ratoon as second crop and fetches high market price compared to the locally grown IR 2793-80-1 rice variety.

Fish were allowed to grow to maturity and harvested at 240 Days After Sowing. Rice was harvested in all sixteen plots after120 and 140 days after transplanting (DAT) for Basmati 370 and IR 2793-80-1 respectively. During rice harvesting, fish were transferred to fish “refugia”. After harvesting rice, the ricefields were filled up with water for further growth.

3.3 Field preparation/ plot modifications

Two plain pieces of land each measuring one acre were selected from two farmers, one piece from each farmer. The two pieces of land were separately labeled as Block 1 (Farmer 1), for one piece and Block 2 (Farmer 2) for the other piece respectively. Each of the Block; 1 and 2 were subdivided into eight equal plots each measuring 20 m by 26 m and subsequently, each plot in each block was randomly numbered from1 to 8 (Fig. 2).

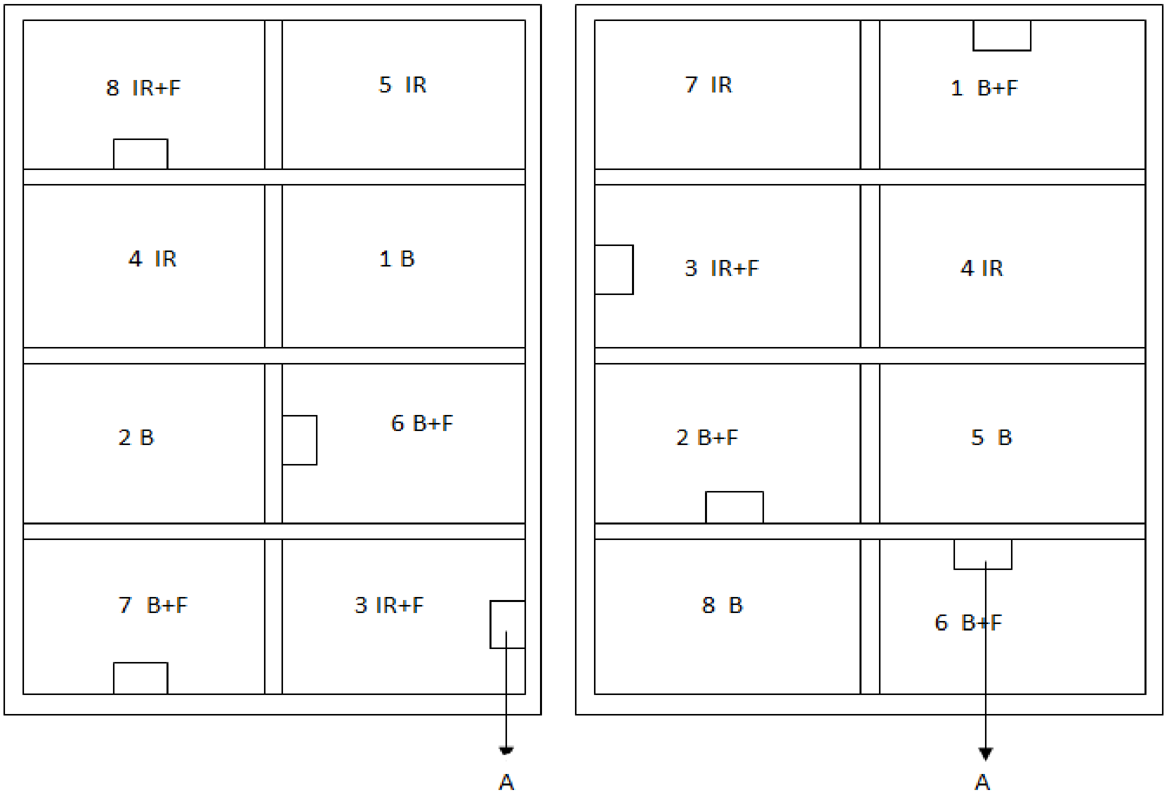

Figure 2. Experiment Layout

KEY: 1-8= Random Numbers IR=IR Rice variety B=Basmati A = Refugia F = Fish

Each of the Blocks 1 and 2 comprised of two controls of each of the two rice varieties; IR 2793-80-1 (IR) and Basmati 370 (B) (monoculture); labeled IR and B respectively and one plot, each of B and IR in combination with a fish culture of Nile tilapia (*Oreochromis niloticus* L.) as IR together with fish (IR + F) and Basmati together with fish (B + F) respectively as rice-fish cultures. The controls and the treatments were randomized in the 8 plots per block and each replicated twice in each block in a complete randomized block design (CRBD) (Fig. 2).

For each plot with fish, a fish “refugia” was constructed by excavating a trench of 10 m by 5.2 m and a depth of 1m at one end of each plot (10% of the entire area of the rice plot) (Fig. 2). The water feeder canal into each treatment plot and the drain were sealed with screens of bamboo sticks to prevent cultured fish from escaping and foreign fish from entering into rice fish plots, respectively. Pesticides and inorganic fertilizer were not applied to the crop in rice-fish culture and no supplementary feed was used for fish while standard application of inorganic fertilizer and pesticides was applied to all rice monoculture plots in amounts recommended by BIS management.

3.4 Land preparation

After delimiting and constructing dykes 45 cm high and 30 cm wide around each plot, the bamboo screens on exit/ drain were closed and water from feeder canal was allowed in to flood each plot at least four days before rotavation (pre-rotavation flooding) to soften the soil and kill submerged weeds. There after flooded plots were rotavated (by use of a tractor-pulled rotavator) and then left fully flooded for a further fourteen days to promote decay of rotavated weeds and minimize growth of fresh weeds.

3.5 Nursery Preparation

Two separate nurseries (one for IR and the other one for Basmati) each measuring 7.5 m by 15 m were delimited from the rotavated flooded plots earmarked for rice monoculture on the fourteenth day and dikes constructed along the boundaries to contain flooded water. The Wet-Nursery Method according to International Rice Research Institute (IRRI, 2007) was used in nursery preparation where Ammonium Sulphate fertilizer (21% Nitrogen) was applied at a rate of 4.2 kg ha^{-1} for Basmati 370 and 4.9 kg ha^{-1} in IR 2793-80-1 by hand broadcast to entire wet seedbeds. Thereafter, water-soaked and sunshine incubated certified paddy rice seeds packed separately in bags were sowed by hand broadcast to the separate nurseries at the rate of 25 and 20 kg for IR 2793-80-1 and Basmati 370 respectively. Soaking of the seeds in water was done for 24 hours and then the soaked seeds were incubated under sunshine for a period of 48 hours (to enhance germination). Thunder fungicide/pesticide was sprayed on seedlings two days before transplanting (6th Day After Sowing) to control rice blasts and insect pests.

3.6 Rice Transplanting

After necessary land preparations and removal of predatory or invasive fish species or other animals from the culture plots, eight-day old nursery raised rice seedlings (10 cm tall from tip of root to that of flag leaf) of both varieties were transplanted in straight lines on wet (not flooded) plots at specific intervals of 20 cm between rows and 16 cm between hills. This translated in to a density of 14014 seedlings in each of control plot but at 10% lesser seedlings density in the rice fish (treatment) plots due to exclusion of plot area occupied by the refugia. Rice seedling transplanting was done on wetland by straight rows method (IRRI, 2007). First irrigation (plots water- flooding by opening feeder canals to allow water into the wet plots to flood them) was done 8 days after transplanting (DAT) followed by gapping (replacing of the dried or destroyed rice seedlings into respective hills by replanting new ones).

3.7 Pesticide and fertilizer application in monoculture rice fields

Sulphate of Ammonia (21% Nitrogen) fertilizer was applied in three splits at 10, 50 and 75 Days After Transplanting (DAT) by broadcasting at a rate of 370.4 kg ha^{-1} for Basmati and 432 kg ha^{-1} for IR in all monoculture plots. Pentagon pesticide and Pearl fungicide were applied in three splits at a rate of 240 ml ha^{-1} and 480 ml ha^{-1} respectively on the 10th, 30th and 50th DAT in all monoculture plots.

3.8 Fish Stocking

Mixed sex fingerlings of Nile Tilapia each weighing an average of 19 ± 0.08 g and length of 8.5 ± 0.07 cm sourced from the Dominion Farm were stocked on the 14th day after transplanting (DAT) rice at a standard stocking density of 3 fingerlings per square meter of the ditch; (3000 fingerlings per hectare). This translated in to 156 fingerlings per plot. Once fish were stocked, water depth in rice-fish plots was raised gradually from 5 cm to 10 cm and finally to a depth of 20 cm at final plant height by 35th DAT and maintained until harvest. Monitoring of the water physico–chemicals parameters and determination of the growth and yield of both rice crop and fish followed.

3.9 Measurements of water parameters

Water quality parameters (dissolved oxygen (DO), pH, temperature and electrical conductivity (EC) were monitored *in situ* weekly for eight months at 0900 and 1600 hrs using TetracCon 340i water DO/pH/conductivity meter/probes made in Germany. Measurements of temperature, dissolved oxygen concentration, pH and Electrical

Conductivity were made from the same spot/point for each treatment (experiment and control plots) by dipping the probe to a depth of 10 cm at 0900 and at 1600 hrs. The probe was allowed to stand for two minutes after which the readings were recorded. Total Alkalinity and Nitrate (NO_3-N) were determined through titration and calorimetric methods respectively in Plant Sciences Department laboratory, Kenyatta University.

3.10 Growth and Yield of rice varieties

Data on plant height was determined at rice harvest by measuring by use of a meter ruler, the height of 10 plants in each of 10 hills randomly picked from an area of 1 m^2. The same was repeated in ten samples per each of the two controls and two treatments plots.

Data on tillers per stool was collected at the end of tailoring phase /vegetative stage of growth of rice (35 and 45 DAT for Basmati and IR respectively) by taking counts of all tillers in each of the 10 hill samples randomly picked from an area of 1 m^2 of each of the experimental plots and the same was repeated for ten samples per plot from experiment and control plots. A similar procedure was done for total effective tillers. The incidence of stem-borers was assessed by taking counts of all dead tillers 84 Days After Transplanting (DAT), in an area of 1 m^2. This was the stage at which stem-borers are reported to have inflicted maximum damage to the rice plants (Viajante and Heinrichs, 1987). This was done by taking counts of total dead tillers per hill in (10) ten hills randomly picked per^{-1} m^2 per treatment and the same repeated in both experiment and control plots.

At maturity120 (B), 140 (IR) DAT), water was drained out from all plots gradually allowing fish to move to the refugia. The following day, rice in all plots was harvested manually by use of long stalk cutting by sickle and put in separate bags per plot. Threshing was done by flailing panicles on threshing racks over tarpaulins. The paddy grains per treatment were sun dried to a constant moisture content of 14%; measured by BIS moisture content meter, digital GP-Grain Pro moisture meter ANALZ ER Model 2211213 made in DENMARK by spreading them on designated drying pans.

For each treatment, 1000-paddy seeds were sampled, weighed and weight recorded. Thereafter all dried paddy grains were separately packed per treatment into 80 kg bags and sold to Bunyala Irrigation Scheme Sacco and gross income recorded per each of the two controls and treatments.

Immediately after harvesting rice, IR + F, B + F and B plots were flooded with water to produce a second crop (ratoon) in Basmati plots and to allow fish to continue growing until the end of maturity period of ratoon by the 226th Days After Stocking (DAS). Harvesting of ratoon and processing was done similarly to that of the main rice crop.

3.11 Growth and Yield of Nile Tilapia (*Oreochromis niloticus* L.)

Monitoring of growth rate of Nile tilapia in the plots was carried out monthly for 8 months by randomly catching 45 fish from each of the rice-fish plot by use of seine fishing hand net. The weight and the length measurements of each fish were taken and the fish were immediately returned to the refugia. The length of each fish was measured from tip of mouth/snout to that of posterior vertebra using a ruler and recorded to the nearest cm. Each of the 45 fish samples from each rice-fish plot were placed in a light plastic bag and the weight to the nearest g recorded from an electronic digital weighing scale balance (CAMRY= Model: EK 3052).

All fish were harvested per treatment plot after 226 Days After Stocking (DAS), using seine net from the ditch after allowing all of them to gather in the fish refugia gradually soon after harvesting ratoon rice. All the fish from each of the treatment plots, IR + F and B + F were counted and weighed. Standard length of fish was determined at harvest by taking length of 45 fish samples randomly selected from each treatment (IR + F and B + F) in each block. Total number and wet weight of all fish per treatment was recorded by aggregating the number of fish and weight of each treatment respectively. The recovery rate (%), specific growth rate (%) and yield (kg ha^{-1}) of fish was determined for each set of IR+F and B+F plots, by using equations (1) to (3) respectively (Usman *et al*., 2021). The following equations were used to determine by calculation, the different growth parameters of fish:

Weight gain (g) = Average final weight (g) - average initial weight (g)

Weight gain (%) = Mean final weight − Mean initial weight X 100

$$\text{Recovery rate (SR, \%)} = \frac{\text{Number of fish harvested}}{\text{Number of fish stocked}} \text{ X } 100 \text{ …......…..........….....} \quad (1)$$

$$\text{Specific growth rate (\%)} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1} \text{ X } 100 \text{ ……………………….................} \quad (2)$$

W_1= the initial live body weight (g) at time T_1 (day) and W_2= the final live body weight (g) at time T_2 (day).

$$\text{Yield (kg ha}^{-1}\text{)} = \frac{\text{Total weight of the fish harvest (kg)}}{\text{Area of all plots (ha)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

3.12 Net income determination for culture systems

Rice and fish were sold and Gross Income (GI) from sale of variety of and fish of each treatment was recorded. To find Gross Expenditure, all the costs of production were summed up. Net Income (NI) was calculated as the difference between Gross Income (GI) and Gross Expenditure (GE) as follows:

1. Gross Income (GI) = (Sales of rice + Sales of fish).
2. Gross Expenditure (GE) = Total Variable Costs (Seeds, fertilizer, feed for fish, fingerlings, fertilizer, and hired labor, electricity) + Total Fixed Costs (land rent, digging ditches, building embankments).
3. Net Income (NI) = Gross Income - Gross Expenditure.

3.13 Statistical analysis

Data collected on selected physico-chemical parameters of water, rice and fish growth parameters were tested for homogeneity of variance and normal distribution using Levene's and Kolmogornov–Smirnov tests, respectively. When the homogeneity of variances was achieved, ANOVA was used to test for significant differences in physico-chemical of water, rice and fish growth parameters and yield. Significant means were separated using the Tukey test. Results are presented as means with standard errors. The level of significance of 5% was adopted in all statistical analyses.

CHAPTER FOUR

RESULTS

4.1 Water quality parameters

The survival, growth and productivity of fish in a rice field are determined by the physico-chemical parameters of water. Table 1a and 1b show the results of monthly means (± S.E.) of selected water physico-chemical parameters (Dissolved Oxygen (DO), temperature, pH, Electrical Conductivity (EC), NO_3-N and Alkalinity) recorded in the rice fields and refugia for 8 months.

4.1.1 Dissolved oxygen

In all plots, the mean values of dissolved oxygen (DO) were generally higher in the afternoon (1600 hrs) than in the morning (0900 hrs) in both the rice fields and fish refugia. In both rice varieties, the DO values were significantly ($p \leq 0.05$) higher in rice monocultures than in integrated rice fish cultures and fish refugia in the morning but was similar in all plots in the afternoon. In the morning, DO in integrated rice fish cultures and fish refugia was below the 5 mg l^{-1} but rose gradually as the day progressed. At 0900 hrs, the DO ranges were 5.03 ± 0.1 - 5.08 ± 0.09, 3.94 ± 0.08 - 3.98 ± 0.07 and 3.29 ± 0.16 -3.5 ± 0.11 mg l^{-1} in rice monocultures, integrated rice fish cultures and fish refugia respectively. The afternoon values ranged between 6.18 ± 0.23 and 4.83 ± 0.09 mg l^{-1}.

4.1.2 Water Temperature

At 1600 hrs the average water temperature was generally higher than at 0900 hrs in all plots. Temperature showed no significant ($p \geq 0.05$) difference across all plots during the day but in temperature was significantly ($p \leq 0.05$) higher in the afternoon than in the morning.

Table1a. Mean (± S.E) water physico-chemical parameters at 0900 hrs.

	Rice culture			Fish refugia		
Water parameter	**B**	**IR**	**B+F**	**IR+F**	**B+FR**	**IR+FR**
DO (mg l^{-1})	5.08±0.09^a	5.03±0.1^a	3.98±0.07^b	3.94±0.08^b	3.5±0.11^b	3.29±0.16^b
Temperature (^{o}C)	23.9±0.02 ^{a}	23.4±0.07^a	24.3±0.33^b	24.1±0.12 ^{b}	23.1±0.17^a	21.95±0.07^c
pH	5.42±0.02 ^{a}	5.48±0.02^a	5.97±0.03^a	5.37±0.01^a	5.29±0.01^a	5.29±0.01^a
EC (µS cm^{-1})	261.48±45.00^a	248.33±40.38^a	199.86±13.45^b	182.04±13.88^b	197.76±19.02^b	204.39±18.53^b
NO$_3$ (mg l^{-1})	0.45±0.00^a	0.55±0.00^a	0.32±0.00^b	0.39±0.01^b	0.23±0.00^b	0.28±0.29^b
Alkalinity (mg l^{-1})	23.14±0.03^a	26.39±0.03^b	24.49±0.02^a	27.49±0.04^b	22.5±0.00^a	25.4±0.00^b

Mean values in the same row followed by the same superscript letter(s) indicate not significant difference ($p \geq 0.05$).

Key: IR=IR Rice variety B=Basmati F = Fish FR=Fish Refugia

Table1b. Mean (± S.E) water physico-chemical parameters at 1600 hrs.

	Rice culture		Rice-Fish		Fish refugia	
Water parameter	**B**	**IR**	**B+F**	**IR+F**	**B+FR**	**IR+FR**
DO (mg l^{-1})	5.74±0.13 ^{a}	6.18±0.23^b	5.65±0.14^a	5.78±0.13^a	5.05±0.07^c	4.83±0.09^c
Temperature (^{o}C)	29.36±0.08^a	27.19±0.15^b	29.06±0.10^a	28.13±0.08^c	27.89±0.06^b	26.72±0.045^b
pH	6.76±0.04^a	6.73±0.03^a	6.55±0.04^a	6.52±0.03^a	6.44±0.02^a	6.42±0.02^a
EC (µS cm^{-1})	280.64±51.78^a	201.77±33.07^b	203.03±14.47^b	186.14±14.68^b	213.49±19.01^b	205.89±18.66^b

Mean values in the same row followed by the same superscript letter(s) indicate not significant difference ($p \geq 0.05$.

Key: IR=IR Rice variety B=Basmati F = Fish FR=Fish Refugia

The temperature range was 24.3 ± 0.33 and 21.95 ± 0.07 in the morning, and then rose to between 29.36 ± 0.08 and 26.72 ± 0.045 in the afternoon with no discernible pattern across all plots.

4.1.3 Water pH

At 1600 hrs the average water pH was significantly ($p \leq 0.05$) higher than at 0900 hrs in all plots. The pH in all the plots remained slightly acidic throughout the study, ranging from 5.29 ± 0.01 to 6.76 ± 0.04. The average pH values were not significantly ($p \geq 0.05$) different between rice monocultures, the integrated rice fish cultures and fish refugia.

4.1.4 Water Electrical Conductivity (EC) (μscm^{-1})

The mean EC was significantly ($p \leq 0.05$) higher in rice monocultures than in integrated rice fish cultures both at 0900 and 1600 hrs. Also, for both rice varieties and cultures, the mean EC was significantly higher at 1600 than at 0900 hrs. However, there was no significant ($p \geq 0.05$) difference in EC between the rice varieties in rice monocultures and between integrated rice fish cultures as well fish refugia even though it was slightly higher in rice monocultures than in integrated cultures. Notable, EC in rice monocultures both at 0900 and 1600 hrs showed two distinctive peaks each at 1st and 3rd months, corresponding to the time of application of inorganic fertilizers.

4.1.5 Nitrates

Nitrate concentration observed was significantly ($p \leq 0.05$) higher in rice monoculture (0.45 ± 0.003 to 0.55 ± 0.003) compared to in both integrated rice-fish (0.32 ± 0.004 to 0.39±0.01) and fish refugia (0.23 ± 0.00 to 0.28 ± 0.29). There was no significant ($p \geq 0.05$) difference between the rice fish cultures and fish refugia.

4.1.6 Alkalinity

Total alkalinity differed ($p \geq 0.05$) significantly between rice varieties with higher values in all cultures of IR than Basmati cultures.

4.2 Indices of rice growth and yield

Results of means on selected rice growth parameters and yield are presented in table 2. There were no significant ($p \geq 0.05$) difference between rice monoculture and integrated rice fish cultures of the same rice variety in terms of rice height, total tillers, effective tillers and 1000 grain weight but Basmati were significantly ($p \leq 0.05$) taller than IR in all cultures. However, dead tillers were significantly ($p \leq 0.05$) higher in the rice monocultures, (IR and B) than in integrated rice fish cultures, (IR + F and B + F). Mean rice yield was highest (4616 ± 313.53 kg ha^{-1}) in IR rice monoculture and lowest (3656 ± 192 kg ha^{-1}) in B integrated rice–fish culture (Table 2). Although not significant ($p \geq 0.05$), yields were higher in monocultures than in their respective integrated rice–fish systems. Also, there was significant ($p \leq 0.05$) difference in rice yield between varieties of rice monocultures (IR and B) and between their integrated rice–fish systems (IR + F and B + F). Also, yields were significantly ($p \leq 0.05$) higher in all cultures of IR (IR, IR + F) than in all Basmati cultures.

4.3. Fish Growth parameters and yield in integrated rice fish cultures

The results of fish growth parameters and yield are presented in Table 3. In terms of final weight, recovery rate, specific growth rate and fish yield, there was no significant ($p \geq 0.05$) difference between the IR and B rice–fish cultures.

Table 2. Mean (± S.E) indices of rice growth and yield in rice monoculture and integrated rice fish cultures.

Growth parameter	IR	IR+F	B	B+F
Height at harvest (cm)	73.29± 0.49^{a}	73.19 ± 0.70^{a}	124.45± .96^{b}	123.53 ± 0.85^{b}
Total tillers hill^{-1} m^{-2}	29.93 ± 0.24^{a}	29.68 ± 0.55^{a}	26.63 ± 0.07^{a}	26.28 ± 0.2^{a}
Dead tillers hill^{-1}m^{-2}	5.83 ± 1.55^{a}	3.85 ± 0.13^{b}	4.80 ± 0.20^{a}	3.03 ± 0.13^{b}
Effective tillers hill^{-1}m^{-2}	25.53 ± 0.08^{a}	25.4 ± 1.55^{a}	21.83 ± 0.19^{a}	21.48 ± 0.39^{a}
1000 grain weight (g)	21.73 ± 0.89^{a}	20.93 ± 0.74^{a}	21.43 ± 0.36^{a}	20.38 ±0.31^{a}
Rice yield (kg ha^{-1})	4616± 13.53^{a}	4136± 83.8^{b}	3944±327.9^{c}	3656 ± 192^{d}

Means in the same row with same superscript letter(s) indicate no significant different ($p \geq 0.05$).

Key: IR=IR Rice variety B=Basmati F = Fish

Table 3. Mean (± S.E) fish growth parameters and yield.

Growth parameters and yield	**B + F**	**IR + F**
Mean stocking weight (g)	19 ± 0.08^{a}	19± 0.08^{a}
Mean harvest weight (g)	112.03 ± 0.132^{a}	112.04± 1.08^{a}
Mean harvest length (cm)	17.1± 0.10^{a}	16.96 ± 0.10^{a}
Mean stocking length (cm)	8.5± 0.07^{a}	8.5 ± 0.07^{a}
Recovery rate (%)	49.04 ± 4.14^{a}	49.36 ± 4.66^{a}
Growth rate (g/day)	0.41^{a}	0.41^{a}
Specific Growth Rate (%)	3.42^{a}	3.42^{a}
Fish yield (kg ha^{-1})	164.81 ± 15.66^{a}	165.9 ± 13.93^{a}

Mean values followed by the same superscript letter (s) in each row indicate no significant difference ($p \geq 0.05$).

Key: IR=IR Rice variety B=Basmati F = Fish

4.4 Mean net income from rice monocultures and integrated rice fish cultures

Mean production expenditure and net income from both rice monocultures and integrated rice fish cultures are presented in Table 4 and 5. Expenditure was higher in integrated rice fish cultures than in rice monocultures, 31.43 and 27.89% for IR + F and B + F respectively. Mean net rice income from rice monoculture (IR) and (B) and integrated rice-fish (IR+F) and (B+F) ranged between KES 40,835.38 ± 8361.8 and 121,887.82 ± 8763.3 in IR monoculture and integrated B + F culture respectively with mean net income from IR + F and B falling in between (Table 4 and 5). Although rice yield was higher in monocultures than in integrated cultures, net income from integrated rice fish cultures was slightly higher than from their respective monocultures but not significant. The net income from integrated rice fish cultures was significantly higher in B + F than from IR + F.

Table 4. Net income from rice monocultures and integrated cultures.

Income Data	**B + F**	**B monoculture**	**IR+ F**	**IR monoculture**
Rice yield (kg ha $^{-1}$)	3,656 ±192^{a}	3,944 ±327.90^{ab}	4,136± 183.8^{bc}	4,616± 13.53^{c}
Fish yield (kg ha $^{-1}$)	164.81 ±15.66^{a}	-	165.9 ±13.93^{a}	-
Rice Gross Income (KES ha $^{-1}$)	205,528.85 ± 10817	221,754.81± 18474	144,711.54± 6444	161,538.46± 10991
Fish Gross Income (KES ha $^{-1}$)	74,163.5 ± 7047	-	74,661.1 ± 6268	-
Rice Net Income (KES ha $^{-1}$)	144,080.58±10697^{a}	88,491.63±1826^{b}	83,143.08±644^{bc}	40,835.38± 10795^{d}
Rice + Fish Gross Income (KES ha $^{-1}$)	279,692.31±11313.	221,754.83±18474	219,372.59±9116	161,538.48±10991
Rice + Fish Expenditure (KES ha $^{-1}$).	157,804.46 ±10731^{a}	133,263.17±205.27^{b}	157,804±10731^{a}	120,703.08±196^{b}
Rice + Fish Net Income (KES ha $^{-1}$)	**121,887.85 ±8763.3^{a}**	**88,491.63±141596^{b}**	**61,568.13±7061.3^{b}**	**40,835.38± 361.8^{c}**

Mean values followed by the same superscript letter (s) in each row indicate no significant difference ($p \geq 0.05$).

Key: IR=IR Rice variety B=Basmati F = Fish

Table 5. Summary of Input Costs and Economic Income Comparisons to a farmer between Rice monocultures and integrated Rice-Fish cultures.

Production data for Rice-Fish and Rice alone culture (Basmati 370 and IR)				
Data	**B+ F**	**B monoculture**	**IR+ F**	**IR monoculture**
Stocking density (fingerlings ha^{-1})	3000	0.00	3000	0.00
Mean weight at stocking (g)	19 ± 0.08	0.00	19 ± 0.08	0.00
Mean weight at harvest (g)	112.03 ± 0.132	0.00	112.04 ± 1.08	0.00
Mean length at harvest (cm)	17.1 ± 0.096	0.00	16.96 ± 0.1	0.00
Mean stocking length (cm)	8.5 ± 0.07		8.5 ± 0.07	
Specific length gain (cm day^{-1})	0.038	0.00	0.037	0.00
Mean weight gain (g day^{-1})	93.03	0.00	93.04	0.00
Specific mean weight gain (g day^{-1})	0.412	0.00	0.412	0.00
Survival Rate (%)	49.04 ± 4.14	0.00	49.36 ± 4.66	0.00
Culture period (days)	226	0.00	226	0.00
Fish yield (kg ha^{-1})	164.81 ±15.66	0.00	165.9 ±13.93	0.00
Fish Gross Income /ha (KES)	74163.5 ± 7047.8	0.00	74661.1 ± 6268.65	0.00
Rice Gross Income (KES) ha^{-1}	205528.85 ± 10817.31	221754.81 ± 18474.07	144711.54± 6444.22	161538.46 ± 10991.3
Rice Net Income (KES) ha^{-1}	144080.5769±10697	88491.63462 ± 18268.	83143.07692 ± 6444	40,835.38 ± 10,795
Rice + Fish Gross Income (KES) ha^{-1}	279692.31±11313.	221754.83 ± 18474	219372.59 ± 9116	161538.48 ± 10991
roduction Expenditure (KES) ha^{-1}	157804.46± 0.14	133,263.17± 205.27	157804.49 ± 0.18	120,703.08 ± 196.27
Rice + Fish Net Income (KES) ha^{-1}	121887.8237± 8763.3	88491.63269±14150.96	61568.13±7061.3	40835.38654 ± 8361.8

Key: IR=IR Rice variety B=Basmati F = Fish FR=Fish Refugia

CHAPTER FIVE

DISCUSSION

5.1 Water quality parameters

There is a specific set of water characteristics that are crucial for optimal performance of aquaculture system (DeLong *et al.,* 2009). Monitoring the water physico-chemical in paddy-aquatic animal water is essential to determine the suitability of aquatic environment for the growth of aquatic organisms.

5.1.1 Dissolved Oxygen (DO)

All aquatic organisms need DO for respiration and metabolic processes for the production of energy required for growth and development (Hamuna *et al.,* 2018). Generally, fish growth and yields are greater in aquatic ponds with higher DO concentration (Bartholomew, 2010). In this study, all rice cultures and fish refugia had in the morning a DO level close to 4 mg l^{-1}, the minimum recommended for tilapia growth (Boyd and Tucker, 2015; Sousa *et al.*, 2018) and rose gradually to over 5 mg l^{-1} in the afternoon. The observed low DO levels in the morning could be because of respiration by fish and other aquatic organisms while photosynthesis was low due low Photosynthetically Active Radiation (PAR).

Optimal DO levels reached in the afternoon can be attributed to increased photosynthesis (by algae, aquatic weeds and phytoplankton) due to high light intensity in the afternoon. The findings of the present study are consistent with Sriyasa *et al*. (2015) findings that DO level rises with increase in PAR as the day progressed with a maximum DO being recorded between 14:00 and 16:00 in the afternoon and thereafter continued to decrease till early morning. This pattern of lowest dissolved oxygen in the early morning, and increasing during daylight to peak late in the afternoon and thereafter decreasing at night is similar to that reported elsewhere (Diemer *et al.*, 2010). In the morning, both integrated cultures had lower DO than monocultures which can be attributed to consumption of oxygen by fish.

Bhatnagar and Singh (2010) suggested that DO level greater than 5 mg l^{-1} is essential to support good fish production. In this study, DO was ≥ 3 mg l^{-1} across all plots which is within the suitable range for fish growth. The findings of the present study are consistent with those of Victory *et al.* (2018) who recorded a DO mean value of 5.13 ± 1.04 and range of 4.0-7 mg l^{-1} in an integrated fish cum rice culture pond.

5.1.2 Water temperature

Water temperature is among the most crucial environmental factors that control the aquatic species physiological behaviour and distribution (Moundiotiya *et al.*, 2004). Omweno *et al.* (2022) suggested an optimum range from 25 to 30°C for the growth of Tilapia and a temperature range of 20–30°C has been recommended for optimum growth and survival of most tilapia species (Makori *et al.*, 2017). The temperature range recorded during the present study is therefore within the ideal range for optimum growth of Nile tilapia, an indication that water temperature in integrated rice fish culture is suitable temperature for growth of tilapia.

5.1.3 Water pH

Water pH is a key indicator of the quality of water which affects fish metabolism and physiological processes with significant control on ammonia toxicity. It influences many other parameters, including the rate of nitrification and it is therefore important to maintain pH at levels that are acceptable to both fish and plants. Nile tilapia can tolerate water pH between 5 and 10 but performs optimally at a pH range of between 6 and 9 (DeWalle *et al.*, 2011) which is consistent with findings of this study of slightly acidic pH (5.29 ± 0.01 - 6.76 ± 0.037) in both integrated rice cum fish cultures and monocultures. In this study, both the integrated rice fish plots and the fish refugia had slightly acidic pH but within the range recommended as optimal for fish growth. Although tilapia can tolerate a pH as low as 3.7 and as high as 11.0, Ghozlan *et al.* (2017) and Omer (2019) recommended a pH range of between 6.5 and 9.0 as being optimum for most tilapia species and while Rebouças *et al.* (2016) suggested a range of 5.5 to 9.5.

In this study, the acidity observed could be attributed to the low buffering effect of water due to the recorded low alkalinity resulting in accumulation of carbon dioxide which lowers the pH. The low pH could also be due humic acids resulting from the decomposition of aquatic weeds and rice stalks left over. In this study, higher pH values were recorded in the afternoon than in the morning. During the day pH increases as CO_2 is utilized by photosynthesis and therefore less carbonic acid driving pH values up while at night, respiration increases concentrations of CO_2, which interacts with water to produce carbonic acid (H_2CO_3), lowering the pH.

5.1.4 Electrical Conductivity (EC)

Electrical conductivity is a critical water quality parameter in aquaculture because it regulates fish growth and development (Kumar *et al.*, 2023) by influencing primary productivity (Bhatnagar and Devi, 2013). EC primarily indicate water salinity, which affects a fish's ability to maintain osmotic balance and can lead to osmotic stress. High conductivity, or saltiness, can harm freshwater fish by causing water loss and can alter entire fish communities by favoring salt-tolerant species over freshwater-dependent ones. Conversely, high conductivity can signal water pollution, which negatively impacts aquatic life. According to Stone *et al.* (2013), the ideal conductivity in a fish pond is a range from 100 to 2000 µS cm^{-1}.

In this study, EC range of between 182.04 ± 13.88 and 280.64 ± 51.78 µS cm^{-1} falls within the EC range suitable for optimal fish growth and therefore the EC in water in rice fields in Bunyala Irrigation Scheme is suitable for culture of fish in rice fields. The slightly higher EC values in monocultures than integrated cultures could be due to the application of inorganic fertilizers. However, the no significant difference between the monocultures and integrated cultures could imply that the fertilizing effect of fish excreta was near to a level almost equivalent to that of inorganic fertilizers application in rice monocultures. The high EC values recorded throughout the day in this study could be an indication of continuous decomposition of organic matter due to favourable water temperature recorded during the study.

5.1.5 Nitrate-N

Except for levels above 90 mg l^{-1}, Nitrate–N is not toxic to fish (Stone and Thomforde, 2004). The findings of the current study of 0.28 - 0.35 mg l^{-1} in integrated rice-fish farming cultures is consistent with the range of 0.1 mg l^{-1} to 4.0 mg l^{-1} described by Santhosh and Singh (2007) to be favourable for fish culture. During this study, levels of nitrates were highest in rice monoculture which can be attributed to the application of nitrogen containing fertilizers. In this study, the low nitrate level recorded in rice fish farming cultures compared to rice monocultures could be mainly due to uptake by rice and aquatic microphytes without external input as in monocultures that received synthetic fertilizers.

5.1.6 Total Alkalinity

Although Alkalinity buffers an increase in pH, it has little express influence on fishes although low alkalinity water is generally biologically less productive compared to those with high values. Aquatic systems with alkalinity above 100 mg l^{-1} are highly productive compared to oligotrophic systems that have < 50 mg l^{-1} alkalinity (Meera and Bijoy, 2010). Boyd *et al*. (2016) reported 20 mg l^{-1} as suitable for fish pond culture. In this study, the integrated rice-fish farming cultures had low alkalinity of between 24.49 ± 0.02 and 27.49 ± 0.04 mg l^{-1} which may be less ideal for fish growth. The low alkalinities could be due to the acidic soils but can be mitigated by adding agricultural lime to increase the buffering capacity of the water so that pH does vary considerably and to increase water alkalinity.

5.2 Rice growth indices and yield

5.2.1 Rice growth indices

Yield is among the most significant and multifaceted traits in rice which is controlled by quantitative genes and external environmental factors (Wang *et al.*, 2012; Zhang *et al.*, 2017). Rice production is constrained by both abiotic and biotic stresses, with report of an annual loss of about 10% of yield due to insect pests among rice farmers in developing countries (Warda, 2008). In Kenya, the major rice pests are the African white rice stem borer (*Maliarpha separatella* Ragonot), Pink stem borer (*Sesamia calamistis*) and Spotted stem borer (*Chilo partellus* (Swinh.) (Kega *et al.*, 2017).

In the present study, the number of dead tillers was significantly higher in rice monocultures than in integrated rice cultures even though the panicle number per unit area and per plant, filled grains per panicle and the weight of 1000 grains across the rice farming systems did not vary significantly. This is consistent with Rasowo *et al*. (2008) who recorded considerably fewer incidences of stem-borers in rice fish polyculture compared to rice monoculture. Further, Rasowo *et al*. (2008) found that stem borers reduced the rice potential yield by 43% in rice monoculture compared to 13% in rice cum fish polyculture and concluded that fish can be used by farmers to manage some rice insect pests responsible for reduced yields. Krishnaiah and Varma (2012) estimated rice yield losses across India to vary from 11.2 to 40.1% and 27.6 to 71.7% due to dead hearts and white ear heads respectively. Kega *et al.* (2016) found a strong positive relationship between rice yield losses and stem borer, *M. separatella* population levels. In Kenya, yield losses of up to 45% due to rice insect pests have been reported (Diagne *et al.*, 2013).

On the other hand, two golden apple snail species, *Pomacea canaliculata* and *Pomacea maculate* are also a major problem of rice and their damage could lead to more than 50% yield loss and a 10% increase in labour and production costs (Phu, 2020). In Kenya, significant infestations of *P. canaliculata* have been observed in Mwea Irrigation Scheme

(MIS) affecting over 550 acres of rice crop in 2020 and spread to other regions is perhaps inevitable given the water connectivitiness and extensive reproduction indicated by widespread presence of egg masses (Buddie *et al*., 2021).Farmers in MIS have observed that with at least a moderate level of infestation (> 20% of cultivated area) came with substantial rice yield reduction and increased pesticides use to control apple snail (Constantine *et al.,* 2023). In addition, the use of hired labor to collect egg masses and snails impacts negatively on net income (Constantine *et al.*, 2023).

To control pests, diseases and weeds, rice farmers result to non-judicious application of agrochemicals. Although these agrochemicals are an important component in the management of crop diseases and pests, their excessive use is now a major global concern as they are not only often uneconomical but are also an obstacle to sustainable agriculture because they lead to negative impacts on environment and food safety. Moreover, some of the agrochemicals indiscriminately kill both pests and their natural enemies at the same time.

Bio-based integrated pest management (IPM) and culturing of fish in paddy fields are two methods used to increase the productivity and profitability of rice farming (Ahmed, 2020). Integrated rice fish farming is one of the eco-friendly IPM key component for suppressing pests and weeds and work without affecting the growth and yield of the main crop. Integrated rice fish farming is one of the eco-friendly integrated pest managements (IPM) strategies that have been adopted to reduce the use of pesticides in controlling rice insect pests. IPM consist of a combination of several compatible and complementary practices that maintains pest populations below the economic injury level (EIL), thus reducing excessive use of hazardous pesticides. Mariyono (2023) observed that the population of natural enemies of pests increased where rice fish farmers applied no pesticides and partially substituted inorganic fertilizers with organic ones with apparent outcome of decreased production costs and the resultant increased income. Since in this study neither pesticides nor inorganic fertilizers were used in integrated rice fish cultures, it is possible that the population of natural enemies of rice pest was maintained which could have led to lower pest infestations resulting in the observed lower dead hearts than in monocultures.

Despite its nascent stage in Kenya and borrowing from where it has been adopted, integrated rice fish farming systems can potentially be a technology for increasing rice production in an environmentally and economically sustainable manner. In Kenya, while comparing panicles and dead hearts per stool, Rasowo *et al*. (2008) concluded that fish can be used to manage rice pests responsible for reduced yields. Fish in the rice fields have been shown to feed on some insect pests in addition to reducing weeds by feeding or uprooting them. Halwart *et al*. (2014) found that common carp (*Cyprinus carpio*) and Nile tilapia decreased snail populations by between 58–87 % and 48–87 % respectively.

The present study found that integrating fish into rice farming could serve as an integrated pest management technique to eliminate these of agrochemicals. This is because significantly higher number of dead tillers was recorded in rice monocultures where pesticides were used compared to rice-fish cultures in which no pesticides were applied. This may partly be attributed to the presence of fish that may have predated on rice pests. This is consistent with observation by Razzak *et al.* (2007) that tilapia decreased rice pests in the rice cum fish cultures and that there was also higher total number of arthropods in rice monoculture than integrated rice fish culture, an indication that fish reduces insect pests of rice in the fields. Further, Wan *et al.* (2019) reported that fish decreased the need for pesticides by 23.4% due to the observed reduction in both herbivore insects and weeds abundance. According to Halwart *et al.* (2012), fish in rice fields act as natural rice pests' predators even though fish may not solely suppress populations of rice pests but their noteworthy role cannot be ignored.

In the present study, the non-use of pesticides in rice fish cultures may be an indication that fish were substantially effective in controlling rice pests and weeds than pesticides since there were more dead tillers/hearts in rice monocultures where pesticides were used than in rice fish cultures. However, since fish may not sufficiently control rice pests, additionally other IPM practices are needed. This may include planting of pest resistant rice varieties in integrated rice fish farming to further reduce the need for pesticides for the benefit of the rice farmers and environmental protection.

Although rice cultivation is a victim of climate change, under intensive production, flooded fields are a leading agricultural source of greenhouse gases (GHGs); carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2014; Arunrat and Pumijumnong, 2017; Arunrat *et al.,* 2018) and is a significant driver of climate change (Smith *et al.*, 2014). Integrated rice fish farming has been touted as a climate-smart agriculture (CSA) solution to "green" the rice production as it can increase productivity, improve climate resilience and reduce GHGs (Hu *et al*., 2016). Studies have further shown that rice-fish culture could substantially reduce requirement for synthetic chemicals and therefore less pollution and negative impact on the environment (Dwiki *et al.,* 2023). Also, Wambugu *et al.* (2020) found that using fish in rice fields eliminates the use of pesticides. This is supported by the findings of present study that rice can be grown sustainably in integrated rice fish cultures with zero inorganic fertilizers, pesticides and herbicides without compromising on yield and income. The none use of synthetic agrochemicals not only reduces the cost of rice farming, it also leads to production of organic rice and fish that are likely to fetch higher prices and could be an economic incentive for farmers to adopt integrated rice fish farming.

5.2.2 Rice yield

Most rice in Kenya is grown as a monoculture under continuous flooding (MOA, 2009); a mode of production that prioritizes single rice yield and results in foregoing "by-products". Due to agronomic and environmental challenges related to the intensification of rice monoculture, rice farming in Kenya is today faced with declining rice yields as a result of low water use efficiency and productivity, and soil exhaustion as well as climate change impacts and it has simultaneously failed to deliver on food security. Addressing these challenges requires to shift focus away from the current intensive monoculture, which depend on intensive application of synthetic inputs that have caused environment degradation and biodiversity decline (Tilman *et al.,* 2011), to ecological intensification systems that can enhance productivity as well as environmental sustainability (Gomez-Gonzalez *et al.,* 2022; MacLaren *et al.*, 2022).

As a form of ecological intensification, integrated rice cum fish farming system creates sustainable agro-ecosystems that eliminates the need for synthetic agrochemical, provides an additional revenue stream from fish and utilizes the concept of circular economy within the household. Although some scientists and farmers widely hold the view that fish in rice fish culture increases rice yield (Tsuruta *et al.,* 2011), the issue is subject to debate with literature presenting contradictory results on the effects of rice fish culture on rice yield. For instance, Ren *et al.* (2014) recorded significant increase of rice yield in rice-fish culture. Tsuruta *et al.* (2011) on other hand noted that rice yield under integrated rice fish plots was 20% higher than that in the rice monoculture plots which they attributed to the fertilizing effect of the fish excrement. Similarly, Ahmed and Garnett (2011) found that yield of Aman rice variety in integrated farming was 12% higher than rice monoculture. They concluded that, the increase in rice yield may probably have been that the movement of fish helped to increase dissolved oxygen levels, stirred up soil nutrients, and controlled plankton, aquatic insects and plants that compete with rice for nutrients and solar energy.

Contrary to these observations, though not significant, this study found higher rice yield in rice monocultures than in the integrated rice fish cultures, 12 and 8% higher for monoculture IR and Basmati rice varieties respectively. This is supported by results of a study that showed no significant effect of rice-fish co-culture on rice yield (Mirhaj *et al.*, 2013). Further, Wambugu *et al.,* (2020) found a slightly lower rice yield from rice-fish culture (no fish feeding) fields than from rice monoculture fields but similar rice yields where fish were fed. They attributed rice yields in rice-fish where fish were fed to improved aeration of soil and water due to fish movement, increased soil fertility as a result of fish excreta and fish feed leftovers and reduced insect populations. Nair *et al.* (2010) explained that the slightly lower rice output in simultaneous rice – fish culture system might be due to the reduced rice planted area as the refugia used about 19% of the total plot area.

However, in the present study, based on comparable rice planted area, rice yields between rice monocultures and the integrated rice cum fish cultures of both rice varieties showed no significant yield difference, an indication that fish did not affect rice yield irrespective of the rice variety. Any difference in yield between the two rice cultures could be accounted for by the actual rice planted area. This is consistent with the findings of Ahmed and Garnett (2011) who found no significant difference in rice yield between Boro variety rice under monoculture and in integrated system.

Since based on an equivalent area occupied by the rice, the yield difference between rice monocultures and rice fish cultures was not statistically significant; this study confirms that fish can be raised in rice fields with no agrochemicals and without compromising rice yield. This could be attributed to a number of reasons including reduced competition for nutrients and solar energy between rice and aquatic plants (phytoplankton, weeds) (Liang *et al.,* 2022) as fish predate on them. Furthermore, fish consume various natural feed sources (bacteria, zooplankton, snails, benthos) and excrete excess nutrients (Zhang *et al.,* 2008), thus accelerating the turnover of organically bound nutrients. Also, fish movement at the bottom may cause the release of fixed nutrients from soil to water which are absorbed by the rice plants (Annie *et al.*, 2019). Therefore, reduced competition for resources, release nutrients from the soil and the fertilizing effect from the fish excrement probably maintained rice yield in this study. According to Tsuruta *et al*. (2010), a well-designed agro-ecosystem can reduce the use of inorganic fertilizers and that the rice yields of such a rice-fish culture can be equal to that of rice monoculture. In the present study, inorganic fertilizers and pesticides were not used in rice fish culture, yet there was no significant reduction in rice yields compared to rice monoculture where both pesticides and inorganic fertilizers were used. This further translated into savings on cost of pesticides, inorganic fertilizers and labour of their application. The overall effect was higher net income return from rice fish cultures than rice monocultures. Also, non use of agrochemicals on the farm makes rice fish culture a sustainable agricultural enterprise. Simultaneously, rice cum fish culture using fish becomes a system of harvesting and transforming the energy from weeds and pests into harvestable biomass which would have been an energy loss to the farmer.

In integrated rice fish culture, rice yield depends on area planted with rice which is dictated by the size of refugia area and the fish stocking density. According to Hu *et al.* (2016), there is a threshold for fish stocking density below which, rice yield in rice–fish systems (RFSs) is not reduced. Further, Wu *et al.* (2012) found if the fish refugia occupy <10% of the field, rice yield is not affected because it can be compensated through enhanced rice growth due to the presence of fish and “edge effect” of the refugia.

5.3 Fish performance parameters and yield

5.3.1 Fish performance parameters

The survival rate of fish in ricefields depends on various factors including water quality and predation. In the present study, average survival rates (49.36 ± 4.14 % in IR+F, 49.04 ± 4.66 % in B+F) were recorded in both rice varieties. These rates are consistent with 51.4% reported by Mohammed *et al*. (2015) and approximately 43% by Tsuruta *et al*. (2011). The low survival rates recorded in this study may be due to combined effects of mortality, predation by eaglets, mongoose, poaching by human and as well as escape of fingerlings from ricefields during flooding.

In terms of specific growth rate (SGR), Savin *et al.* (2012) recorded a value of 3.6% in tilapia (*Oreochromis niloticus* L.) similar to a specific growth rate of 3.46% reported by Rad *et al.* (2006) under recirculating aquaculture system where fish were. Makori *et al*. (2017), working in the same County as this study recorded an overall SGR range of between 1.8% and 3.8% in fish reared in earthen fish ponds under semi-intensive culture. This is consistent with SGR of 3.42% recorded during the present study, an indication that in the ricefields, there was sufficient natural food for fish and water quality did not affect fish growth. However, under intensive rearing, the SGR of tilapia was between 4.90 ± 3.03 and 4.98 ± 2.28 depending on of the feed quality (Rahman *et al.*, 2022), suggesting supplemental feeding and application of organic manure to stimulate phytoplankton growth may be necessary to improve SGR.

5.3.2 Fish yield

There are number of mutually dependent factors that influence fish production that include environmental, stocking density, the feed quality and quantity, water parameters and other aspects of aquaculture application. The fish size at stocking and the culturing period also determine fish yield. The current study recorded no significantly difference in fish yield between the rice fish cultures of the two rice varieties, an indication that Nile tilapia can be cultured with both Basmati 370 and IR 2793-80-1. Similarly, Ahmed and Garnett (2011) did not find any significant difference in fish yield between Boro and Aman rice varieties.

The type of culture influences fish yield, with male mono-sex yielding more than mixed-sex. In the present study, mixed sex Tilapia weight at harvest was 112.04 g which compares well with those of Sah *et al.* (2019) who recorded the harvest weights of 133.7 g and 101.5 g in monosex and mixed sex Tilapia respectively. Similarly, Githukia *et al.* (2015) recorded average weights of 200.8 ± 0.81 g and 123.4 ± 0.76 g for male monosex and mixed sex fishes respectively. Opiyo *et al.* (2020) found that after culture period of 180 days, the final body weights were 174.34 ± 3.71 and 148.06 ± 4.60 g for male tilapia and mixed-sex tilapia 148.06 ± 4.60 g respectively.

Further, the present study recorded fish yield of about 165.9125 kg ha^{-1}in mixed-sex tilapia (*Oreochromis niloticus* L.) which is lower than 352.4 kg ha^{-1} which Omondi (2020) recorded for male mono-sex tilapia within the same rice irrigation scheme and using the same Basmati 370 rice variety. Mridha *et al.* (2014) also recorded male monosex yield of 317.01 ± 9.54 kg ha^{-1}. According to Githukia *et al.* (2015), male monosex perform better as they use most their energy on muscle development while in the mixed sex, energy is spent on reproductive activities. Several scholars have also suggested that monosex male population minimizes recruitment and thereby competition between recruits and stocked fish which, in mixed sex populations, can significantly reduce harvested yields (Nieves, 2017). Tilapia mixed sex population attain sexual maturity early and start reproducing before they reach a marketable size (Kalima *et al.*, 2020), reducing the harvestable yield and value (Umita *et al.,* 2019). Since Tilapia also has prolific reproduction rate with multiple spawning cycles, mixed-sex could lead to overcrowding, and competition for available food resulting in reduced percentage of marketable fish and final yield.

On a positive note, since 60% of the tilapia biomass produced in the ‘mixed-sex’ is attributed to reproduction (Little *et al.,* 2003), mixed-sex culture may be ideal where small fish size do not matter, as in the case of the preparation of fishmeal. The advantages of mixed-sex are the possibility for fish farmers to produce their own fry and for market since the country needs to produce more than 100 million fingerlings each year to meet demand in the aquaculture sector in Kenya (Musa *et al.*, 2012). In the rural areas in Africa and Asia where there is demand for small-sized tilapia (less than 200 g) has been established provides another market (Hernández *et al.,* 2014). Males grow faster than the females, are more uniform in size, and larger than the females who tend to use more of their energy for maturing gonads instead of growing (Forgako, 2016). The male monosex culture is therefore better because it produces large sized fish to meet the needs of urban and international markets (Little and Edwards, 2004). The farming male monosex has also the advantage of that it reduces the negative environmental effects of escapees of exotic species inter-breeding with wild species (Beardmore *et al.,* 2001).

Supplementary feeding has been used as a strategy to increase fish yield. In India, the average fish yield in rice fish system with supplementary feeding was 501.1 kg ha^{-1} (Baruah and Borah, 2006) compared to 314.32 kg ha^{-1} yields without supplementary feeding (Nahar, 2010). Similarly, Frei *et al.* (2007) recorded 515 ± 85 kg ha^{-1} yield in non-fed group of carp/tilapia mixed culture and 540 ± 65 kg ha^{-1} in tilapia monoculture with supplementary feeding. In the current study a fish yield of 164.81 ± 15.66 kg ha^{-1} was recorded under no supplementary feeding. The low yield could be attributed to lack of supplementary feeding but also due to the fact that the fish culture used was mixed sex which has been associated with stunted growth and low yield.

Although supplementary feeding increases fish yield, it may not translate into higher returns depending on the feed cost. This is confirmed by Mridha *et al.* (2014) who recorded a higher benefit-cost ratio with no feed and lower where commercial feeds were used. In addition, supplementary feeding does not meet the goal of converting conventional agriculture systems into sustainable ones to meet the growing market demand for organically grown foods and products. It does not also address the growing concern over the quality of rice and fish produced with extensive use of chemical fertilizers, pesticides, and aqua-drugs in intensive fish culture and rice cultivation (Rico *et al.,* 2013). Also, where commercial fish feeds are used, it is not sustainable production as uneaten fish feed decompose in the water using up oxygen and produces ammonia and other elements that are poisonous to fish and become a major source of aquatic pollution. Since Wambugu *et al.* (2020) observed a net return of 27.1% from rice-fish fields with fish feeding compared to 6.2 and 4.7% from rice-fish without feeding and rice monoculture respectively, supplemental fish feeding may therefore be desirable. In the rice–fish farming system, economic return from fish fed on a formulated feed was substantially more than that from those fed on commercial fish feeds due to the higher feed cost of the later (Mridha *et al.,* 2014).

Apart from the high cost, commercial fish feeds are also associated with pollution/ eutrophication which can be mitigated through the use of farm-made formulated rations consisting of locally available materials including rice by-products (broken rice, rice bran, hulls) and food waste from households could be used. This can be augmented with organic fertilization with livestock manure to stimulate the growth of natural fish food. This can reduce rice and fish production costs while producing sustainable organic rice–fish farm products whose demand is high and market value is much higher than conventional ones.

5.4 Economic returns from rice monoculture and rice fish cultures

Rice–fish farming is the most practiced integrated agriculture–aquaculture (IAA) systems (Nayak *et al.,* 2018). Rice–fish farming efficiently utilizes farm-based resources to produce carbohydrates and protein, and generates additional income to farmers while reducing environmental pollution (Ahmed and Garnett, 2011; Hu *et al.,* 2016).

In this study, it was observed that the introduction of fish into rice field increased initial production cost (field modification, cost of fingerings) but also the benefits, though the benefits outweighed the costs. Although the rice yield was higher in rice monocultures than in integrated rice fish cultures, the net income return from integrated rice fish cultures was higher than from rice monoculture for both varieties. The income could even be higher if survival rates are improved and predation and human poaching of fish are minimized. However, even though in integrated rice–fish no pesticides and fertilizers were used as in monocultures, rice yields were not statistically different for both rice varieties.

Compared to their respective monocultures, the net income returns were 14.63 and 17.48% higher for integrated Basmati and IR respectively. The higher net income from B + F than IR + F is because Basmati is an aromatic variety has higher market price than non-aromatic IR. Despite the higher cost of production in rice-fish farming than in rice monoculture farming, Syaukat and Julistia (2019) found that rice-fish farming earned significantly more income compared to monoculture farming. Similarly, compared to rice monoculture, the integrated rice-fish culture system reduced the cost of production and increased the economic benefits and quality of both rice and fish (Wang *et al.,* 2019). A higher income from the integrated rice fish could be as a result of an extra income from fish (Hu *et al.,* 2016).

In this study, the, higher net income return from integrated rice fish cultures can be attributed to lower production cost due to savings from the cost of agrochemicals and labour for their application which were not used, and the additional income from sale of fish. The per unit income from fish was higher compared to equivalent rice unit since fish had a higher market value than rice. Higher income from integrated IR and Basmati in this study is consistent with findings of Berg *et al.* (2017) that attributed the higher income to sale of fish and decreased costs of agrochemical inputs for the rice–fish farmers compared to rice to monoculture. Apart from the farming income, Rahman *et al.* (2012) observed increased human labour employment due to integrated rice fish farming. The beauty of rice-fish systems landscape can also stimulate agricultural ecotourism, contributing further to diversified local livelihoods. It is also expected that with reduction in cost of ricefields modifications which is an initial major capital expenditure in integrated rice fish cultures, the net income from integrated cultures will subsequently increase.

A farmer`s income can further be increased by use of genetically improved fish species cultured in polyculture systems together with high commercial value aquatic species like crayfish, shrimps and freshwater prawns which because of their different feeding habits can maximize production by utilizing all natural feed resources available in the ricefields. This potentially provides an opportunity for further diversification of production and income sources, and reduces production costs and risks. Overall, the income analysis from this study indicates that integrated rice–fish farming can be a financially profitable farming enterprise alternative to rice monoculture, and rice yield can be maintained with less or no chemical synthetic inputs.

5.5 Socioeconomic benefits

Since rice growing in Bunyala is a seasonal activity that lasts for only 4 months per year, it leaves the farmers, youth and women who provide labour idle for most part of the year (Mutero *et al.,* 2004) yet they require employment and income all year round. Since rice-fish farming is labour intensive, its labour requirement is high and therefore creates employment opportunities across all seasons especially during the lean seasons when there is no rice cultivation. Where rice-fish farming has been adopted, it has led to considerably more gendered job opportunities compared to rice monoculture farming. Some activities associated with rice-fish farming such as the preparation of farm-made feeds and fish feeding require less toiling compared to weeding and pesticides application in rice monoculture farming (Islam *et al.,* 2016).

Rice–fish farming could result into evolution of an aquaculture value chain and creation of new business opportunities that create new off-farm employment and income opportunities. Overall, multiple benefits accrue from integrated rice-fish cultures including diverse nutritious food, increased household incomes, availability of foods to boost the nutritional status of rice farmers households, employment for women and youth, species and ecosystem biodiversity, resources (land, water and labor use) efficiency, and resilience to climate change (Dubois *et al.,* 2021) as well as reduced use of agrochemicals.

Since it is not necessary to use agrochemicals, the rice and fish products from integrated rice fish farming systems can be certified as organic food or green food, and can be sold at a premium price in the market. The growing consumer demand for organically grown products in Kenya and globally presents a viable opportunity for rice and aquaculture farmers to adopt integrated rice fish organic farming practices to satisfy the growing market for organic products and reap from higher prices for their produce.

Since horizontal expansion of irrigated rice and aquaculture is constrained by availability of suitable land; rice fish farming fields creates opportunity for efficient utilization of scarce production resources while availing fish at household level. This could increase fish consumption to fight the "triple burden" of under nutrition, malnutrition—obesity and micronutrient deficiencies which are the leading causes of poor health in rural areas in Kenya (Obiero *et al.*, 2019). Islam *et al.* (2015) study showed that integrated rice fish farming system (IRFFS) had a positive and noteworthy impact on household inform of income, and quantity and frequency of fish consumption at household level. Socially, integrated rice fish farming was acceptable to the community in the study area since it was in no conflict with the government, local norms and religions as well as the existing farming practices of other crops.

5.6 Conclusions

During the study, with exception of total alkalinity, the selected water physico-chemical parameters including DO, temperature, pH, electrical conductivity and NO_3-N were within the suitable range for fish survival and growth and as a result the following recommendations are made.

i. Water temperature (17 - 33^oC), dissolved oxygen (3.9 - 9.0 mg l^{-1}) and pH (7.2 - 8.6), EC (182.04 - 280.64) and NO_3-N (0.32 - 0.39) in integrated rice fish cultures were all within the favorable range for tilapia fish for growth. The H_o**:** Physico-chemical parameters of water in integrated rice-fish cultures are not suitable for fish growth is rejected. However, there is need for liming the rice fields to maintain suitable pH.

ii. Both rice and fish yields were similar to those under rice monoculture and aquaculture production systems respectively. The H_o**:** Basmati 370 and IR 2793-80-1 rice varieties are not suitable for integrated rice-fish culture is rejected.

iii. On equal rice planted area, the yield of Basmati 370 and IR 2793-80-1 rice varieties in monoculture and integrated rice-fish culture were not significantly different; therefore, the two varieties are suitable for integrated rice-fish culture. However, there is need to replace these rice varieties with high end pest resistant varieties of the same quality and higher yield. The H_o**:** There is no significant ($p \geq 0.05$) difference in rice yield between rice monocultures and integrated rice-fish cultures is rejected.

iv. The net income from the rice–fish system was significantly ($p \leq 0.05$) higher than from rice monoculture with 8 and 10% higher for Basmati and IR rice varieties. The H_o: There is no significant ($p \geq 0.05$) difference in income between rice monocultures and integrated rice-fish cultures is rejected.

v. The integrated rice-fish cultures can be an economically sustainable and competitive alternative to rice monoculture.

vi. Rice can be grown in concurrent integrated rice-fish system without the need for inorganic fertilizers and pesticides without compromising rice yield.

5.7 Recommendations

i. Despite the various researches showing the viability and potential benefits of integrated rice fish systems in Kenya, rice farmers may be lacking awareness of these systems. There is therefore need to create awareness, training, provide extension services to promote the adoption of integrated rice fish farming among the rice and fish farmers across the country.

ii. Further, research is recommended on on-farm rice-fish polyculture integration with high value aquatic animal species like crustacean species (freshwater prawns, shrimps, lobsters and crayfish), poultry and duck across the major rice growing areas

iii. Formulation of fish feeds using farm hold wastes and rice by-products should be explored.

iv. Production of biofertilizers from rice by-products (rice straws and husks) for use in integrated of rice-fish farming is recommended.

v. Though low yielding, Basmati rice variety is more profitable than IR, whether in monoculture or in integrated system and therefore farmers should be encouraged to switch to Basmati.

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