MULTIDIMENSIONAL EVALUATION OF THE IMPACTS OF AGRICULTURAL INTERVENTIONS TO ACHIEVE FOOD SECURITY IN MALAWI

By

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ABSTRACT

Malawi's food and nutrition security heavily relies on rainfed agricultural production, which is prone to the effects of climate change, such as floods and dry spells. To improve the situation, policies have been established as a guide to assist in the implementation of agricultural technologies in the country. This study aims to evaluate the effect of two national policies on addressing nutrition, economics, and food security by introducing modern/existing technologies in the Phalombe district in Malawi. To gain insight into the representative farm operations, financial, demographic, and consumption behaviors of smallholder farmers, the data was obtained through a combination of focus group discussions, expert opinions, and various published reports, including both government and non-government sources. The farm simulation model (FARMSIM) was utilized to analyze district-level crop and livestock farm operations. In this study, four irrigation technologies (treadle pump system, motorized pump system, solar-powered system, and river diversion irrigation system) were assessed among the agricultural interventions implemented in Malawi. Also, seven land uses (i.e., corn, onion, bean, rice, tomato, leaf vegetable, and cabbage) were developed and simulated under irrigation scenarios. The irrigation systems and land use scenarios were evaluated based on economics, productivity, nutrition, and risk. The treadle pump and leafy vegetable scenario were generally identified as the most preferred combination. In addition, the productivity and riskiness of the other scenarios can be improved by selecting the best combination of crop and irrigation systems. The study concludes that government and private investment in subsidies for large-scale irrigation systems, as well as improvements to market prices and infrastructure, are necessary to boost food security and enhance the livelihood of smallholder farmers in rural Malawi.

This thesis is dedicated to my mother, who nursed me but never saw me grow into the person I am now. And also, to my daughter Colleen, this is for you.

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LIST OF ABBREVIATIONS

APES	Agricultural Production Estimates
APSfarm	Agricultural Production Systems farm
APSIM	Agricultural Production Systems sIMulator
CE	Certainty Equivalent
CIMMYT	International Maize and Wheat Center
DARS	Department of Agricultural Research Services
DSSAT	Decision Support System for Agrotechnology Transfer
EPA	Extension Planning Areas
FAO	Food and Agriculture Organization
FARMSIM	Farm Income Simulator
FDA	Food and Drug Administration
FGDs	Focus Group Discussions
FIFAD	FISD Finance Foe Agricultural Development
FISP	Farm Input Subsidy Program
FLIPSIM	Farm Level Income and Policy Simulation Model
GDP	Global Domestic Product
GoM	Government of Malawi
HIV	Human Immunodeficiency Syndrome
AIDS	Acquired Immunodeficiency Syndrome
IPCC	Intergovernmental panel on Climate Change
IRR	Internal Rate of Return
Kg	Kilogram
L	Liter
MATLAB	Matrix Laboratory

Mk	Malawi Kwacha
NMNP	National Multisector Nutrition Policy
MP Irr	Motorized Power Irrigation system.
NCFI	Net Cash Farm Income
NGOs	Non-Governmental Organizations
NIFA	National Institute of Food and Agriculture
NIP	National Irrigation Policy
NPV	Net Present Value
NUTBAL	Nutritional Balance Analyzer
OXFAM	Oxford Committee for Famine Relief
RD Irr	River diversion irrigation system
RP	Risk Premiums
SDG	Sustainable Development Goals
SDRF	Stochastic Dominance with Respect to a Function
SERF	Stochastic Efficiency with Respect to a Function
SIMETAR	Simulation & Econometrics to Analyze Risk
SP Irr	Solar-Powered Irrigation system
SRI	Systems of Rice Intensification
STOA	Science Technology Options Assessment
TP Irr	Treadle pump Irrigation system
USDA	United States Department of Agriculture
WFP	World Food Program
WII	Weather Index Insurance
WHO	World Health Organization

1.0 INTRODUCTION

Food security continues to be a major challenge in developing countries, including Africa. A recent study indicated that most countries are not on the path to meeting the Zero Hunger goal by 2030 set by the United Nations Sustainable Development program to transform our world (United Nations, 2022). The Food and Agriculture Organization (FAO) reported that there was a significant level of food insecurity among the population in Africa (OECD/FAO, 2021). For instance, 60% of the population was categorized as having medium to acute food insecurity, and approximately 26% experienced severe food insecurity (FAO et al., 2021). Meanwhile, the issue of food insecurity has persisted in smallholder farmers' households for many years (García-Oliveira et al., 2022). The primary cause is their dependence on rainfed agriculture for sustenance and income (Adeyanju et al., 2023). However, in recent times, rainfed agricultural production has faced mounting climatic challenges, including floods, extended dry spells, and infestations of pests and diseases (Sasson, 2012). Additionally, smallholder farmers encounter various obstacles, including soil erosion, inadequate farm inputs (such as fertilizers and hybrid seeds), insufficient access to credit, low levels of adoption of agricultural innovations, inadequate market infrastructure, unfavorable policies, and low market prices(Adeyanju et al., 2023; Fontan Sers & Mughal, 2023). As such, this has led to decreased production, income, and food insecurity in most African regions (Pritha Mitra. et al., 2022).

To combat hunger and boost economic growth, various interventions and technologies are being introduced and implemented. These include measures related to crop production, marketing, livestock, extension services, soil, and water management, as well as food and nutrition. In addition to technical intervention, several policies, such as food policy, Southern African Development Community food and nutrition strategy, and marketing strategies, have been formulated and implemented. Meanwhile, different international and local organizations such as World Food Program (WFP), Food and Agriculture Organization (FAO), International Fund for Agricultural Development (IFAD), United States Agency for International Development (USAID), and government departments have pooled resources to improve productivity levels, decrease yield losses, decrease food insecurities, and enhance nutrition status (African Union Commission, 2014). Despite the various initiatives, food and nutrition security continue to be a pressing concern in developing nations, with adverse effects on human well-being, the environment, and the economy. In Malawi, just like any developing country, efforts are being made to improve food insecurity challenges. Different agricultural interventions are being implemented, including livestock management, soil and water management, irrigation technologies, mechanization, and food processing (WFP, 2019a). In addition, the nation has formulated and updated its policies and strategies to guide various stakeholders involved in efforts to combat hunger, boost the economy, and improve the well-being of people, especially those living in rural areas (WFP, 2022). However, there has been little focus on evaluating the suitability of national policies for implementing agricultural interventions in the country. In addition, it is essential to understand how these policies interact and how best to implement them for optimal impact.

This study sought to investigate how two Malawian national policies, namely the National Irrigation Policy (NIP) and the National Multisector Nutrition Policy (NMNP), can be utilized to enhance food and nutrition security through the introduction of modern technologies or the optimization of existing ones in the country. Insights gained from this study can help to deepen our understanding of national policies and their effects on smallholder farmers. It can also facilitate a thorough evaluation of the strengths and weaknesses of these policies before their implementation in the field. Ultimately, this knowledge can be leveraged to better coordinate technical interventions, local and national policies, and foreign aid efforts, thereby enabling the achievement of sustainable food security.

2.0 LITERATURE REVIEW

2.1 Agricultural Production in Africa

2.1.1 Crop Production

Agriculture is the main sector that plays a key role in food security and economic transformation in Africa (Adams et al., 2020). However, contrary to developed countries, in Africa, smallholder farmers are the dominant workforce in agriculture. This sector is also important as it contributes the largest part of countries' Global Domestic Product (GDP) in most developing countries. In Africa, crop production is mostly rainfed but, in small part, also irrigated to maximize land use and productivity (Bjornlund et al., 2020Bjornlund et al., 2020).

In developing countries, farmers grow a variety of crops, such as cereals, tubers, pulses, and horticultural crops. Even though there is a large dependence on agricultural production, and it is the main source of income for the majority of the population, smallholder farmers in developing countries are food insecure, experience high rates of poverty and are economically poor (Adams et al., 2020). In addition, due to economic and technological constraints, it is known that smallholder farming is characterized by low levels of inputs and outputs. Farmers in developing countries face many challenges in agricultural production, including but not limited to the use of uncertified seed, agricultural policy, lack of appropriate technologies, poor markets, and climate change (Chilongo, 2004). For instance, in some developing countries such as Malawi, Mozambique, and Mali, some interventions are placed in the wrong areas; as such, farmers do not utilize the technology fully. As a result, this ends up worsening food insecurity issues (Binswanger-mkhize, 2009). Studies show that adoption, use of appropriate technologies, and good management systems significantly impact the lives of smallholder farmers and rural communities in terms of food security and economic growth (Clarke et al., 2017).

2.1.2 Livestock Production

Livestock production is essential in most developing countries. It is one of the most important resources for most poor rural farmers to achieve economic and social status (IFAD, 2020). Smallholder farmers rely on livestock production as they contain proteins, fats, and many vitamins, which are necessary for human health as well as for economic growth after the sale (Steinfeld et al., 2006). The most common livestock in Africa are cattle, chickens, goats, and pigs (FAO, 2005). Currently, most of the land has been put under crop production to protect land rights, and farmers source feeds for their own livestock (Kere et al., 2021). Due to insufficient land, smallholder farmers practice a mixed farming system whereby crop and livestock production is done on a single land to maximize land use (O.Arara, 2010). In some regions, for example, in the northwestern part of Kenya, some farmers grow low-input sorghum along the riverbanks and feed their livestock the crop residues when the rains are insufficient, and there is no pasture for the farm animals. Some commercial farmers in Sudan and Ethiopia engage in irrigated mixed farming. This resulted in an increase in animal feed throughout the year and stability in income (O.Arara, 2010). Also, in Ethiopia, farmers are involved in irrigation schemes that use crop remains and irrigation water for livestock during the dry season (O.Arara, 2010). The most notable challenges of livestock production in most African countries include; inadequate water resources as they compete with humans, poor animal health because of mismanagement of resources, lack of shelter as they are kept within the homestead, lack of feed, especially for large livestock species such as cattle, poor quality feed is also a problem for free-range livestock because there is no control over resources, poor management of pest and diseases, climate change, and livestock owners in urban areas have difficulties in extension services from livestock officers presenting their issues to the government (Umutoni et al., 2015). Despite these challenges, livestock production has a lot of benefits to smallholders include improving food security, employment opportunities, savings, acts as insurance and for economic growth (Otte & Knips, 2005). Livestock farming acts as an asset that can be easily changeable to cover other expenses like school fees and health insurance (IFAD, 2007).

2.2 Agricultural Production in Malawi

2.2.1 Crop Production

In Malawi, just like many other developing countries, the agricultural sector accounts for 42% of the GDP and 81% of export earnings (FAO, 2018). In Malawi, agricultural production is both rainfed and irrigated and the majority of food is produced by smallholder farmers (GoM, 2017). Farmers grow crops such as maize, millet sorghum, sweet potato, and cassava during the rainy season, and horticultural crops are usually irrigated. In Malawi, the total agricultural land is estimated to be 7.7 million ha. However, this land is divided into estates and smallholder farmers. Overall, estates comprise 16% of the agricultural land, and farmers cultivate 84% (MoAIWD, 2015). Smallholder farmers mainly produce subsistence food with only small quantities for sale.

Agricultural production is affected by several factors, such as climate change, lack of agricultural inputs (seeds, fertilizer, farm equipment), inappropriate technologies, and declining soil fertility (Chirwa, 2005). In Malawi, many forms of agricultural interventions have been implemented to improve crop production and combat food insecurity. These interventions include irrigation technology, manure management, livestock management, and soil and water conservation (GoM, 2017). Meanwhile, in collaboration with World Bank and other international organizations, the government of Malawi is working to achieve zero hunger, which is one of the agenda for Sustainable Development Goals under the United Nations. It is hypothesized that with the right strategy, agricultural production will be increased, and food security can be restored.

2.3 Food Security and Nutrition Status of Smallholder Farmers in Malawi

Malawi's food security depends on rainfed agriculture, and it is measured by the availability of maize. However, due to several factors like dry spells, floods, unreliable rainfall, land degradation, and an increase in the cost of farm inputs, productivity remains low (WFP, 2019b). The majority of people who suffer from these consequences are rural smallholder farmers who rely on their production for consumption(Kerr et al., 2016). This affects the nutrition intake of smallholder households, especially young children and women. In addition to the yield gap, due to a lack of sufficient variety of foods, poor food quality, unsafe foods, and poor health to benefit from the food consumed, this situation is even direr in the region. A recent study in Malawi indicated that 10% of the total population is food insecure and needs urgent humanitarian assistance (GoM, 2020). Also, for many Malawian children, approximately 37% are stunted, and 4% suffer from acute malnourishment (UNICEF, 2018). In rural areas, the diet comprises cereals, starchy roots, and vegetables. This poses serious health problems as it cannot meet the required nutrients in the body. Micronutrient deficiencies, primarily stemming from a lack of vitamin E, iodine, and iron, have considerable public health implications (FAO, 2010). These nutrients are required in small quantities to build, develop, and maintain the body. It is reported that a deficiency of these micro-nutrients in the body could result in anemia, intellectual disability, and maternal and neonatal deaths, especially for vulnerable groups (Dickinson et al., 2014).

Throughout the years, Malawi, like other developing countries, has been fighting to achieve Sustainable Development Goal 2 (SDG 2): Zero Hunger goal. According to the 2018 World Food Program survey conducted in Malawi, the nation has not yet achieved the SDG 2 objective. The survey also identified certain constraining factors, such as gender inequalities, underdeveloped markets, reliance on subsistence agriculture, and inadequate irrigation (WFP, 2019b). To improve food security and nutrition status amongst smallholder farmers, the government established a Farm Input Subsidy Program (FISP) whereby rural smallholder farmers can purchase farm inputs at a low price(Fatch et al., 2021). The package includes seeds such as pulses, cereals, and fertilizer (basal and top-dressing fertilizer). This program assists approximately half of the rural farmers. As a result, there has been a significant increase in maize yield, which has increased calories among rural farmers. Meanwhile, the impact of FISP on dietary diversification seems limited, as micronutrient deficiency is still a major issue among the families of smallholder farmers (Ecker & Pauw, 2014). Also, the Malawi government, non-governmental organizations, and developmental partners are emphasizing crop diversification and growing cash crops to ensure that farmers have a variety of foods to improve their nutrient intake (WFP, 2019b). Growing cash crops enables rural farmers to buy other foods to supplement their diet. Additionally, long-term strategies such as irrigation investments have been given greater concentration to ensure an increase in productivity and improve food security, especially in dry rural areas (Ringler, 2013) . This is because farmers grow different crops two or more a year, some of which are vegetables. As such, this helps to improve nutrient intake and farmers' wellbeing as vegetables contain micronutrients (Ringler, 2013).

2.4 Challenge of Agricultural Production in Africa

In Africa, including Malawi, agricultural production faces many challenges, and the most vulnerable people working in this area are rural women and children whose survival depends on agriculture (Adomako & Ampadu, 2015). Nonetheless, climate change stands out as one of the significant global stressors. This has increased temperatures, affecting rainfall patterns and the amount and water availability for irrigation (Ofosu et al., 2014). r. These chemicals tend to harm plants and human health when the concentration exceeds the safe amounts (Adomako & Ampadu, 2015). Also, a lack of agricultural inputs is a key challenge in developing countries. For instance, Shimeles et al. (2018) study showed that most farmers, especially women in Sub-Saharan Africa, have difficulties acquiring farm inputs such as improved seeds, fertilizer, machinery, and training, resulting in low crop yield.

Furthermore, it is noted that most African countries rely heavily on rainfed agriculture and not irrigated agriculture despite having a lot of monetary resources allocated to irrigation technology (Mayo et al., 2015). Also, most developing countries do not have stable markets where farmers can sell their products at better prices. Farmers grow and sell their crops to middlemen or vendors at a low cost, hindering the farmers from obtaining the required profits and improving financially (Shimeles et al., 2018a). It is noted that African farmers have a greater possibility of improving food production and having better revenues if different elements of agriculture sectors are better developed as farmers manage the entire production, storage, processing, transport, marketing, and distribution independently (Shimeles, 2018).

2.5 Agricultural Innovations/Interventions to Improve Sustainable Production

a) Manure Management

In the world, especially in Africa, undernutrition is increasingly high due to food insecurity (FAO et al., 2017). According to FAO (2017), one of the reasons for food insecurity is the depletion of land, which has led to low agricultural production levels. Land degradation is crucial, and some causes include the removal of the vegetative cover and the low use of manure application that helps improve and maintain soil fertility (Agegnehu et al., 2014). Studies in Ethiopia and Malawi showed that applying organic manure could restore depleted soils (Ndambi, Pelster, Owino, et al., 2019). Organic (compost) manure can be made from plant residues, animal wastes, or both (Edwards & Hailu, 2011). Manure-making requires locally available resources like dry to green grass or crop residues, animal wastes, and other composting aids. Organic manure can improve soil fertility, aeration, return nutrients, improve soil structure, and drainage (Edwards Sue & Hailu, 2011). studies show that manure costs are relatively small when compared to inorganic fertilizers and they have similar impacts when applied to the soil (Ndambi, Pelster, & Owino, 2019). As such, this can help farmers to reduce their operating costs that, ultimately improves their well-being. Despite having many benefits, manure management is challenging for smallholder farmers due to a lack of knowledge on the methods of collecting animal wastes, insufficient workforce, and capital (Ndambi, Pelster, Owino, et al., 2019).

b) *Agricultural Loan*

In Malawi, just like many other developing countries, smallholder farmers and small business entrepreneurs face challenges getting credit access due to inappropriate amounts of assets to put as collateral. This, in turn, results in most of the farmers not having the required income to buy farm inputs, adopt various improved agricultural technologies, and improve food security (Diagne & Zeller, 2001). Also, the high interest rates hinder farmers and small enterprises from accessing the loans (Shams Allie & Demiryürek, 2020). Over the past years, several microcredit institutions have emerged to assist smallholder farmers and small business enterprises with access to capital to improve agricultural production and economic livelihood. These credits are in the form of either cash, agricultural inputs (e.g., seeds and fertilizer), or farm equipment (e.g., irrigation kits and farm machinery). For example, Foundation for Irrigation and Sustainable Development (FISD) Finance for Agricultural Development (FIFAD) in Malawi has been providing loans for solar irrigation, livestock production, agricultural inputs, and crop production (FISD, 2019). Considering the significance of these credits to the economy of the country, the Malawi Government, Non-Governmental Organisations (NGOs), and international organizations have assisted in improving the availability of funds in Malawi (Durevall et al., 2010). Over the years, despite the challenges faced by microcredit institutions, there have been many relevant successes reported in agricultural production and small business due to the availability of loans. Some of the achievements include increased investments in self-employment, especially for women and youth. These, in turn, resulted in improvements in health, education, and empowering women (Meerendonk & Juergens, 2016).

c) Soil and Water Conservation

One of the potential challenges to agricultural production in Malawi is climate change(USAID, 2020). This is because it has negatively affected rainfall as it has become insufficient and unreliable (Nhemachena et al., 2020). Meanwhile, some other regions may experience high rainfall amounts that cause flooding and loss of soil fertility. In some areas of Africa, including Malawi, it is predicted that climate change will bring more frequent droughts and low precipitation (IPCC, 2007). These have negatively affected countries' food security, economy, safe drinking water (Nhemachena et al., 2020). Over the years, several interventions have been introduced in Malawi to mitigate the climate change impacts. Sustainable soil and water conservation is one of those interventions. Soil and water conservation are those practices that enhance and improve soil structure, retain water, reduce soil erosion, help with better managing drainage, and enhance soil fertility (Sosola et al., 2010). In Malawi, there are several soil and water conservation activities that have been practiced by smallholder farmers, including zero tillage, swales mulching crops, using manure, field contour ridges, and box ridges (Nhemachena et al., 2020). However, these interventions have faced challenges, such as technical know-how, poor adoption rate, and lack of equipment. Concerning the low adoption rate, farmers are generally looking for immediate return. Therefore, it is hard to convince farmers to adopt an innovation if the benefits will only appear in the long run. Also, for interventions that rely on standard measurements, such as swale, the lack of tools can be discouraging for smallholder farmers (Sosola et al., 2010). Despite the challenges, several success stories have been reported that improved soil loss, water retention, and yield (Kambauwa et al., 2015). For example, studies showed that conservation agriculture could increase crop yield by 4% to 30% depending on agroecological region and the impact of climate change(Kambauwa et al., 2015).

d) Genetics

Plant genetics is one of the interventions that has been adopted widely to improve crop production and food security. With the effects of climate change, there are prolonged droughts, high temperatures, higher frequency floods, salination, low water table, and erratic rainfall patterns (IPCC, 2007; Nhemachena et al., 2020). As one way of improving crop yield, several enhanced seeds have been created in developed and developing countries with some characteristics to stand extreme conditions (Ronald, 2011). In developed regions such as North America, there has been the successful development and adaptation of genetically modified seeds. As a result, farmers in these regions have realized increased yield without increasing land by using improved seeds (Ronald, 2011). This is because these seeds can survive extreme conditions such as high temperatures and dry spells and are resistant to pests and diseases.

In Malawi, just like many other developing countries, the government has promoted genetically modified seeds, such as maize, rice, common beans, and groundnuts. In Malawi, the staple food is maize, and food shortages are mainly measured based on the availability of maize (Fatch et al., 2021). As such, more efforts have been made to promote genetically modified maize seeds, unlike other seeds. For example, the country has about 29 genetically modified maize seed varieties, while this number is much lower for other crops (GoM, 2007). However, local farmers are still encouraged to save and store seeds to preserve genes in their seed banks (Andersen Regine et al., 2022). Several factors have led to decreased availability of local varieties in Malawi, including droughts, urbanization, government policies, and the high adoption of genetically modified varieties (GoM, 2007). Despite the improvement in genetically modified seed varieties, there are many challenges faced by farmers, including a lack of technical know-how to conserve the germplasm; as such, there is a need to support different institutions to collect information on the germplasm, which are useful by plant breeders (Andersen Regine et al., 2022).

e) Machinery

Mechanization is one of the interventions for sustainable agriculture because it helps to improve crop production, especially in developing countries such as Malawi (Muller et al., 2017). In Malawi, most agricultural activities, such as weeding, ploughing, irrigating, harvesting, and transporting, are done manually with human labor (Muller et al., 2017). For performing these activities, smallholder farmers use basic farm tools such as hoes, axes, pangas, and treadle pumps in crop production. As a result, this led to a decrease in crop yield due to a lack of labor to work on the farm, crop failure, and crop losses during harvesting and transportation. In addition, manual labor in the long term negatively affects human health, which affects household or communal development (Muller et al., 2017). Meanwhile, in some cases, engine power is used by commercial farmers or estates that resulted in increased yields, leading to improved food security in the region (Behrendt & Paparas, 2020). This is because mechanization results in increased cropping area, low use of hired labor, and relatively lower cost than manual labor

(Silver et al., 2016). Furthermore, mechanization has positively impacted small-sized farms, especially in Bangladesh and South Asian countries, by increasing their profits (Silver et al., 2016). For example, in Bangladesh, about 60% of the smallholder farmers cultivate on land less than 0.2 ha, and many farmers mostly use power tillers in rice fields (Ahmed A, 2013).

In Malawi, the majority of farm operations are done by hand by smallholder farmers. This is because engine machinery is expensive compared to human labor, and farm sizes are small (less than 0.5 ha) and very fragmented, which is not ideal for using heavy machinery (Silver et al., 2016). For example, in Malawi, using tractors faces many challenges because of a lack of technical know-how or training, leading to high operational costs, expensive breakdowns, and poor-quality work (Freeman et al., 2008). Also, governmental policies and involvements have led to difficulties for farmers to access farm machinery. For instance, farm machinery is generally expensive, and due to governmental policies, it is hard for farmers to access loans to purchase sophisticated farm machinery. While the government promotes mechanization, it is essential to train experts who can advise on the farm machinery to purchase and assist in fixing during break down. In addition, legislators should promote policies that will allow smallholder farmers to use and purchase farm machines at low costs (Kumi, 2014).

f) Livestock Management

Livestock management is an intervention that continues to play a significant role in the lives of smallholder farmers in Malawi. This is because the intervention assists farmers greatly in times of shocks such as floods and drought, as their financial assets are very limited (Banda et al., 2011). In addition, reports show that livestock intervention is important for farmers' livelihood right after crop production. Livestock farming has several benefits, including 1) during food shortages or shocks, farmers sell livestock and use the money to buy foodstuffs and other needs (Freeman et al., 2008), 2) livestock products contain essential nutrients such as fats, proteins, and vitamins that are important for human health (Nanganga & Safalaoh, 2020) they help in the transportation of farm produce and 4) they produce manure, which is essential for soil health improvement (Banda et al., 2011).

In Malawi, the common livestock reared includes cattle, dairy cows, goats, poultry, and pigs (FAO, 2005). Livestock interventions are essential in the country. However, most rural smallholder farmers raise livestock with no proper management, so the production rate is very low (Goyder & Mang, 2009). Compared to rural areas, livestock farming is a bit more successful in urban areas and with farmer groups/associations, especially for pigs, dairy cattle, and poultry farming (Goyder & Mang, 2009). However, only a few people raise livestock in urban areas compared to rural communities. This is because, in urban areas or farmers' groups, livestock are raised intensively, and animals are well-managed and well-fed. Reports show that livestock interventions adoption rate are low by smallholders because most of the farmers lack knowledge on the management of the livestock, animals easily gets attacked by pest and diseases (Nanganga & Safalaoh, 2020), farmers lack financial resources to provide livestock with proper feed and housing, livestock extension officers are very few, lack of resources to assist farmers that are in hard-to-reach areas, and low prices of livestock productions at the market (Banda et al., 2011; Goyder & Mang, 2009). To improve livestock intervention, there is a need to build capacity amongst small rural farmers in management, housing, and feeding to improve animals' health and productivity. Also, there is a need to train more livestock extension workers to bridge the knowledge gap and accelerate the adoption of interventions (Nanganga & Safalaoh, 2020).

g) Irrigation Technology

In Africa, including Malawi, food production heavily relies on rainfed agriculture, leading to low productivity and resulting in food shortages amongst farmers and rural people. This happens because of changes in rainfall patterns and severe climate conditions (AGRA, 2019). Irrigation farming is one of the interventions that has been largely promoted to address food insecurity challenges and poverty reduction in both developed and developing countries (Lautze, 2020). Irrigation farming allows farmers to grow crops more than once without relying on rainfall amounts and frequency. This, in turn, improves food security and living standards amongst smallholder rural farmers because they can produce more and generate more income compared to the rainfed system. Irrigation farming is much more successful in developed countries than in African countries (Ringler, 2013). Compared to Latin America and Asian countries, which irrigate 14% and 35% of the land, respectively, it is reported that in Africa, only 6% of the land is cultivated under irrigation despite having the potential to enhance productivity by 50% (AGRA, 2019). This is because developed countries have adequate systems at all levels, which help manage the irrigation systems more effectively (Playán et al., 2018). Also, in developed countries, rural farmers have a bigger landholding size, and income per capita is also high compared to developing countries (Kirpich et al., 1999).

In Malawi, irrigated agriculture plays an important role in improving the lives of poor farmers (World Bank, 2021). Surface (gravity) irrigation is commonly practiced among small holder farmers. There are different systems that are commonly practiced by smallholders, and these include treadle pump irrigation system, solar powered irrigation systems, river diversion irrigation systems and motorized pimp irrigation systems (MoAIWD, 2015) . As such this enhances crop production as compared to rainfed agriculture only (Nhamo, et al., 2016).

Additionally, crops grown under irrigation are usually cash crops, such as rice, green maize, and vegetables, which enables farmers to increase their income and improve their well-being (ESRC & DFID, 2016). As a result, farmers are managing to pay school fees for their children, build houses thatched with iron sheets, buy motorcycles or bicycles as well as eat healthy foods.

Over the years, Malawi has been affected by frequent droughts, dry spells, and floods. As such, irrigation farming tends to be a sustainable strategy for coping with these critical situations (Nhamo et al., 2016a). Surface Irrigation is a commonly used method by smallholder rural farmers. This is because it is easy to operate and maintain and less expensive than drip and sprinkler systems (FAO, 2002). However, irrigated farming faces many constraints in Malawi. One of the major challenges is underutilization. For instance, only 25% of the land is currently under irrigation out of 408,000 hectares of potential land despite the available water resources in the country (AGRA, 2019; Wiyo & Mtenthiwa, 2018). This is due to insufficient financial support, as irrigation requires significant investments (Nhamoet al., 2016). This affects agricultural growth negatively and continues to pose a risk to rural people's food and nutrition security (Jica, 2021). In addition, the lack of a stable market affects rural communities. Most of the farmers do not have accurate information about the prices of the products; as such, vendors/traders take advantage and buy produce at low prices. As such, farmers do not gain the whole profits from irrigation farming (Jica, 2021). Finally, there is a shortage of extension officers and technicians to assist in irrigation farming and to maintain irrigation systems. As such, there is no proper management of irrigation schemes, and they are easily damaged and abandoned shortly after the initial operation (ESRC & DFID, 2016).

h) *Agricultural Insurance*

Due to extreme weather conditions resulting in decreased crop yield in most developing countries, including Malawi, the risk of food insecurity, malnutrition, and economic growth has increased (Zulu, 2017). In such cases, the most affected people are the rural communities. For instance, in Malawi, the country's food security is largely measured by the availability of rainfed maize, which is the country's staple food (Hess, 2005). Therefore, a staggering rise in the occurrence of extreme weather events can significantly impact the smallholders in Malawi. In addition, since the country's economy largely depends on agriculture, for example, the sector approximately contributes 28% to countries GDP (GoM, 2017). As such, an increase in extreme weather events potentially threatens financial stability and food security. Moreover, it is reported that, on average, around 1.7% of the country's GDP is affected by extreme events such as drought (Makaudze, 2016).

Most of the agricultural production in Malawi is rainfed. Farmers have traditionally developed some mitigation strategies to minimize the negative impacts of extreme events. The most notable strategies include irrigation farming, crop diversification, use of hybrid seeds, and purchase of livestock (ex-ante management). Also, farmers engage in off-fam activities, such as small businesses, to manage the risk (Coulibaly et al., 2015). Even though some of these strategies have been around for decades, they are reasonable solutions to the new challenges we face in the 21st century, including climate change and globalization. Credit or loans is another mechanism that most farmers use to cope with the disaster, as farmers can get large amounts of money and refund in installments (GoM, 2018a). However, not all farmers can get the loans because the interest rates in some cases are too high, and the collateral required may not be available to the farmers (Shams Allie & Demiryürek, 2020b). Another way farmers cope with disaster is by getting assistance from the friends and close relatives (Rahut et al., 2021). Even though these have the potential to protect farmers from disaster, it is only for a short while and cannot be used in cases where the whole region has been affected.

Over the years, many countries in Africa, including Malawi, have introduced a formal risk coping mechanism for smallholder farmers (Hess, 2005). Like many other insurances, the advantage of this type of mechanism is that it allows many people to join and accumulate enough money to compensate a few who experience losses from weather shocks (Ceballos et al., 2016). In Malawi, the government introduced sustainable market-based agricultural insurance to smallholder farmers in collaboration with the World Bank and other developmental organizations to assist farmers in times if of crop failure due to weather shock(Makaudze, 2016). One of the most important insurances that was introduced through this program is called the Weather Index Insurance (WII). The WII goal was to provide farmers with risk protection against weather risk. As such, it aimed to promote economic growth, improve food security, and contribute to rural agriculture development. The program was piloted in several districts in Malawi, such as Mchinji, Balaka, Kasungu, Neno, Nkhotakota, and Lilongwe (Makaudze, 2016). The program initially only insured groundnut producers but later expanded to growers of maize and other cash crops. Unfortunately, the program encountered many challenges and failed at the pilot stage. Some notable reasons for failures include withdrawal of the lending institution from the program, low adoption rate as many of the farmers did not understand the program, lack of trust, and lack of funds to pay the premiums to the insurance company (Smith & Watts, 2001).

Despite obstacles in Malawi, agricultural insurance has been successful in developed countries such as India and the United States (Hess, 2005). This is because, in India, agricultural insurance is mandatory for farmers and helps them to have easy access to low-cost agricultural inputs and loans from the government (Senapati, 2020). Additionally, the system receives subsidies in other countries, such as the United States, where it covers diverse weather-related risks (Hudson et al., 2020). Insurance programs in other African countries, such as Senegal and Ethiopia, have been effective; however, they still rely on aid from international organizations to cope with severe shocks (Makaudze, 2016). Studies suggested a need to establish policies that can assist in expanding insurance markets. One potential approach to achieve this objective could involve enhancing insurance infrastructure, providing targeted education to both agricultural producers and insurance providers, and implementing government subsidies for certain insurance offerings (USAID, 2006).

i) *Drought Tolerant*

In Malawi, droughts and dry spells have greatly impacted rainfed agriculture and threatened crop yield (Kassie et al., 2014). Therefore, to improve the situation, the Department of Agricultural Research Services (DARS) in Malawi, in collaboration with international research institutions, developed several drought-tolerant seeds. For instance, the International Maize and Wheat Improvement Center (CIMMYT) worked with DARS to develop over 18 drought-tolerant maize varieties (Katengeza et al., 2018). In addition to maize, several drought-resistant crops such as sorghum, millet, beans, and cassava have been developed by the research station and distributed to farmers whose areas are prone to dry spells and droughts(Ahmad et al., 2011). These crops that are tolerant to drought possess distinctive characteristics such as early maturation, the ability to endure extended periods of dry weather, immunity to significant pests and diseases, and a high yield potential (Holden & Fisher, 2015; Katengeza et al., 2018). Studies have shown that the adoption of drought-tolerant seeds has increased among communities that especially experienced long periods of dry spells in which the difference in crop yields between regular and drought-tolerant seeds were observed (Holden & Fisher, 2015). In the past, the adoption of drought-tolerant seeds has been hindered by the fact that many farmers allocate a smaller portion of their land for hybrid/drought-tolerant crops while devoting a larger portion of their land to local seeds. Several success stories were reported for applying drought-tolerant maize seeds in Malawi, such as increased crop production by up to 44% above the regular seeds (Katengeza & Holden, 2021).

2.6 Summary of the Agricultural Interventions

Table 1. Summary of major interventions to improve food security in Malawi

Intervention	Benefits	Challenges	Adoption Rate	References
Irrigation technology	• Increased yield production • Crop diversification • Source of employment • Source of income • Improves literacy level amongst farmers and extension workers	• High initial capital cost • Lack of technical knowledge of advanced systems such as sprinkler and drip irrigation • Lack of financial support • Absence of stable markets	• 25% of potentially irrigable land is developed.	• (IPS, 2008) • (ESRC & DFID, 2016) • (Nhamo et al., 2016a) • (Jica, 2021)
Conservation agriculture	• Improve soil structure. • Enhance water retention. • Reduce soil erosion. • Improve soil drainage. • Enhance soil fertility. • Increase yield	• Lack of appropriate tools • The absence of specialized knowledge among rural farmers concerning the construction of conservation structures, particularly those that necessitate precise measurements, represents a notable challenge.		• (Ngwira et al., 2014) • (Sosola et al., 2010) • (Kambauwa et al., 2015)
Manure management	• Improves soil fertility. • Improve soil aeration. • Replace soil nutrients loss. • Enhance soil structure and drainage. • Reduce farm operation cost as it is less expensive than inorganic fertilizer	• Lack of knowledge on the methods of collecting animal waste to make manure. • Insufficient workforce to produce and transport the manure		• (Ndambi, Pelster, & Owino, 2019) • (Edwards Sue & Hailu, 2011) • (Lindizgani & Chinangwa, 2006)

Table 1. (cont'd)

Livestock management	• Increase farmers' income. • Provide essential nutrients (e.g., fats, proteins, and vitamins) to farmers. • Facilitating the transportation of agricultural produce. • Supply waste materials that are converted into nutrient-rich manure, which is vital for maintaining soil health	• Livestock are susceptible to pests and diseases due to inadequate housing and care. • Lack of financial support • Lack of extension workers		• (Freeman et al., 2008) • (Nanganga & Safalaoh, 2020) • (Banda et al., 2011)
Crop insurance	• Improve the livelihood of farmers and their families as they get compensated when crops are lost due to disasters such as floods, drought, pests, and diseases. • Increases crop production and farmers income	• Lack of trust in insurance institutions • Lack of funds as farmers are struggling with paying the insurance premiums. • Lack of major institutions to support the program. • lack of knowledge about agricultural insurances	• None	• (Ceballos et al., 2016) • (Makaudze, 2016)

Table 1. (cont'd)

Loans	• Allow farmers access to farm inputs and equipment. • Increase numbers of small business • Improve literacy level. • Improve households' economic wellbeing. • Increase self-employment	• High-interest rate • Lack of appropriate assets to act as collateral	• Around 11.7% of farmers have access to credit	• (Diagne & Zeller, 2001) • (Meerendonk & Juergens, 2016) • (Shams Allie & Demiryürek, 2020b)
Machinery	• Increase cropped production area. • Increased crop yield • Reduce labor costs	• Lack of technical expertise • Government policies hinder farmers from accessing farm machinery. • Lack of agricultural extension support	• Less than 13% of farmers	• (Silver et al., 2016) • (Freeman et al., 2008) • (Malaidza & Strong, 2018) • (Kumwenda et al., 2020)

2.7 Modelling Tools

Farm Income Simulator (FARMSIM) Model

FARMSIM is one of the whole farm models that is used to predict the impacts of farm technologies on nutrition and economic livelihood at a household level. For instance, the model evaluates farming systems such as livestock management, finance systems, marketing structure, crop production, and risk management. The model incorporates Simetar add-ins and has been programmed in Excel, making it user-friendly and adaptable in many developing countries (Richardson et al., 2008). The model uses a stochastic base and alternative scenarios to simulate the nutrition and economic impact of new technologies on the farm. The FARMSIM model has been largely used in developing countries such as Ethiopia and Kenya to assist in decision-making. The model has proven to be valid and accurate as it can simulate data from real agricultural activities (Bizimana & Richardson, 2019). For instance, FARMSIM has been used to analyze the impact of food consumed at the household level in Ethiopia (Bizimana & Richardson, 2010), assess the effectiveness of agricultural technologies in developing farms (Bizimana & Richardson, 2019a; Bizimana & Richardson, 2018). Also, some studies have used FARMSIM to evaluate or understand adoption factors of the technology among farmers by ranking the technologies based on their risk (Bizimana & Richardson, 2019). This enables decision-makers to strategize different management and financing option to successfully implement, adopt, and sustain the technology (van den Berg et al., 2019). The model has four components, and these include crop, livestock, nutrition, and financial sections. FARMSIM simulates all the farming activities at a village, district, or regional level and provides probable income or nutrition status at a household level. For the nutrition analysis, FARMSIM considers three items in food analysis: agricultural production and consumption at a household level, food purchased from the market, and food donated by both local and international organizations. Then standard nutrient score is multiplied by the quantities consumed by the family to find the nutrient requirements for calories, calcium, iron, proteins, vitamin A, and fat. The total nutrients obtained are the combination of the consumption of foods from farm produce and market purchase and those from livestock products such as beef, pork, chicken, eggs, milk, and butter. For comparison, the model uses the minimum daily nutrient requirements per adult in relation to the recommendation from FAO and World Health Organization (WHO), and USDA. Additionally, FARMSIM simulates up to 15 crops and different livestock such as goats, cattle, and chicken on a farm. The models estimate key output variables such as annual net cash farm income, annual ending cash reserve, net present value, and benefit-cost ratio. Internal rate of return and annual family nutrients consumption of proteins, calories, fat, calcium, iron, and vitamin A.

2.8 Limitations of Agricultural Interventions to Enhance Food Security and Income

In Africa, food and nutrition security and income for smallholder farmers can be achieved through effective agricultural interventions and policies. The success of these strategies depends on several factors, such as the methods used in the implementation, farmers' willingness to adopt, funds, technical expertise, and good leadership to facilitate the whole process (Shimeles et al., 2018b). However, in general, agricultural interventions have faced implementation challenges. For example, Malawi has placed considerable emphasis on leveraging the agricultural sector to combat hunger. Notwithstanding, the nation continues encountering difficulties in effectively implementing various interventions and programs to ensure food security. Herein are a few constraints associated with agricultural interventions and policies to address food insecurity and poverty in Malawi.

- Most agricultural interventions are implemented on a small scale (less than 2 ha). This affects the overall yield and income of the household (Adams et al., 2020).
- Not all interventions are economically viable and can be sustained under small-scale farming (Makaudze, 2016).
- Small-scale farming is limited in terms of land and financial resources, and this affects the marketing, management, and sustainability of the technologies (Shams Allie & Demiryürek, 2020).
- Not all interventions have a direct influence on improving food and nutritional security. For instance, certain interventions primarily focus on environmental conservation, requiring farmers to determine the optimal crop combinations for achieving the necessary nutrients (Zelaya et al., 2017).
- Despite having good policies or interventions, the country depends on donor aid or credit from big institutions such as World Bank to implement the programs, thereby only achieving a few components. Also, this results in giving back all the benefits the country obtains to the lending institution, thereby preventing the country from making necessary improvements (Adhikari et al., 2019).
- Most programs related to food security and income enhancement are implemented in rural areas whose capacity is limited to sustain the program; as such, once the program ends, most people fail to continue doing what they were taught or solve any issue faced (World Bank, 2016).

Next Step

A more comprehensive understanding of the interplay between various policies and interventions is necessary to facilitate their effective implementation and enhance outcomes to enhance food and nutrition security among rural households in the country.

3.0 MULTIDIMENSIONAL EVALUATION OF THE IMPACTS OF AGRICULTURAL INTERVENTIONS TO ACHIEVE FOOD SECURITY IN MALAWI

3.1 Introduction

Food production remains a major global issue and affects food and nutrition security. According to the FAO of the United Nations, food security involves conditions in which people have access to a safe and balanced diet to meet a healthy lifestyle (FAO, et al., 2019); whereas nutrition security is met when the food quality is also considered to reduce the related malnutrition illness (USDA, 2022). Some important nutrients include protein, iron, calcium, carbohydrates, vitamins, and fats for a healthy lifestyle (Bokeloh et al., 2005). Over the world, especially in developing countries, food production has been affected by a growing population and climate change (United Nations, 2004). Meanwhile, the demand for global production is expected to increase by at least 50% by mid-century (P. Smith & Gregory, 2013). This has stressed agricultural resources such as land and water and causes many problems such as deforestation, land degradation, siltation, and increased greenhouse gas emissions (García-Oliveira et al., 2022).

In the past few decades, the food security problem has worsened in developing countries, especially Africa (García-Oliveira et al., 2022) . This is because African countries rely on rainfed agriculture for food production, which is prone to the effects of climate change, such as persistent dry spells and floods (Bokeloh et al., 2005). In addition to the impacts of climate variabilities, other domestic and international factors affect food insecurity in the region. Some of these factors include a lack of farm inputs, conflicts between countries, poor policies on food distribution, low levels of income, pests, and diseases (Hassan Al-Baguri, 2014). For example, according to the FAO, over twenty million people were food insecure in 2020 in African countries such as Kenya, Ethiopia, Somalia, and South Sudan due to the manifestation of locusts that destroyed most agricultural fields (FAO, ECA, et al., 2019). This resulted in low productivity, thus pushing more people to depend on humanitarian support for food (African Center for Strategic Studies, 2018). Also, for the past two years, many households have been affected by COVID-19 as income has decreased, food prices have increased, and food supply has reduced. On the other hand, studies have pointed out that governments/leaders from developing countries face challenges in reasoning properly or implementing effective strategies to solve related problems of food insecurity (Clover, 2003). This has increased malnutrition in most households, especially for children under five and vulnerable groups (FAO et al., 2019).

To lessen the problem, there has been much support from international organizations to developing countries to assist the agricultural sector in improving food production (ADF, 2011). Some of the technological investments include Conservation Agriculture, agroforestry, rainwater harvesting, irrigation technology, Systems of Rice Intensification (SRI), organic fertilizer, hybridization, and livestock management (Suri & Udry, 2022). Based on the Science Technology Options Assessment (STOA), these technologies can potentially improve productivity and food security and positively affect smallholder farmers (Suri & Udry, 2022). However, despite the positive impacts, these interventions still face adoption challenges by smallholders in developing countries. Several factors such as lack of skills to implement technology, inadequate labor force, and high cost of materials/technologies (Mwangi & Kariuki, 2015). These challenges differ from region to region and are categorized as social, economic, institutional, environmental education, and/or household characteristics; as such, there is a need to use an integrated approach to address the food insecurity problem.

Many modeling tools have been developed for simulating integrated crop and livestock systems (Rehman & Hussain, 2016, McDonald et al., 2019). These models essentially assist decision-makers in establishing effective policies in the agricultural sector to improve yield, nutrition, and economic livelihood (Clarke et al., 2017). Some whole farm models that have been used to simulate agriculture systems including Agricultural Production Systems farm-APSfarm (Cox et al., 2009), Farm Level Income and Policy Simulation Model-FLIPSIM (Richardson & Nixon, 1986), Decision Support System for Agrotechnology Transfer-DSSAT (Hoogenboom et al., 2019), and Farm Income Simulator-FARMSIM (Bizimana & Richardson, 2019a). APSfarm was developed from Agricultural Production Systems sIMulator (APSIM) to analyze economic and ecological effects using alternative resources such as land, time, irrigation water, livestock, and labor on a single farm. The model uses household surveys, experts' opinions, and focus group discussions on collecting information about different farming activities (Cox et al., 2009). Another model is FLIPSIM, which simulates whole-farm systems (Richardson & Nixon, 1986). The tool uses a Fortran computer program to simulate the impact of alternative technologies on different farming systems and income. The model can be used for any crop, livestock, and farm size. Another form of modeling is the Decision Support System for Agrotechnology Transfer (DSSAT), a software used to assess management options on a farm. The tool combines different variables of agricultural parameters such as crop, soil, and weather. This helps decision-makers to answer what-if questions by running different simulations. This assists in making an effective decision in agricultural production. One of the most recent integrated crop and livestock models is FARMSIM, which predicts the nutrition and economic impacts of different technologies such as livestock management, farming systems, marketing structure, crop production, and risk management on a household farm. Also, the model uses stochastic data to simulate the base and alternative scenarios for critical variables that are important for decision-making (Bizimana & Richardson, 2019).

Studies show that adopting and using the right technologies and sound management systems (policies) significantly improve the livelihood of smallholder farmers and rural communities in terms of food security and economic growth (Madu, 1989, Mwangi & Kariuki, 2015). Therefore, this study aims to examine the real-world impact of the national policies to address nutrition and food security by introducing modern technologies or better using the existing ones in Malawi. Specifically, the objective of the study are to 1) compare the profitability of four irrigation systems for a large-scale implementation; 2) assess the productivity of alternative land use and irrigation scenarios; 3) meet the nutritional requirements of the study population at the lowest cost by identifying the best combination of crop production and livestock product consumptions for given land use scenarios; and 4) rank alternative land use and irrigation scenarios based on the susceptibility to net cash farm income losses.

3.2 Methodology

3.2.1 Study Area

Phalombe is one of the districts in the southern region of Malawi, with an average elevation of 766 m above sea level. It has six Extension Planning Areas (EPA), namely: Kasongo, Mpinda, Naminjiwa, Nkhulambe, and Waruma. The district has 116,987 farm households, and it has a total land of 128,000 ha, out of which 73,880 ha is arable land. The average land holding size is 0.5 ha. The soil and climate are favorable to the majority of crops grown in the country. Smallholder farmers grow crops such as cereals, roots, and legumes during the rainy season (November to March), and several horticultural crops are grown under irrigation (April to October). Farmers also rear various livestock such as cattle, goats, pigs, and chickens. However, due to inadequate resources, most livestock are managed under a free-range system (NSO, 2006). This poses a substantial risk in meeting their full potential.

The Phalombe district was selected for this study because it is one of the districts where the impacts of climate change, such as floods and prolonged dry spells, are more pronounced (Government of Malawi, 2015). Meanwhile, approximately 40% of the population in this district is food insecure (IPC, 2021). In order to address these challenges, governmental and non-governmental organizations, such as the department of irrigation, the WFP, FAO, and Oxford Committee for Famine Relief (OXFAM) have been implementing different interventions (e.g., irrigation technology, soil and water conservation, livestock management, and food and cash transfer) to help improve the district's overall socioeconomic conditions as related to food insecurity, land degradation, and climate change related issues. Among these interventions, expanding irrigated lands and promoting irrigation technologies are the most popular due to their potential long-term positive impact on improving food security in small households while mitigating the negative impacts of climate change on crop production. The Phalombe district can be an ideal location to test this hypothesis as the region is rich in both surface and groundwater resources. Currently, the main irrigation systems practiced include solar-powered systems, treadle pump systems, river diversion systems, and motorized pump systems (MoAIWD, 2015).

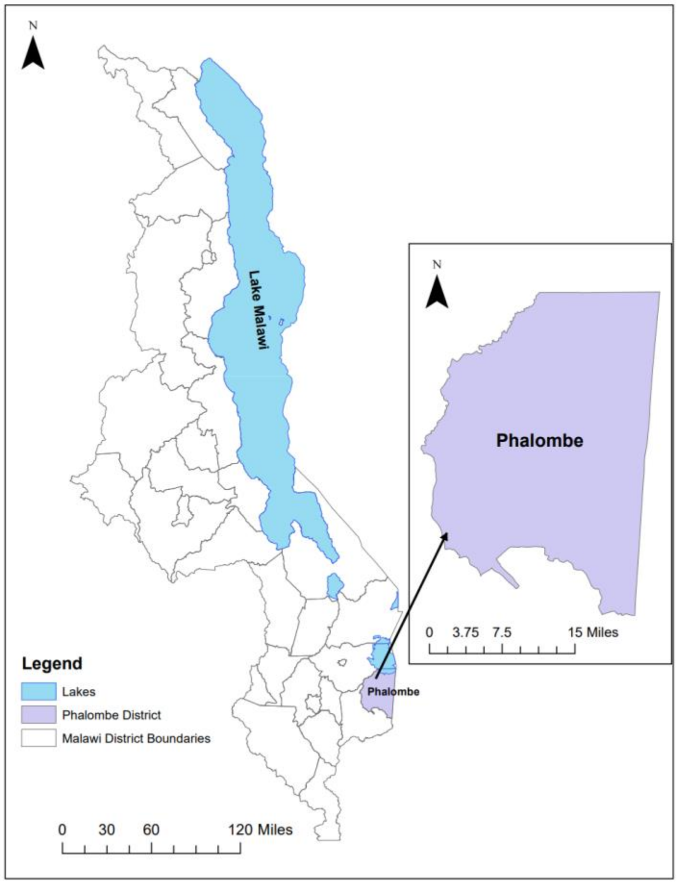

Figure 1. Map of Malawi showing the area of study

3.2.2 Data Collection

The study utilized data from both primary and secondary sources. We obtained the primary data through household surveys, focus group discussions (FGDs), and experts' opinions from the Phalombe district in Malawi. The study also utilized Agricultural Production Estimate (APES) data obtained by the Phalombe district agricultural office for the 2020–2021 growing season. This information helped us to understand common agricultural practices in the district and develop representative farm operations, finance, demographic, and consumption behaviors. The data collected included information about all the crops grown in the district under rainfed and irrigation, farm operation costs, market prices, major livestock compositions, costs/benefits of livestock operations, benefits obtained from livestock, and their market prices. All these data components were collected in reference to FARMSIM model requirements (Bizimana & Richardson, 2019). Based on our findings, the main crops grown in the district include corn, rice, pigeon peas, millet, and beans under rainfed and horticultural crops under irrigation (MoAIWD, 2016). We also obtained data from local agricultural extension officers from the Phalombe district and the WFP country report for 2019 on the quantity of food consumed by the household from the farm, purchased from the market (such as meat, eggs, cooking oil, fish), and donated food items (corn, pulses, cooking oil)(WFP, 2019a). Furthermore, the FARMSIM model requires information on the cash expenses to analyze the financial and nutrition status of the district at a family level (Bizimana & Richardson, 2019). Therefore, our survey data also included all this information at the household level for the Phalombe district. For the secondary data, we used reputable governmental documents, NGOs' reports, and peer-reviewed publications to supplement the primary survey data.

3.2.3 Farm Income and Nutrition Simulator (FARMSIM)

The FARMSIM model is one of the most comprehensive integrated farm models and is used to predict the probable impacts of different farming interventions on nutritional and financial well-being at the household level (Bizimana & Richardson, 2017). The model evaluates different components of farming systems, such as livestock management, finance systems, marketing structure, crop production, and risk management (Richardson et al., 2008). The model uses the Simulation & Econometrics to Analyze Risk (Simetar) tools to evaluate the different risks associated with agricultural interventions (Richardson et al., 2008). In addition to different agricultural management scenarios, the model accounts for the uncertainty in the system using a stochastic simulator to generate probabilistic outputs.

The model has been largely used in developing countries such as Ethiopia and Tanzania to assist in decision-making. The model has proved to be valid and accurate and is able to simulate data from real agricultural activities. Some of these applications include analyzing the impact of food consumed at the household level in Ethiopia (Bizimana et al., 2020), assessing the effectiveness of agricultural technologies at the farm scale (Bizimana & Richardson, 2019), and evaluating the potential adoption rate of a technology based on farmers' risk factors (Bizimana & Richardson, 2019). Such capabilities enable decision-makers to strategize different management and financing strategies to successfully implement, adopt, and sustain new technologies (Van den Berg et al., 2019). The model has four components that include a crop section, livestock section, nutrition section and financial section. FARMSIM can simulate all the farming activities at a village, district, or regional level and provide plausible income and nutrition status at a household level for five years. For the nutrition analysis, FARMSIM uses the amount of harvest from crops and livestock products consumed by the family, purchased from a market, and donated by international organizations. Using the standard nutrient score, the model calculates nutrient requirements for the family's calories, calcium, iron, proteins, vitamin A, and fat. The minimum daily nutrient requirements per adult are obtained from FAO, the World Health Organization, and the United States Department of Agriculture (USDA) (FDA, 2020). Table 1 summarizes the minimum requirements for nutrients per adult used by the model for nutrition simulation. Additionally, FARMSIM simulates all the crops and animal products that are sold by the household at the market to estimate the potential income for the family per hectare.

Table 2. Minimum nutrients requirements per adult equivalent (FDA, 2020)

Nutrients Requirements per adult equivalent	Amount
Calories	2353
Grams of protein	41.25
Grams of fat	39
Grams of calcium	1
Grams of iron	0.009
Grams of vitamin A	0.0006

3.2.4 Description of Scenarios

As discussed earlier, the goal of this study is to examine the impact of two national policies in Malawi to address nutrition and food security for smallholder farmers. These policies include the National Irrigation Policy (NIP) (MoAIWD, 2016b) and the National Multi-Sector Nutrition Policy (NMNP) (GoM, 2018). NIP Table A1 in the appendix was established with the goal of advancing the development of irrigation infrastructure so that more land is irrigated. The implementation of the policy involves three key steps: 1) the Development of new irrigation systems, 2) the Adoption of catchment management practices to safeguard water resources, and 3) the Empowerment of the beneficiaries with training to maintain the longevity of the irrigation infrastructure and enhance their capacity to manage the systems (MoAIWD, 2015). Also, NMNP (Table A2) was developed to promote nutrition security in all sectors so that every individual is healthy enough to undertake the country's development. The policy is linked to agriculture as it promotes crop diversification and consumption of different foods to improve diets and meet nutritional requirements for all age groups, especially vulnerable populations such as children, pregnant women, and older adults. It also encourages the private sector to invest in agricultural production, marketing, and processing of nutritious foods (GoM, 2018b).

To achieve this goal, four irrigation systems are introduced to a newly irrigated area in the Phalombe district in addition to existing agricultural land uses. Within a recently irrigated region, seven distinct crops are introduced for each individual irrigation system. Figure 2 presents an overview of modeling strategies to address the overall goal of this study under four distinctive objectives. In general, Objectives 1 and 2 address the propriety of the NIP by identifying the best irrigation and land use scenarios, considering the profitability of irrigation systems and productivity of the mixed rainfed and irrigation agricultural systems. Meanwhile, to address the priorities of the National Multisectoral Nutrition Policy, Objectives 3 and 4 are completed by identifying the balance between the inflow and outflow of goods into the district and ranking the most desirable ones according to the risk of the cash farm income for smallholder farmers.

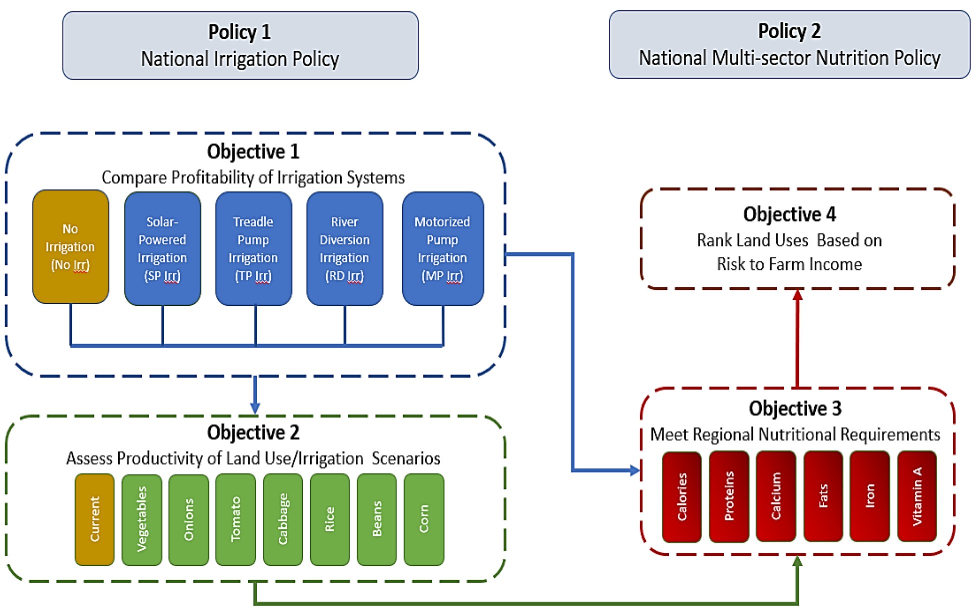

Figure 2. Schematic representation of land use and irrigation scenarios to address two national policies

3.2.4.1 Assessing the Feasibility of the National Irrigation Policy

Over the years, Malawi has been affected by frequent droughts, prolonged dry spells, and floods; as such, irrigation farming appears to be a sustainable strategy for coping with these critical situations (Nhamo et al., 2016). In Malawi, irrigated agriculture plays an important role in improving the lives of poor farmers; however, it is done both by the estate and smallholder farmers. Previous studies have reported that smallholder farmers can increase their production by 100% from irrigation farming compared to rainfed farming (Nhamo, Matchaya Greenwell, et al., 2016). Additionally, crops grown under irrigation are usually cash crops, such as rice, corn, and vegetables, which enables farmers to increase their income and improve their well-being (ESRC & DFID, 2016).

Surface irrigation is a commonly used method by smallholder rural farmers. This is due to its ease of operation and maintenance, as well as its cost-effectiveness compared to drip or sprinkler systems. (FAO, 2002). However, other irrigation methods are practiced by smallholder farmers, including treadle pump systems, solar-powered systems, motorized pumps, and river diversion methods (MoAIWD, 2015). However, irrigated farming faces many constraints in Malawi. One of the major challenges is the under-utilization of land. For example, despite the presence of water resources such as rivers and groundwater in the country, only 25% of the potential land area of 408,000 hectares is presently being irrigated. (AGRA, 2019; GoM et al., 2012; Wiyo & Mtenthiwa, 2018).

As discussed in Section 2.2, the Phalombe district was selected to examine the feasibility of implementation of the NIP with the goal of increasing crop yields and income while reducing the negative impacts of climate variabilities on agriculture production. The district has the potential to irrigate 15,000 ha of agricultural land; however, the current irrigated area is about 3,650 ha or about 25%. This is due to a lack of financial support, as irrigation requires large capital investments (Nhamo, Matchaya Greenwell, et al., 2016).

To evaluate the impacts of the new intervention (i.e., introducing a new irrigated technique and area) at both smallholder and district governmental levels, two growing seasons were evaluated. The rainy season was treated as a current/base scenario and comprised crops such as corn, peas, sorghum, millet, potatoes, rice, and groundnuts, as outlined in the Agricultural Production Estimates (APES) for Phalombe 2020–2021 growing season. Meanwhile, the alternative scenario is the combination of both irrigated and rainfed crops under different irrigation systems. In this district, the main irrigated crops include corn, tomatoes, cabbage, onions, and leafy vegetables. However, other crops, such as beans and rice, were recommended for this region under the irrigated system (IFAD, 2020). Therefore, based on the existing and potential opportunities for expanding irrigated lands, 28 new scenarios were evaluated that include four irrigation technologies (i.e., treadle pump systems, solar-powered systems, river diversion systems, and motorized power systems) and seven cropping systems (i.e., leafy vegetables, onions, tomato, cabbage, rice, beans, and corn). All of these scenarios are implemented on the new 11,350 ha irrigated land while the current rainfed (73,880 ha) and irrigation (3,650 ha) scenarios remain intact.

We conducted cost analyses for the implementation and upkeep of newly introduced irrigation systems based on the sample designs provided by Phalombe District Irrigation Office for each scenario, as presented in Table A3. These costs were assumed to be incurred by the household farmers. In the FARMSIM model, the capital cost was assumed to be a technology loan with a 10% interest rate, and the maintenance cost was assumed to be a fixed cost. In this study, the only difference among the alternative land use scenarios is the capital and maintenance costs for irrigation systems, water expenses for different crops as their amounts differ among crops, and the length of the growing season that affects labor costs. In addition, based on the local knowledge, we assumed that the required water to irrigate the new land is available, farmers are willing to take additional lands into cultivation, the farm inputs expenses are met, and the market is open to absorb new crop production. Finally, to compare the profitability of four irrigation systems for a large-scale implementation (Objective 1), we used the Net Cash Farm Income (NCFI). NCFI allows for comparing irrigation systems based on the total farm profit. NCFI is calculated by subtracting the total cash income from the total cash expenses.

3.2.4.2 Identifying Land Use with the Highest Productivity

In Malawi, smallholder irrigated farming, most of the time, is individualistic. For instance, an irrigation scheme can have different crops grown by individual farmers. This prevents farmers from obtaining better farm inputs and marketing prices, as it is hard to bargain with suppliers and buyers. In this study, we assessed the effect of allocating all the new production land (i.e., 11,350 ha) for monoculture production; farmers can benefit from using larger machinery and effective farming, such as planting and harvesting. Meanwhile, monoculture farming has many drawbacks, such as a higher chance of crop disease outbreaks. However, for this study, we tried to understand and narrow down the types of irrigation systems and crop production that are the most beneficial to farmers.

As such, the productivities of four different irrigation systems with seven monoculture crop scenarios were evaluated. Here, productivity is referred to as the feasibility and profitability of economic investment for new land development under irrigation systems. To achieve this, the study utilized the Net Present Value (NPV) and Internal Rate of Returns (IRR) as an indicator for this purpose (Objective 2). NPV is an effect that indicates the viability of an investment (Rich & Rose, 2017). A positive NPV shows that the income generated is greater than the costs invested. In contrast, a negative NPV shows a loss since the income generated is less than the costs incurred in the investment. On the other hand, IRR was also found to be a good criterion to assess the feasibility of an investment/intervention being able to sustain itself through the profits generated from the sales of the farm produce. Thus, the combination of irrigation and land use scenarios with the highest NPV and IRR is considered the most productive.

3.2.4.3 Assessing the Feasibility of the National Nutrition Policy

Malawi's food security depends on rainfed agriculture, which is mainly measured by corn availability (Hess, 2005). However, due to several factors like dry spells, floods, unreliable rainfall, land degradation, and an increase in the cost of farm inputs, productivity has remained very low (WFP, 2019). Most people who suffer from these consequences are rural households who rely on their own food production for consumption (Kerr et al., 2016). This affects the nutrition intake of smallholder farmers, especially young children, women, and other vulnerable groups such as those affected by HIV & AIDS (USAID, 2014). In addition to the yield gap, malnutrition is even worse due to the lack of variety of foods and poor food quality in some regions. A recent study in Malawi indicated that 10% of the population was food insecure and needed urgent humanitarian assistance (GoM, 2020). This poses serious health problems as it cannot meet the required nutrients in the body. Some of the micronutrients that are important are vitamin A, iodine, calcium, and iron. As such, their deficiency significantly impacts public health (FAO, 2010; USAID, 2014). These nutrients are required in small quantities to build, develop, and maintain the body. Some studies have pointed out that deficiency of these micro-nutrients in the body could result in anemia, intellectual disability, and maternal and neonatal deaths, especially for vulnerable groups (Joy et al., 2015).

Throughout the years, Malawi, like other developing countries, has been fighting to achieve Sustainable Development Goal 2 (SDG 2): Zero Hunger goal (Cosgrove et al., 2022). The World

Food Program survey conducted in 2018 in Malawi showed that the country has not yet met the SDG 2 goal and identified some limiting factors such as gender inequalities, underdeveloped markets, dependence on subsistence farming, and limited irrigation (Malawi Government, 2018). Different interventions have been introduced and implemented to improve smallholder farmers' food security and nutrition status. Some programs, such as the Farm Input Subsidy Program (FISP) provides farm inputs at a low price (Malawi Government, 2018; Schiesari & Mockshell, 2016). The package includes seeds (e.g., cereal, legumes) and fertilizer (basal and top-dressing fertilizer). This program assists approximately half of the rural farmer population. As a result, there has been a significant increase in corn yield, which has increased calories among rural farmers.

Meanwhile, the impact of FISP on dietary diversification seems limited, as micronutrient deficiency is still a major issue among farmers (Ecker & Pauw, 2014). Also, the Malawi government, non-governmental organizations, and developmental partners are emphasizing crop diversification and the growth of cash crops to ensure that farmers have a variety of foods to improve their nutrient intake (MoAIWD, 2016). This is because growing cash crops enables rural farmers to buy other foods to supplement their diet. Long-term strategies such as irrigation investments have also been prioritized to increase productivity and improve food security, especially in rural areas (Ringler, 2013). Reports show that farmers grow different crops under irrigation one to two times a year, including horticultural crops. This helps improve nutrient intake and farmers' well-being, as vegetables contain micronutrients (Ringler, 2013).

FARMSIM simulates alternative land use and irrigation scenarios in this study and for 5 years. The model reports nutrition variables such as calories, proteins, vitamin A, fats, calcium, and iron for each land use scenario. In the case of a nutrition deficiency detected at the district level, an optimization analysis is conducted to meet the minimum daily requirements according to the USDA dietary guideline (USDA, 2020). The food considered for purchasing includes egg, milk, beef, goat, meat, chicken, pig meat, and butter. The inputs to the optimization algorithm were price and nutritional information for all crops and purchasing food. The optimization analysis was conducted for the deficient nutrition variables at the district level (i.e., Objective 3). The objective of the analysis was to find the best strategy or combination to meet the required nutrients at the lowest costs under all scenarios. Thus, linear programming was utilized to achieve this objective. Linear programming is a method that utilizes linear equations and inequalities to identify potential solutions for present issues and difficulties encountered. (Mallick et al., 2020). Thus, linear optimization was achieved by defining the objective function, decision variables, and different constraints. The cconstraints were identified and defined as a set of linear equations and inequalities, and each decision variable was non-negative. As such, using this method, a possible strategy was defined that meets the required nutrients at the lowest cost and can reduce the effects of malnutrition. In this study, MATLAB 2022a was used to perform optimization analysis. As such, our optimization algorithm was applied to the results obtained from the four irrigation systems and seven irrigation land use scenarios.

Based on local food consumption culture, several products were identified, including milk, butter, eggs, goat meat, beef, and pork, to help meet the nutritional deficit. Table A4 shows the required nutrient values for each product. Using the nutrient values in Table A4, a set of equations for decision variables was developed to minimize the purchasing cost of market goods (Equation 1). In this case, the decision variables are Xi, which represents the quantity of the consumptive products and C_i is the cost per unit product (Table A4).

$$C = X_1 \times C_1 + X_2 \times C_2 + X_3 \times C_3 + X_4 \times C_4 + X_5 \times C_5 + X_6 \times C_6 + X_7 \times C_7 \qquad (1)$$

3.2.4.4 Risk Analysis and Ranking of Alternative Scenarios

The implementation of agricultural technologies entails an inherent risk factor. To address this, our study employed scenario analysis to assess and rank the various irrigation technology scenarios based on the level of risk involved. Different methods, such as means, standard deviation, and coefficient of variations, can be used to rank the scenarios. However, some of these methods are not robust enough to clearly show the differences in the risk pertaining to each technology (Chernobai & Rachev, 2007). Different studies have recommended a utility-based ranking approach to show a comparison among different technologies and rank the scenarios (Geissel et al., 2017). This helps decision-makers in choosing the preferable technology for adoption. Using the Simetar function, different alternative scenarios can be ranked using Certainty Equivalency (CE) (Dörfler et al., 2021), Stochastic Efficiency with Respect to a Function (SERF), Risk Premiums (RP), and Stochastic Dominance with Respect to a Function (SDRF) (Richardson et al., 2008). In this study, we opted to use SERF option because of its ability to evaluate profits or certainty equivalence under a range of risk aversion coefficients (i.e., from 0 – risk neutral to 1 - wealth/risk averse) for different technological scenarios. As such, using this approach, a decision maker can assess the behavior of different technologies under risk coefficients and select one that gives the highest CE in all cases. As such, preferred technologies have higher CE than baseline at all levels of risk (Richardson et al., 2008). In this study, the land use scenarios and irrigation technologies were further analyzed and ranked in terms of risk.

3.3 Results and Discussion

3.3.1 Comparison of Irrigation Systems

The comparison of irrigation systems was evaluated based on the profitability of the irrigation systems using the NCFI metric. NCFI refers to the returns obtained from the different technologies to find which irrigation system is profitable to smallholder farmers and has the potential to return high income. The study evaluated a total of 70,000 potential outcomes based on varying levels of unpredictability or randomness, comprised of 500 stochastic simulations per year for five years and seven crops under four irrigation systems. The findings indicated that the use of treadle pump systems has the greatest potential for boosting the average income of farmers (Mk2,114,918), followed by river diversion systems (Mk1,534,152), motorized systems (Mk1,340,313), and solar-powered systems (Mk1,085,500), as shown in Figure 3. The results also showed a higher range of NCFI for the solar-powered systems ranging between Mk -1,647,530 to Mk4,907,608 per family per ha per growing season. Meanwhile, this range is the smallest for the treadle pump systems (Mk-427,915 to Mk4,699,307) because the average initial cost (Mk50,547.00) and the operating costs (Mk7,527) per family per growing season are much smaller than the other irrigation systems. Solar-powered irrigation systems were found to have the least NCFI in 5 years because of their higher initial cost (Mk1,143,947) and operating costs (Mk62,198) per family. This is in line with other reports that have also pointed out the costs of solar-powered systems to be higher and affected smallholder irrigation farming in terms of operation and management (MoAIWD, 2015; National Planning Commission, 2021). This is because the high cost of maintaining the system results in reduced income for farmers to allocate toward other ventures. Furthermore, it was assumed that the prices of the farm produce on the market are the same regardless of which irrigation system is used in production but differ from the rainfed produce. An imbalance between demand and supply causes a variation in price during the irrigation season, where demand for this period is higher than the available supply, leading to an increase in price. Despite the profitability of treadle pumps, research indicates that they are not suitable for large-scale implementation when compared to solar-powered systems or river diversion system.

This is because treadle pump systems utilize shallow wells and have a small head; as such can only irrigate a small piece of land, approximately 0.1 ha, and requires more human labor to pump water manually. As such, it may be challenging for farmers to utilize the potential land due to a labor shortage. On the other hand, solar-powered systems were found to have higher potential when the capital cost is subsidized by the government or developing agencies take up the capital cost of the systems from the farmers(Kelley et al., 2010). However, these types of systems can be more profitable and less risky if they are implemented for high-value crops to increase farmers' returns.

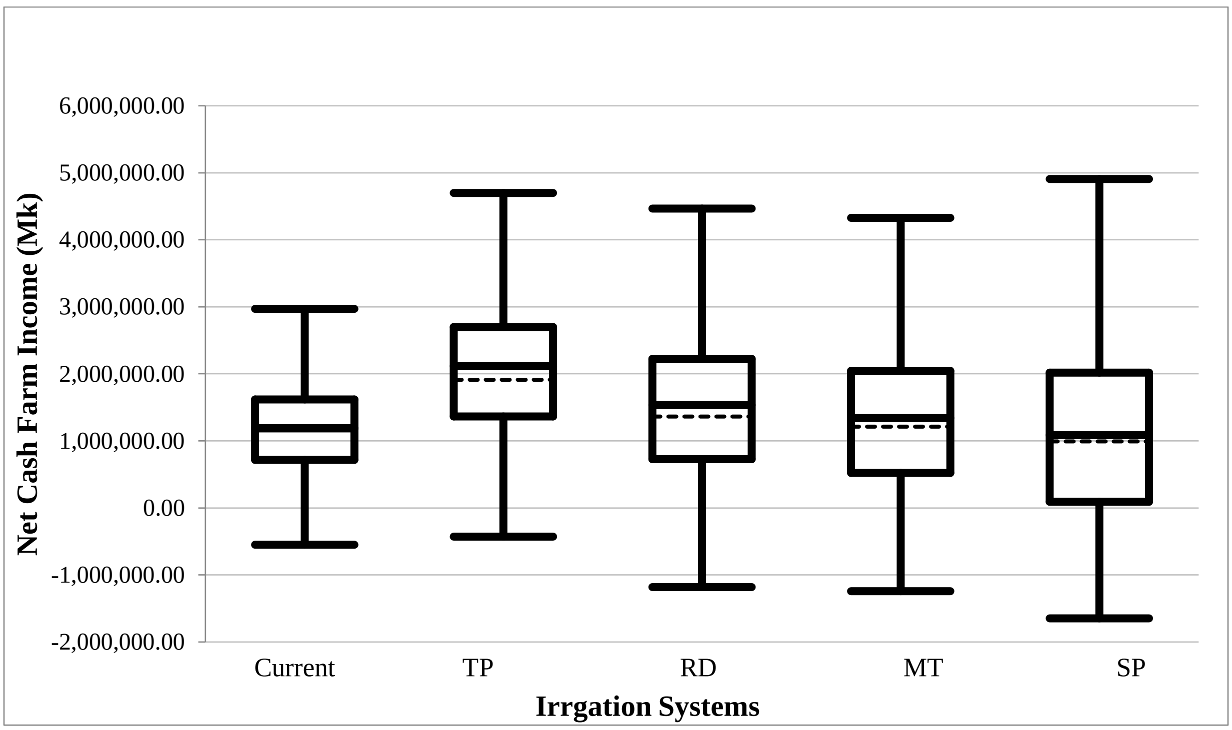

Figure 3. The comparison of four irrigation systems, including Treadle Pump Systems (TP), River Diversion Systems (RD), Motorized Pump Systems (MT), and Solar-Powered Systems (SP), was conducted based on the Net Cash Farm Income (NCFI) when compared to the current scenario. The dotted lines in the box plots show the mean NCFI that each system is anticipated to produce, and the solid lines mark the median NCFI values between the two quantiles

To compare different irrigation systems' performance for each land use scenario (i.e., corn, onions, cabbage, leafy vegetable, tomato, rice, and beans), a Tukey range test was conducted (α =

0.05) (Abdi & Williams, 2010). Table 2 shows that the means for NCFI were statistically different for corn, leafy vegetables, tomato, rice, and beans. However, the NCFI means for onions and cabbage were not statistically different for river diversion and motorized pump systems. Further, in all simulations, treadle pump systems were found to have the highest NCFI means under all scenarios with the highest return from leafy vegetables. On the other hand, solar-powered systems had the lowest NCFI means in all land use scenarios compared to other alternative irrigation systems.

Table 3. Statistical comparison of irrigation systems and each land use scenario based on NCFI means (vertical comparison)

Scenarios	Land use Scenarios						
	Corn	Onions	Cabbage	Leafy vegetables	Tomato	Rice	Beans
Current (rainfed)	1,429,634[b]	1,429,634[c]	1,429,634[c]	1,429,634[e]	1,429,634[e]	1,429,634[b]	1,429,634[b]
Treadle pump	1,525,552[a]	2,592,901[a]	2,254,698[b]	3,914,243[a]	1,711,876[c]	1,566,196[a]	1,475,417[a]
River Diversion	556,239[c]	1,628,691[b]	1,290,487[d]	3,207,301[b]	2,312,720[a]	913,588[c]	837,219[c]
Motorized pump	481,871[d]	1,620,682[b]	1,248,175[d]	2,902,443[c]	2,007,005[b]	599,254[d]	522,764[d]
Solar-powered	16,568[e]	1135615[d]	758,207[d]	2,411,721[d]	1,521,033[d]	114,941[e]	165,68[e]

[*] Values followed by the same letters are not significantly different (α = 0.05)

The horizontal comparison of NCFI means for all land use scenarios for each irrigation system is presented in Table 3. Similar to the previous analysis, the Tukey test was used to examine the significant differences among the land use scenarios at α = 0.05. Results from Table 3 showed that leafy vegetables are the most profitable land use scenario under all irrigation systems with the highest NCFI mean per family per ha, whereas corn land use had the lowest returns under all irrigation systems. In general, agricultural productions under the treadle pump systems are the most profitable. Additionally, the leafy vegetable was found to have the highest NCFI under all irrigation systems. To enhance the income of farmers through small-scale irrigation, the top priority should be given to leafy vegetables across all irrigation systems, with tomatoes following closely and onions being ranked third.

Table 4. Statistical comparison of land use scenarios for each irrigation system based on NCFI means (horizontal comparison)

Scenarios	Land use scenarios						
	Corn	Onions	Cabbage	Leafy vegetables	Tomato	Rice	Beans
Treadle pump	1,525,552[f]	2,592,901[b]	2,254,698[c]	3,914,243[a]	1,711,876[d]	1,566,196[e]	1,475,417[g]
River Diversion	556,239[g]	1,628,691[c]	1,290,487[d]	3,207,301[a]	2,312,720[b]	913,588[e]	837,219[f]
Motorized pump	481,871[g]	1,620,682[c]	1,248,175[d]	2,902,443[a]	2,007,005[b]	599,254[e]	522,764[f]
Solar-powered	16,568[f]	1,135,615[c]	758,207[d]	2,411,721[a]	1,521,033[b]	114,941[e]	16,568[f]

[*] Values followed by the same letters are not significantly different (α = 0.05)

3.3.2 Assessing the Productivity of Land Use and Irrigation System Scenarios

As discussed above, the treadle pump system had the highest probability of increasing farmers' income, and the leafy vegetable land use scenario had the highest profitability compared with other alternative land use and irrigation scenarios. While these results are essential to assess farmers' profit margins, they do not clearly indicate whether the interventions will have higher returns once implemented. As such, econometric matrices such as NPV and IRR were used to identify a land use scenario that could generate a higher return from investment in irrigation systems. (Juhász, 2011; Rios, 2017). During the study, NPV and IRR were calculated for all the alternative land use and irrigation scenarios.

Table 4 shows that leafy vegetables have the highest probability of generating returns under all irrigation systems compared to other land use scenarios. However, the highest IRR was calculated under the treadle pump system (5.12), followed by the River Diversion system (0.38), the motorized pump system (0.37), and finally, the solar-powered systems had the least IRR (0.13) under all scenarios. Moreover, the results show that bean, rice, and corn land use scenarios had the lowest IRR under all irrigation systems. According to the results, the scenarios with negative IRR (presented in red fonts in Table 4) have small cash flows that are lower than the initial investment and, as a result, cannot sustain themselves in the long term.

On the other hand, the NPV results (Figures 4 and A1 to A3) show that the tomato land use scenario under the treadle pump had the highest NPV, followed by leafy vegetables and onions. Whereas corn, rice, and beans land use scenarios under solar-powered showed the lowest NPV compared to other alternative land use scenarios (Figures 4 and A1 to A3). Considering positive IRR for all scenarios above, the most effective combination of land use and irrigation scenario is the irrigated tomato crop production under the treadle pump system. In contrast, the least productive scenario is corn production under the solar-powered irrigated system. Finally, cabbage production under the river diversion and motorized pump system should not be considered for irrigated land expansion under the river diversion and motorized pump systems.

Therefore, the result of this section can provide valuable information about the productivity of a combination of land use and irrigation system that can be useful for landscape planning and providing subsidies to promote different technologies. For example, the government/farmers may allocate crops with high returns to costly irrigation systems to sustain the technology.

Table 5. Internal Rate of Returns (IRR) values for all combinations of land use under different irrigation systems

Land use scenarios	Irrigation technologies			
	Treadle Pump	River Diversion	Motorized Pump	Solar powered
Corn	0.70	0	0	0
Onions	5.41	0.07	0.04	0
Cabbage	5.45	-0.01	-0.01	0
Leafy vegetables	14.53	1.88	1.83	0.90
Tomatoes	8.71	0.69	0.74	0.00
Rice	0.73	0	0	0
Beans	0.29	0	0	0
Average	5.12	0.38	0.37	0.13

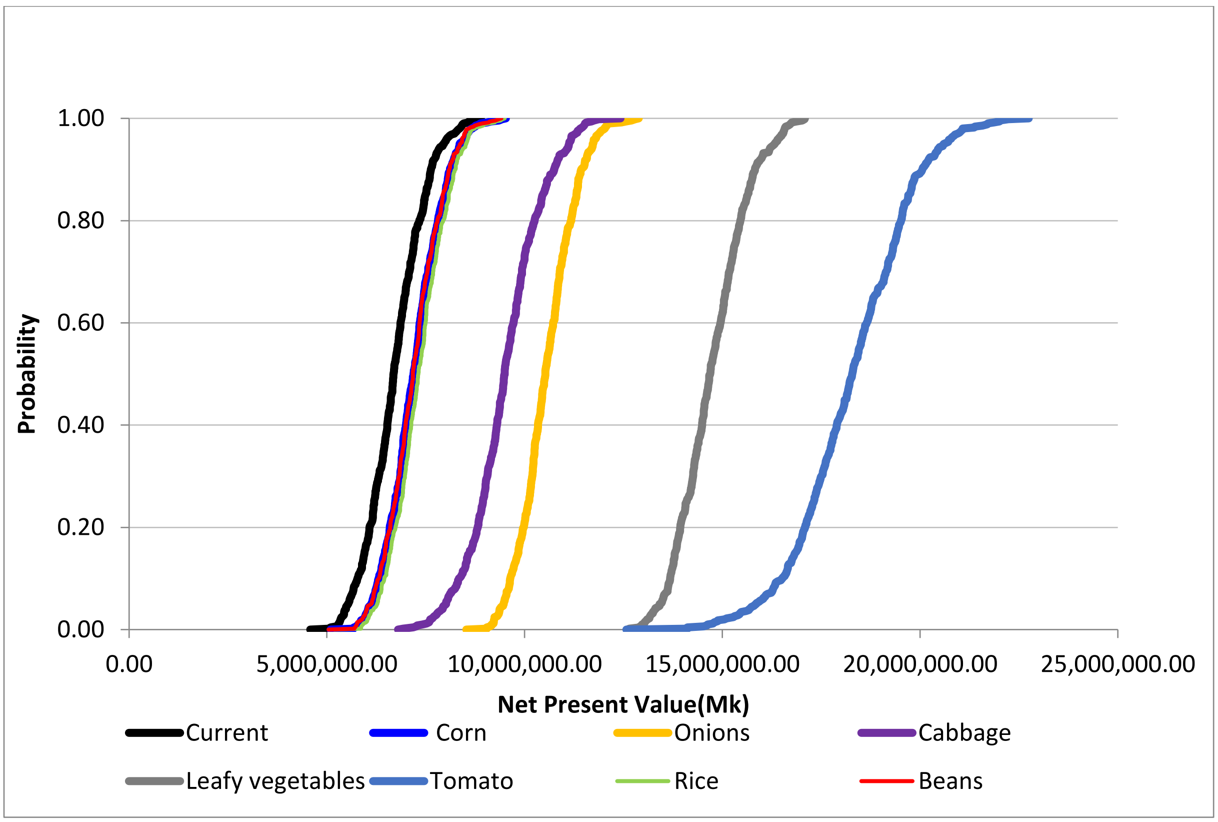

Figure 4. Net Present Value for land use scenarios under the treadle pump irrigation system

3.3.3 Nutrition Analysis

3.3.3.1 Nutrient Outputs of Different Land Uses for both Current and Irrigated scenarios

The FARMSIM model was also utilized to estimate the nutrition outputs of different land use and irrigation systems. The obtained results were compared against nutrient requirements per adult equivalent for the Phalombe district. The simulation results largely depend on the crops grown in the district, especially the number of products the household consumes from the crops and livestock, food purchased from the market, and donations from humanitarian and non-governmental organizations. Multiplying the number of food items by their respective nutrient scores gives the total nutrients consumed by a household. However, it is important to note that the availability of household income to purchase additional food can also impact the results.

According to FAO and USDA nutrition standards (USDA, 2020), the current production system generally satisfies the district's nutritional needs, except for calcium, as shown in Table 5. This was also the case for all irrigated scenarios, as presented in Tables A5 to A8. Figures 6 and A4 show the nutritional output of various land uses normalized to match the minimum nutritional needs. The analyses indicate that neither the current land use nor the irrigated scenarios can fulfill the minimum nutritional requirements for the district. As a result, we ran the model again with the objective of selling excess nutritional outputs, particularly calories, to increase the farmers' income. The additional funds generated from this process could be utilized to purchase supplementary food to bridge the nutritional gaps. After the necessary adjustments were made (Tables A9 to A12), the findings indicated an excess of iron, fats, and vitamin A. However, the values for calcium and protein are the lowest when compared to the minimum requirements (Table 5). The findings align with previous reports that have highlighted the overdependence on starchy foods in developing nations and the inadequate intake of animal products, including meat, eggs, and milk, in the diets of rural households (WFP, 2022).

Table 6. Nutrient requirements per adult equivalent for both current and irrigated scenarios for the Phalombe district

Nutrition variable	Current scenario	Irrigated scenarios	Adjusted irrigated scenarios	Minimum nutrient requirements	Needs adjustments
Calories	Excess	Excess	Meet	2353 (cal)	No
Protein	Deficit	Excess	Deficit	55 (g)	Yes
Fat	Excess	Excess	Excess	39 (g)	No
Calcium	Deficit	Deficit	Deficit	1 (g)	Yes
Iron	Excess	Excess	Excess	0.009 (g)	No
Vitamin A	Excess	Excess	Excess	0.0006 (g)	No

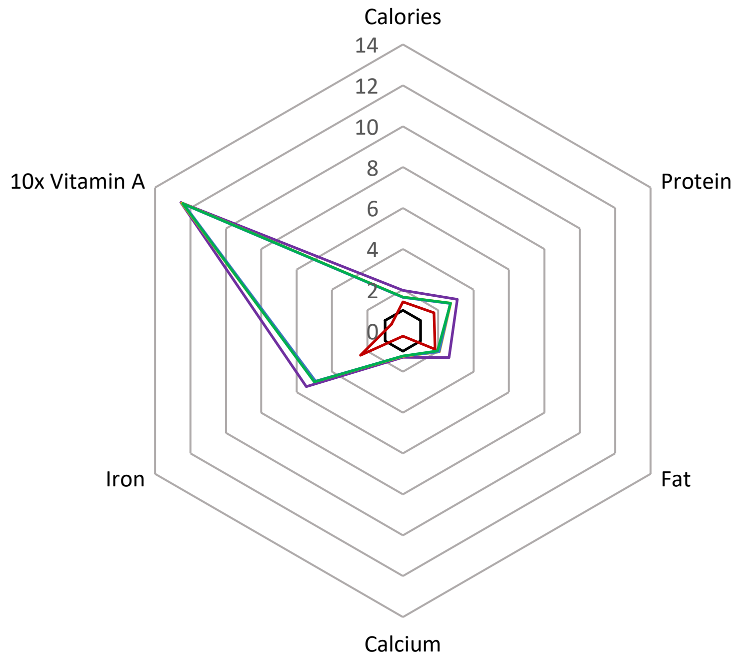

Figure 5. The nutritional output of various Leafy vegetables land use normalized to match the minimum nutritional needs (black line) of the population in the Phalombe district and under different irrigation systems (current/no irrigation (red), solar-powered (green), treadle pump (purple), motorized pump (blue), and river diversion (orange))

Across all land use scenarios, including the current one, there were an excess of calories since, in Malawi, the primary meal typically consists of starchy foods such as maize, rice, and millet, and there is limited consumption of animal products. These food items are high in calories. For instance, the data collected from the survey conducted in Phalombe district indicates that households consume roughly 80% of the grain they produce (i.e., 3,327 cal), which provides more than 2,353 minimum calorie requirements per person on average. Generally, the average calorie for alternative land use and irrigation systems varies from 2,585 to 3,767 due to the expansion of the irrigated land. However, there were more calories under treadle pumps, river diversion, and motorized pumps than solar-powered systems. The variation in nutritional values observed across different irrigation systems is attributed to the way in which the model was constructed. In FARMSIM, the nutritional evaluation is performed based on the available financial resources. For example, the preliminary analysis of nutritional data (Tables A5 to A8) indicated that, although the consumption rate was consistent across different land use and irrigation systems, the treadle pump irrigation system scenarios demonstrated a higher amount of nutrition compared to other irrigation systems. This is because the amount of cash available for purchasing additional food largely determines the nutritional content of the diet. As a result, land use scenarios involving solar-powered irrigation systems had lower nutrient levels due to the limited funds available for buying supplementary food.

3.3.3.2 The Impacts of Irrigation on Farmers' Incomes and Human Health

After balancing the calorie consumption, there was a notable positive change in NCFI in some land use scenarios under different irrigation systems such as corn, rice, and beans (Table S13). After the surplus agricultural productions were sold to the market, the NCFI increased between 5% to 80% for various land use and irrigation systems compared to the current scenarios. This phenomenon, known as "income path," exhibits greater potential for impacting the nutrition of farm families compared to production (Bizimana et al., 2020). When the caloric balance was achieved, the primary crops targeted were starchy foods (e.g., corn and rice) with a relatively low market price. Consequently, this could be one of the reasons why, in some instances, the changes in NCFI are insignificant. Conversely, after reaching caloric equilibrium, pulses such as beans were found to result in an NCFI increase of approximately 80%.

Additionally, under all alternative land use/irrigation scenarios, there was an excess of fats (>39 g), iron (> 0.009 g), and vitamin A (>0.0006 g). These micro-nutrients have a significant impact on human health (FAO, 2021). There was a significant increase in the levels of these nutrients across all land use scenarios that employed irrigation systems, as demonstrated in Figures 5 and S4. Furthermore, this study indicates that expanding the land under irrigation and cultivating horticultural crops, particularly leafy vegetables, can enhance access to micronutrients, such as iron and vitamin A, by more than 100% per adult equivalent. Meanwhile, the minimum protein intake was satisfied and surpassed under some land use scenarios, as seen in Tables A9 to A12. Additionally, calcium was found to be insufficient in all land use scenarios. The calcium and protein deficiency in one's diet affects different age groups (FAO, 2021). For instance, a lack of calcium and protein in the human body can lead to loss of body mass, weak bones, and rickets in young children (FAO, 2008). To combat malnutrition, there is a need to improve market infrastructures in rural areas where people can access different food commodities without any challenges. In addition, there is a need for a varied diet and consuming the recommended number of daily meals (WFP, 2012). This shortcoming is addressed in the next section and through the optimization process.

3.3.3.3 Optimization of Stakeholders' Production and Consumption to Meet the District Nutrient Requirements at the Lowest Cost

Linear programming results indicate that milk is the most cost-effective dietary supplement in all land use and irrigation scenarios (Tables 6, A14, A15, and A16) which can meet the deficit nutrients protein and calcium. On average, it is recommended that a household consisting of around six members should consume roughly 2 liters of milk per day as a dietary supplement, according to the findings. The computed expenses indicate that households can allocate approximately Mk600.00 per day for milk, while eggs are seen as a secondary option for supplementing essential nutrients at a low cost. Furthermore, the findings revealed that, among the different land use and irrigation scenarios, milk consumption was the lowest in the case of tomato land use and solar-powered irrigation systems (Table A15). Another possible solution is to enhance and improve livestock interventions, such as poultry and dairy farming, by promoting the participation of farmers/households in raising livestock for easy access to their products.

Table 7. Optimization results for meeting minimum nutritional requirements for the Phalombe district based on the treadle pump irrigation system and different land uses

Purchased goods and associated cost	Land Use							
	Current	Corn	Onions	Cabbage	Leafy Vegetables	Tomato	Rice	Beans
Eggs (kg)	0	0	0	0	0	0	0	0
Milk (L)	98,057,000	97,221,000	96,974,000	95,978,000	96,211,000	94,559,000	97,169,000	97,225,000
Beef (kg)	0	0	0	0	0	0	0	0
Goat meat (kg)	0	0	0	0	0	0	0	0
Chicken (kg)	0	0	0	0	0	0	0	0
Pig meat (kg)	0	0	0	0	0	0	0	0
Butter (kg)	0	0	0	0	0	0	0	0
Total cost (Mk)	26,868,000,000	26,639,000,000	26,571,000,000	26,298,000,000	26,362,000,000	25,909,000,000	26,624,000,000	26,640,000,000
Milk purchase for district L/day	268,649	266,359	265,682	262,953	263,592	259,065	266,216	266,370
Milk purchase per adult L/day	0.731	0.724	0.722	0.715	0.717	0.704	0.724	0.724
Milk purchase per family L/day	2.296	2.277	2.271	2.248	2.253	2.214	2.276	2.277

3.3.4 Ranking Alternative Land Use and Irrigation Scenarios Based on the Susceptibility to Net Cash Farm Income (NCFI) Losses.

The results from section 3.3 show that the most preferred scenario for meeting nutrition requirements at the district level is leafy vegetables land use under the treadle pump irrigation system. Simulations were further performed to rank the alternative land use and irrigation systems based on risk. Using Simetar, the SERF tool was utilized to rank land use and irrigation system scenarios based on normalized CE and NCFI into four classes: Low, Moderate, High, and Extreme. According to Bizimana and Richardson (2019), when ranking scenarios according to risk, the most preferred scenario is the one with the highest CE. Also, the normalized NCFI was used to account for the magnitude of farmer income being affected. Figure 6 shows the risk level is low for leafy vegetables grown under treadle pump, river diversion, and motorized pump systems and moderately risky under solar-powered system. However, it was found that several crops, such as corn, beans, rice, and cabbage, are extremely risky to be grown under solar-powered irrigation systems in the Phalombe district. This is mainly due to the fact that the income generated is very minimal to sustain the irrigation technology itself.

Figure 6. Ranking alternative land use and irrigation scenarios according to four risk levels

3.4. Conclusion

The goal of the study was to evaluate the tangible effects of national policies that aim to enhance the economy, nutrition, and food security in Malawi by adopting new or existing technologies. To achieve this goal, 28 alternative land use (corn, onion, tomato, leafy vegetables, bean, and rice) and irrigation system (treadle pump system, solar-powered system, river diversion system, and motorized pump system) scenarios were evaluated based on the local potential to expand irrigated land. In general, the results from FARMSIM show that irrigated agriculture allows farmers to boost their income and fulfill district level nutritional requirements, including crucial nutrients such as iron and vitamin A, which are essential for human health. Among the land uses and irrigation systems, growing leafy vegetables greatly impacted the farmers' income and nutrition at the household level. However, not all micronutrients can be obtained through irrigated agriculture. By conducting an optimization analysis, this study has demonstrated that farmers can use their income from irrigation to access animal products, such as milk or eggs, as a low-cost way to supplement their diet.

In all the analyses conducted, the treadle pump was consistently identified as the most favored irrigation system, while the cultivation of leafy vegetables was found to be the most profitable land use option that could also be sustained over time. Despite being a profitable option for smallholder irrigated agriculture, treadle pump systems have limitations due to the need for significant human effort and cannot be used on large-scale. Therefore, when considering the goal of expanding this practice on a larger scale, it is important to take these factors into account. Conversely, the solar-powered irrigation system was associated with a lower number of economically viable crops, but with an appropriate pump, it could irrigate a larger area of land while minimizing the need for manual labor.

Based on our research findings, it is necessary to adopt and utilize alternative technologies to accomplish the objectives of national policies. As an example, policymakers could explore alternative combinations of irrigation systems with higher efficiency and more profitable cropping systems as a means of expanding the irrigated land while simultaneously boosting profits. It is also important to account for the risk of income loss to smallholder farmers when undertaking large-scale irrigation expansion, as even small margins of loss can have significant impacts on their livelihoods. Nonetheless, the concept of prioritizing irrigation systems and land use scenarios based on risk assessment can have significant implications and assist decision-makers, producers, and other stakeholders in identifying more effective strategies for promoting the sustainability of irrigated agriculture. For instance, during the study, while crops such as beans, corn, and rice generally thrive under irrigation, our study revealed that cultivating these crops using solar-powered irrigation systems posed economic risks, as their lower returns may not be sufficient to sustain the systems and improve the economic well-being of farmers. Nevertheless, this situation could be ameliorated by adjusting market prices and providing technology subsidies to lower the capital costs incurred by farmers.

This study's focus was restricted to assessing irrigation systems for expanding irrigated lands on a large-scale and did not take into account how climate change and other national policies could potentially influence the overall risk and profitability of the proposed systems, either directly or indirectly. Therefore, future studies should address these shortcomings.

4.0 OVERALL CONCLUSION

Food and nutrition insecurity remains a critical issue in developing countries, including Malawi. In order to tackle the issue of food insecurity, a range of interventions and policies have been designed to enhance the well-being of populations. This study aimed to examine the national policies that aim to improve Malawi's economy, nutrition, and food security using the new and existing technologies. In this study, we evaluated the policy based on the expansion of irrigated land in the Phalombe district. The findings obtained from the literature and research modeling enabled us to comprehend the hurdles that impact food security, the feasible technologies for scaling up agricultural production, and the measures to be taken while introducing agricultural technologies to enhance food and nutrition security, income, and quality of life for rural populations. In this study we developed four objective scenarios for examining the national policies, and results from the model are summarized below:

- Agricultural interventions play a vital role in improving food security and the economy in the country. However, many of these interventions have encountered implementation challenges, including a shortage of resources, which has hindered their ability to achieve the goal of ensuring food security.
- Irrigation technology is one of the interventions that can effectively increase farmers' income and improve food and nutrition security at the household or regional level. For instance, growing leafy vegetables, tomatoes, and onions can increase farmers' income, enabling farmers to purchase extra food commodities to supplement diet and improve their livelihoods. Nonetheless, it is important to carefully consider the type of crop and livestock production before scaling up the use of irrigation practices (IFAD, 2020).

- To maximize the effectiveness of an intervention, participants should be informed of alternative interventions relating to cropping systems and subsequently select the one that can foster economic growth and provide essential nutrients for human health.
- While irrigated agriculture, such as the cultivation of horticultural crops, can supply the majority of the nutrients that humans require, certain essential nutrients like calcium cannot be obtained through crop production alone. Therefore, irrigation interventions should be implemented in conjunction with other measures that can increase access to a diverse range of food items. For instance, enhancing livestock management (i.e., chicken, goats, cattle), improving market infrastructure, and rehabilitating roads to enable rural communities to access a variety of food (Feed the Future, 2016)
- When selecting irrigation technologies, it is essential for participants to comprehend the economic risks associated with the technology, as these risks can have a considerable impact on their livelihoods, potentially hampering the attainment of policy objectives.
- The treadle pump irrigation system was determined to be the most profitable and applicable to the majority of irrigated crops. However, this system necessitates significant human effort. Hence, for widespread implementation, an evaluation of the labor market's capacity and willingness to engage in this endeavor is essential.
- The river diversion system emerged as the second most profitable irrigation system after the treadle pump system based on cash farm income. Nevertheless, climate change projections suggest that drought will likely intensify in the southern regions

of the country (Adhikari and Nejadhashemi, 2016). As a result, it is imperative to explore alternative approaches to irrigation in drought-prone regions, given the expected rise in the frequency and intensity of droughts.

- A solar-powered irrigation system may yield lower cash farm income and less profit, but its potential to irrigate extensive tracts of land is substantial with the use of an appropriate pump. It is, therefore, crucial for decision-makers and stakeholders to identify high-value crops that can be grown under this system to maximize its profitability.
- Among the various irrigation systems investigated, the motorized pump system was ranked third in terms of effectiveness. While most crops can thrive under this method, decision-makers must take into account the potential impact of diesel fuel scarcity in the region, as it could significantly impair production.

5.0 FUTURE RESEARCH

This study was limited to the assessment of four irrigation systems in a single district in Malawi, with the objective of bolstering two national policies aimed at enhancing the income and food security of smallholder farmers. However, this study did not consider the potential impact of climate change, global crisis, and other national policies on the overall risk and profitability of the proposed systems. As such, future studies should seek to address these limitations, including but not limited to the following items:

- It is necessary to develop irrigation strategies tailored to specific sites. This involves identifying potentially irrigable land, corresponding water sources and appropriate irrigation technologies. Accomplishing this requires gathering supplementary data on factors such as soil composition, groundwater depth, surface water availability, and river networks.
- The current study utilized average output/harvest values for all farming households. Therefore, future research may wish to classify farmers into different categories (such as poor, middle, and rich) to evaluate income and nutrition levels more effectively and devise strategies for enhancing them.
- Investigate the potential impact of increasing irrigated land on the surface and groundwater resources and identify the most sustainable irrigation/crop systems for achieving this expansion.
- Evaluate alternative cropping and irrigation systems that smallholder farmers can utilize to optimize irrigated land usage, while concurrently enhancing income, food security, and nutrition.

- Examine the effects of the widespread expansion of irrigation systems throughout the country and their impact on the National Water Policy. This is because irrigation necessitates the withdrawal of significant volumes of water from water sources, potentially impacting the National Water Policy.
- Evaluate other external factors, including the impacts of climate change, funding, human resources, markets, and technical expertise, that could impede the attainment of the objectives of implementing large-scale irrigated agriculture.
- Identify the best approach for disseminating the scientific findings to farmers, policymakers, and donors, to foster sustainable food security at both the local and national levels.
- Research alternative methods for preserving farm produce, including perishable items such as tomatoes, in light of the expansion of irrigated land and subsequent increase in production. It is imperative to incentivize local investors to participate in processing and manufacturing to enhance food preservation efforts.
- Evaluate other potential risks arising from integrating irrigation systems with crop and livestock productions at a national level to ensure the alignment of national policies with the requirements of smallholder farmers.

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APPENDIX

Table A8. National Irrigation Policy (NIP, 2016)

Policy	Policy Statement	Policy Objective
Policy Priority Area 1: Sustainable Irrigation Development	• To gather resources for the advancement of irrigation, it is recommended to employ various approaches such as Public-Private-Partnerships and matching grants.	• Put more land under irrigated agriculture.
Policy Priority 2: sustainable Irrigation Management	• Assist farmers in irrigated agriculture by ensuring the upkeep and enhancement of irrigation facilities in rural areas. • Employ various methods for processing and marketing farmers' agricultural produce to enhance the profitability of irrigated crops.	• Encourage and broaden the practice of growing a variety of crops. • Enable diverse stakeholders and sectors to take charge of managing irrigation systems.
Policy Priority 3: Capacity building	• Creating capacity-building programs that augment the capabilities of various stakeholders. • Increase the number of irrigation specialists at the national and district levels. • Enhance the knowledge of farmers and transition subsistence farming to commercial farming through capacity building at the local level.	• Facilitate the progress of irrigated agriculture by offering capacity-building opportunities to both producers and experts.

Table A9. Multi-Sector Nutrition Policy (NMNP 2018)

Policy	Policy statement	Policy objective
Priority Area 1: Prevention of undernutrition	• Nutrition interventions that are both highly impactful and cost-effective are expanded to all communities.	• Ensure that children under 5, adolescents, school-going children, pregnant women, and other vulnerable groups do not suffer from undernutrition.
Priority Area 3: Treatment and control of acute malnutrition	• The government assumes ownership and provides financing for interventions aimed at managing acute malnutrition.	• Provide treatment and management of acute malnutrition in children under 5, pregnant and lactating women, people living with HIV, and other vulnerable groups.
Priority Area 4: Prevention and management of overweight and nutrition-related Non - Communicable Diseases (NCDs)	• Prevent nutrition related NCDs by using behavior change communication to promote appropriate diets, healthy lifestyles, and physical activity.	• Prevent and address overweight and NCDs related to nutrition
Priority Area 6: Nutrition during an emergency	• Provide a prompt and efficient food and nutrition response to the affected population, particularly vulnerable groups, in times of emergency.	• Improve the implementation of nutrition interventions during emergencies.

Table A10. Average capital and maintenance costs of irrigation systems

Irrigation system	Capital cost/family (Mk)	Maintenance cost/per family (Mk)
Treadle pump	50,547	7527
River diversion	737,845	41,892
Motorized pump	797,267	39,863
Solar-powered	1,143,974	62,198

Table A11. Nutrition values of different products (USDA, 2002) and FARMSIM model default data

Nutrition Facts	X1	X2	X3	X4	X5	X6	X7
	Egg (Per kg)	Milk (Per liter)	Beef (Per kg)	Goat Meat (Per kg)	Chicken (Per kg)	Pig Meat (Per kg)	Butter (Per kg)
Calories	1430	640	6740	1090	2150	6320	7170
Protein (g)	125.6	32.8	82.1	206	186	92.5	8.5
Fat (g)	95.1	36.6	708.9	23.1	150.6	657	811.1
Calcium (g)	1.36	1.19	0.26	0.13	0.11	0.14	0.24
Iron (g)	0.0175	0.0005	0.0072	0.0283	0.009	0.0026	0.00002
Vitamin A (g)	0.0016	0.00041	0	0	0.00042	0.000258	0.007497
Cost MK (*Ci*)	2857	274	2037	959	2999	1388	4200

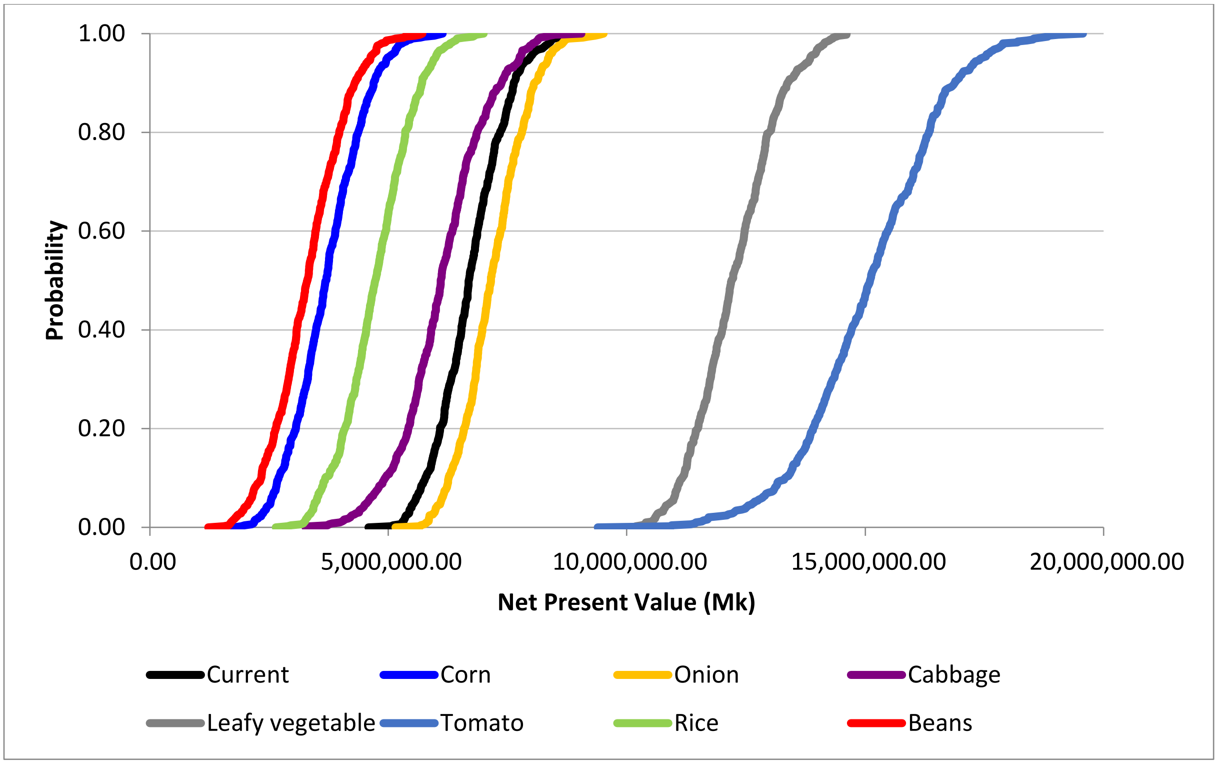

Figure A1. Net Present Value for land use scenarios under the river diversion irrigation system

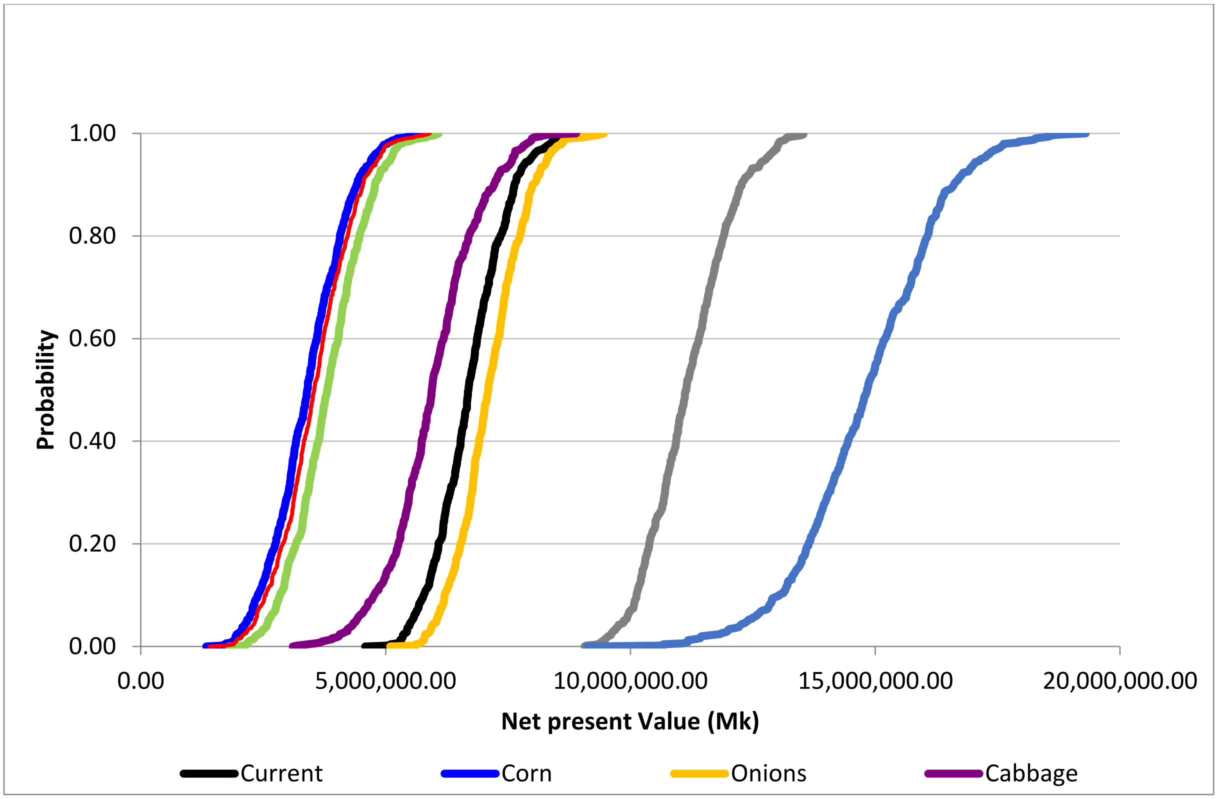

Figure A2. Net Present Value for land use scenarios under the motorized pump irrigation system

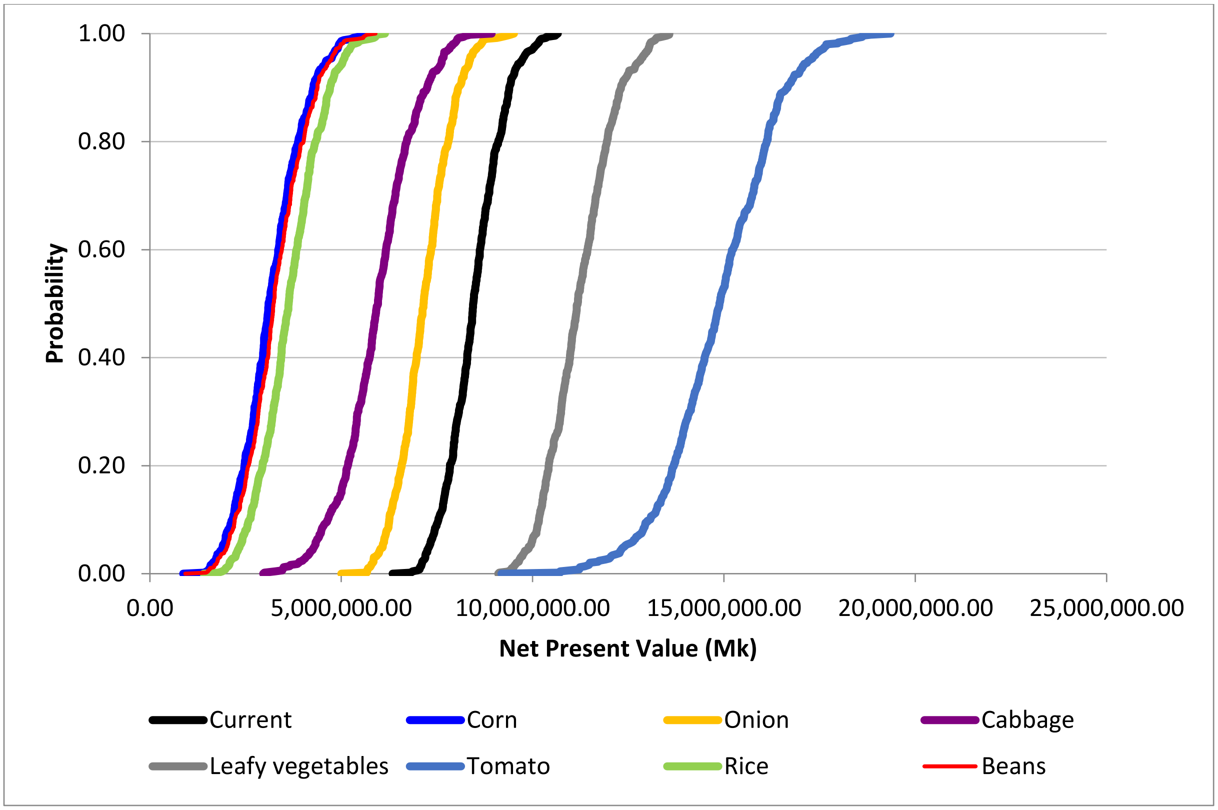

Figure A3. Net Present Value for land use scenarios under the solar-powered irrigation system

Initial Nutrition Analysis of Different Land Uses under Four Irrigation Systems

Table A12. Nutrition outputs per adult equivalent for different land use under treadle pump irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onion	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	3327	3327	3393	3413	3415	3413	3767	3397
Protein (g)	72	72	73	74	74	74	91	73
Fat (g)	71	71	76	77	77	77	81	76
Calcium (g)	0.258	0.2582	0.2661	0.2689	0.2777	0.2757	0.4658	0.2663
Iron (g)	0.022	0.0215	0.0218	0.0219	0.0220	0.0221	0.0273	0.0218
Vitamin A (g)	0.004	0.0039	0.0041	0.0041	0.0041	0.0046	0.0090	0.0041

Table A13. Nutrition outputs per adult equivalent for different land use under river diversion irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	3327	3109	3411	3371	3413	3766	3307	3274
Protein (g)	72	67	74	73	74	91	71	71
Fat (g)	71	69	77	76	77	81	74	73
Calcium (g)	0.258	0.2468	0.2688	0.2748	0.2757	0.4657	0.2602	0.2580
Iron (g)	0.022	0.0201	0.0219	0.0218	0.0221	0.0273	0.0213	0.0211
Vitamin A (g)	0.004	0.0037	0.0041	0.0040	0.0046	0.0090	0.0040	0.0039

Table A14. Nutrition outputs per adult equivalent for different land use under motorized pump irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	3327	3050	3411	3363	3413	3764	3143	3088
Protein (g)	72	66	74	73	74	91	68	67
Fat (g)	71	67	77	75	77	81	70	68
Calcium (g)	0.258	0.2429	0.2688	0.2742	0.2757	0.4656	0.2492	0.2454
Iron (g)	0.022	0.0198	0.0219	0.0217	0.0221	0.0273	0.0203	0.0200
Vitamin A (g)	0.004	0.0036	0.0041	0.0040	0.0046	0.0090	0.0038	0.0037

Table A15. Nutrition outputs per adult equivalent for different land use under solar-powered irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onion	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	3327	2585	3387	3229	3413	3751	2694	2620
Protein (g)	72	57	73	70	74	91	59	58
Fat (g)	71	54	76	72	77	80	57	55
Calcium (g)	0.258	0.2115	0.2672	0.2651	0.2757	0.4647	0.2188	0.2132
Iron (g)	0.022	0.0171	0.0218	0.0209	0.0221	0.0272	0.0177	0.0173
Vitamin A (g)	0.004	0.0031	0.0040	0.0039	0.0046	0.0090	0.0032	0.0031

Adjusted Nutrition Analysis of Different Land Uses under Four Irrigation Systems

Table A16. Adjusted nutrition outputs per adult equivalent for different land use under treadle pump irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	2353	2353	2353	2350	2353	2352	2354	2354
Protein (g)	53	53	54	54	54	54	55	54
Fat (g)	63	63	63	63	63	63	63	63
Calcium (g)	0.231	0.2307	0.2381	0.2403	0.2491	0.2470	0.2617	0.2385
Iron (g)	0.015	0.0150	0.0152	0.0151	0.0152	0.0153	0.0156	0.0152
Vitamin A (g)	0.003	0.0026	0.0028	0.0028	0.0028	0.0033	0.0031	0.0028

Table A17. Adjusted nutrition outputs per adult equivalent for different land use under river diversion irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	2353	2353	2354	2353	2353	2351	2353	2354
Protein (g)	53	54	54	54	54	57	54	54
Fat (g)	63	59	63	62	63	61	60	59
Calcium (g)	0.231	0.2279	0.2403	0.2479	0.2471	0.3151	0.2308	0.2286
Iron (g)	0.015	0.0153	0.0152	0.0153	0.0153	0.0162	0.0153	0.0153
Vitamin A (g)	0.003	0.0025	0.0028	0.0028	0.0033	0.0043	0.0026	0.0026

Table A18. Adjusted nutrition outputs per adult equivalent for different land use under motorized pump irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	2353	2352	2353	2353	2353	2354	2353	2353
Protein (g)	53	53	54	54	54	59	54	54
Fat (g)	63	58	63	62	63	62	59	58
Calcium (g)	0.231	0.2236	0.2403	0.2473	0.2471	0.3194	0.2280	0.2254
Iron (g)	0.015	0.0154	0.0152	0.0153	0.0153	0.0166	0.0153	0.0154
Vitamin A (g)	0.003	0.0024	0.0028	0.0028	0.0033	0.0042	0.0025	0.0025

Table A19. Adjusted nutrition outputs per adult equivalent for different land use under solar-powered irrigation scenarios

Nutrition	Cropping Systems							
	Current	Corn	Onions	Cabbage	Leafy vegetable	Tomato	Rice	Beans
Calories	2353	2352	2355	2353	2354	2359	2356	2352
Protein (g)	53	53	54	54	54	60	53	53
Fat (g)	63	49	62	60	63	61	52	51
Calcium (g)	0.231	0.2241	0.2395	0.2421	0.2471	0.3456	0.2064	0.2033
Iron (g)	0.015	0.0158	0.0152	0.0153	0.0154	0.0171	0.0157	0.0156
Vitamin A (g)	0.003	0.0053	0.0028	0.0026	0.0033	0.0050	0.0020	0.0019

Table 20. Net Cash Farm Income (NCFI) for the current, irrigated and adjusted irrigated scenarios

Cropping system	NCFI for the irrigated scenarios (Mk)				NCFI for the adjusted irrigated scenarios (Mk)			
	Treadle pump	River diversion	Motorized pump	Solar-powered	Treadle pump	River diversion	Motorized pump	Solar-powered
Corn	1,525,552.92	556,239.39	481,871.04	-13,099.09	1,605,379.22	665,258.04	542,587.58	51,182.69
Onions	2,592,901.57	1,628,691.11	1,620,682.51	1,135,615.20	2,673,758.18	1,787,020.91	1,701,300.92	1,226,135.76
Cabbage	2,254,698.08	1,290,487.62	1,248,175.23	758,207.27	2,335,554.69	1,413,029.70	1,326,615.32	840,951.72
Leafy vegetables	3,914,243.96	3,207,301.61	2,902,443.61	2,411,721.81	3,995,001.56	3,068,783.29	2,983,161.03	2,983,161.03
Tomatoes	2,985,558.03	2,311,863.97	2,007,005.96	1,521,033.92	1,586,980.77	1,323,068.24	1,170,044.64	933,619.44
Rice	1,566,196.47	910,485.80	599,254.92	114,941.45	1,792,197.30	761,515.47	665,714.26	665,714.26
Beans	1,475,417.05	833,994.97	522,764.09	16,568.95	1,592,752.97	682,054.22	585,757.95	97,471.01
Current	1,429,634.12	1,429,634.12	1,429,634.12	1,429,634.12	1,510,828.49	1,510,828.49	1,510,828.49	1,510,828.49

Table A21. Optimization results for meeting minimum nutritional requirements for the Phalombe district based on the river diversion irrigation system and different land uses

Purchased goods and associated cost	Cropping system							
	Current	Corn	Onions	Cabbage	Leafy Vegetables	Tomato	Rice	Beans
Eggs (kg)	0	0	0	0	0	0	0	0
Milk (L)	98,057,000	98,374,000	96,969,000	96,116,000	96,208,000	88,534,000	98,045,000	98,294,000
Beef (kg)	0	0	0	0	0	0	0	0
Goat meat (kg)	0	0	0	0	0	0	0	0
Chicken (kg)	0	0	0	0	0	0	0	0
Pig meat (kg)	0	0	0	0	0	0	0	0
Butter (kg)	0	0	0	0	0	0	0	0
Total cost (Mk)	26,868,000,000	26,954,000,000	26,569,000,000	26,336,000,000	26,361,000,000	24,258,000,000	26,864,000,000	26,933,000,000
Milk purchase for district L/day	268,649	269,518	265,668	263,332	263,584	242,559	268,616	269,299
Milk purchase per adult L/day	0.731	0.733	0.722	0.716	0.717	0.660	0.730	0.732
Milk purchase per family L/day	2.296	2.304	2.271	2.251	2.253	2.073	2.296	2.302

Table A22. Optimization results for meeting minimum nutritional requirements for the Phalombe district based on the motorized pump irrigation system and different land uses

Purchased goods and associated cost	Cropping system							
	Current	Corn	Onions	Cabbage	Leafy vegetables	Tomato	Rice	Beans
Eggs (kg)	0	0	0	0	0	0	0	0
Milk (L)	98,057,000	98,856,000	96,973,000	96,180,000	96,208,000	88,046,000	98,359,000	98,651,000
Beef (kg)	0	0	0	0	0	0	0	0
Goat meat (kg)	0	0	0	0	0	0	0	0
Chicken (kg)	0	0	0	0	0	0	0	0
Pig meat (kg)	0	0	0	0	0	0	0	0
Butter (kg)	0	0	0	0	0	0	0	0
Total cost (Mk)	26,868,000,000	27,087,000,000	26,571,000,000	26,353,000,000	26,361,000,000	24,125,000,000	26,950,000,000	27,030,000,000
Milk purchase for district L/day	268,649	270,838	265,679	263,507	263,584	241,222	269,477	270,277
Milk purchase per adult L/day	0.731	0.736	0.722	0.717	0.717	0.656	0.733	0.735
Milk purchase per family L/day	2.296	2.315	2.271	2.252	2.253	2.062	2.303	2.310

Table A23. Optimization results for meeting minimum nutritional requirements for the Phalombe district based on the solar-powered irrigation system and different land uses

Purchased goods and associated cost	Cropping system							
	Current	Corn	Onions	Cabbage	Leafy vegetables	Tomato	Rice	Beans
Eggs (kg)	0	0	0	0	0	0	0	0
Milk (L)	98,057,000	98,800,000	97,058,000	96,764,000	96,204,000	85,089,000	100,079,000	101,140,000
Beef (kg)	0	0	0	0	0	0	0	0
Goat meat (kg)	0	0	0	0	0	0	0	0
Chicken (kg)	0	0	0	0	0	0	0	0
Pig meat (kg)	0	0	0	0	0	0	0	0
Butter (kg)	0	0	0	0	0	0	0	0
Total cost (Mk)	26,868,000,000	27,071,000,000	26,594,000,000	26,513,000,000	26,360,000,000	23,314,000,000	27,617,000,000	27,713,000,000
Milk purchase for district L/day	268,649	270,685	265,912	265,107	263,573	233,121	276,136	277,095
Milk purchase per adult L/day	0.731	0.736	0.723	0.721	0.717	0.634	0.751	0.753
Milk purchase per family L/day	2.296	2.314	2.273	2.266	2.253	1.993	2.360	2.368

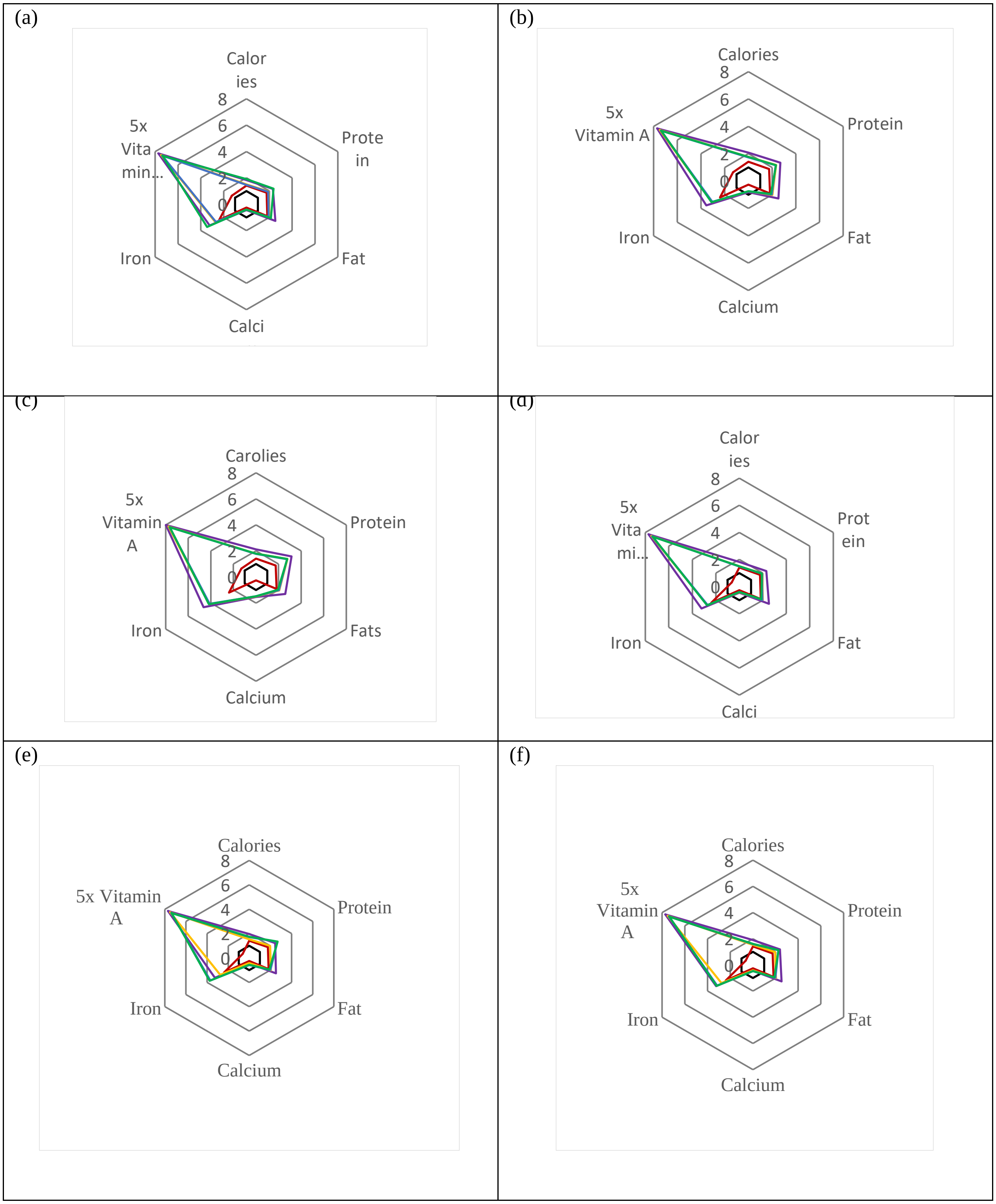

Figure A4. The nutritional output of various land uses (a: corn, b) onion, c: cabbage, d: tomato, e: rice, and f: bean) normalized to match the minimum nutritional needs (black line) of the population in the Phalombe district and under different irrigation systems (current/no irrigation (red), solar-powered (green), treadle pump (purple), motorized pump (blue), and river diversion (orange))