EFFECT OF ORGANIC AND INORGANIC FERTILIZER APPLICATION ON COFFEE (*Coffee arabica* L.) YIELD AND QUALITY AT LUNYANGWA RESEARCH STATION IN MALAWI

MSc (FORESTRY AND ENVIRONMENTAL MANAGEMENT) THESIS

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MZUZU UNIVERSITY

DECEMBER, 2025

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THESIS SUBMITTED TO THE FACULTY OF ENVIRONMENTAL SCIENCES, DEPARTMENT OF FORESTRY AND ENVIRONMENTAL MANAGEMENT IN FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF A MASTERS OF SCIENCE (MSc) DEGREE IN FORESTRY AND ENVIRONMENTAL MANAGEMENT

MZUZU UNIVERSITY

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DECLARATION

I hereby declare that this thesis titled, “Effect of organic and inorganic fertilizer application on coffee (*Coffee arabicae L)* yield and quality at Lunyangwa Research Station in Malawi” has been written by me and is a record of my research work. All citations, references and borrowed ideas have been duly acknowledged. It is being submitted in fulfillment of the requirements for the award of the Master of Science in Forestry and Environmental Management at Mzuzu University. None of the present work has been submitted previously for any degree or examination in any other University.

Fanuel Josiah Matawale Date

____________________________ ______________________

CERTIFICATE OF COMPLETION

I, the undersigned, certify that this thesis is a result of the author's own work, and that to the best of my knowledge, it has not been submitted for any other academic qualification within the Mzuzu University or elsewhere. The thesis is acceptable in form and content, and that satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate through an oral examination held on 10^{th} of April, 2025.

Major Supervisor: Date

Associate Professor Dr Victor Kasulo

____________________________ ______________________

Co-Supervisor: Date

Associate Professor Jarret Mhango

____________________________ ______________________

DEDICATION

This work is dedicated to my son Praise Matawale and my daughter Annastazia Matawale so that the son and my last daughter can follow my example of hard working for higher qualification in their ladder for education.

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Let me also acknowledge the financial support from the National Commission for Science and Technology (NAST) for providing the finances for carrying out part of activities for this research work. This cannot be taken for granted. I also acknowledge guidance provided by my supervisors, Associate Professor Dr Victor Kasulo and Associate Professor Jarret Mhango while doing this study and all technicians who assisted me in this work in soil and compost analysis at Lunyangwa soils laboratory and the technicians who assisted me in analysis of coffee quality at Mzuzu Coffee Planters Cooperative Union Limited. I also acknowledge the support given by my supervisors while carrying out this thesis and this cannot be taken for granted.

ABREVIATION AND ACRONYMS

ACP-EU Co-operation	: African, Caribbean and Pacific Group of States and European Union Co-operation
Ca	: Calcium
EC	: Exchangeable Cation
IF	: Inorganic fertilizers
GDP	: Gross Domestic Product
K	: Potassium
LARS	: Lunyangwa Agricultural Research Station
GoM	: Government of Malawi
MGDS	: Malawi Growth Development Strategies
NAST	: National Commission for Science and Technology
N	: Nitrogen
NO3	: Nitrate
OF	: Organic fertilizers
OM	: Organic Matter
pH	: Power of Hydrogen
P	: Phosphorus
SSA	: Sub Saharan Africa

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ABSTRACT

Coffee production in Malawi has declined due to low external inputs. A study on effect of organic and inorganic fertilizers application on coffee yield and quality was conducted at Lunyangwa research station in 2019/20 season. The objectives of the experiment were: 1) to determine the effect of organic and inorganic fertilizer combinations on coffee on yield and quality; 2) determine the relationships of yield and yield components and 3) To identify the rewarding treatment application on revenue. The treatments consisted of 100%, 75%, 50% and 25% rates of inorganic fertilizers and 100%, 25%, 50% and 75% organic fertilizers giving various combinations. The experiment was laid out in a randomized complete block design with three replicates. The gross plot size was 10m by 7.5m with 16 coffee plants per plot and the net plot was 4.5m by 2m with 9 coffee plants per plot and one coffee plant as a border plant. Catimor 129 was the variety used in the experiment. The growth parameters and yield were collected for analysis. The yield and yield components data were subjected to Analysis of Variance at 5% level of significance using GenStat. The results for 2019/20 season showed significant differences in plant height ($p=<0.001$), stem girth ($p=<0.001$), number of primary branches ($p=<0.001$), bearing branches ($p=0.011$), canopy radius ($p=<0.001$) and yield/ha ($p=<0.001$. There were no significant differences on coffee quality. Plant heights and canopy radius showed significant relationships with yield and can be used to predict yield under organic and inorganic fertilizer application on coffee with adjusted R-Square 0.1850. The economic analysis of treatment combinations showed 50% + 50% in-organic fertilizer as a low-cost alternative technology for resource constrained farmers. The experiment results recommend a combination of 50% organic fertilizer and 50% in-organic fertilizer an alternative suitable technology for sustainable coffee production in Malawi.

CHAPTER 1: INTRODUCTION

1.1. Background

Coffee (*Coffee arabica* L.) is the most widely traded tropical product with an estimated 25 million smallholder producers globally providing income to more than 125 million people mostly in tropical nations (Pham *et al*., 2019; DaMatta *et al*., 2018). The coffee sector has grown into lucrative business downstream, reaching a retail market value of approximately 102 billion USD in 2020 and it is expected to continue expand at a compound annual growth rate of 4.28% from 2021 to 2026 (Steffan, 2022). Up to 80% of the world's production is made by smallholder farmers. Green coffee bean is also one of the major cash crops in East and Southern African countries mainly produced for export purposes. This crop constitutes a significant share of total export value in countries such as Ethiopia, Burundi and Uganda making the sector vital to their economy. The sector is also important in Kenya, Malawi, Rwanda, Tanzania, and Zambia in creating substantial employment and income generation opportunities for the farmers (Nsabimana & Tirkaso, 2019). In Malawi, employment rate is 79.6% and about 64.1% of employed persons work in agriculture and face an uncertain future as current institutions are ill-equipped to deal with increasing pressure arising from unsustainable environmental practices and climate change. The agricultural sector contributes about 28% of the country's Growth Domestic Product GDP and employs 80.5% of which tobacco, tea, sugar and coffee are the main income generating agricultural commodities (GoM_PIII, 2017-2022).

Although coffee ranks fourth after tobacco, tea and sugar in Malawi, it is highly constrained by soil fertility decline and price fluctuations at international market prices (Mnthambala, 2021; Amrouk, 2018; Njoloma *et al.*, 2016). Currently, coffee productivity level in Malawi is estimated at 3kgs cherry per tree (1.43 Mt/Ha) which is often below the break-even point (1.88 Mt/Ha) (EU-ACP survey, 2017). Knowledge about the fate of fertilizer nitrogen in coffee agricultural systems is essential for the improvement of management practices in order to maximize nitrogen (N) recovery by the crop and reduce N losses from the system to a minimum (Fenilli *et al*., 2014). Improving soil fertility by applying both organic and inorganic nutrient sources for good growth of coffee could build more sustainable and resilient farming system which could offer an opportunity to meet global agricultural product needs while maintaining ecosystem integrity (Chipomho *et al*., 2021; Voora, 2021). This is fundamental for improving production and income as indicated by past studies for improved livelihoods in sub-Saharan Africa and a prerequisite for socio-economic development and poverty reduction in rural communities where poverty levels are severe (GoM, 2017-2022). Past studies indicated nitrogen as the most indispensable nutrient for coffee production and yield losses of up to 60% occur when no N fertilizer is applied during reproductive stage (Sadeghian, 2008).

Studies have also shown that nitrogen support to coffee is crucial at vegetative stage and is followed by phosphorus (P), potassium (K), calcium (Ca) or organic matter in many cases as shown by Salamanca-Jimenez (2017) and that coffee plants treated with annual N rates from 280 to 350 Kg per hectare may reabsorb up to 43% of the fertilizer N as gaseous ammonia (NH3), at least 30% of the 360 Kg/ha of the N of surface applied urea can be lost by volatilization (Salamanca-Jimenez *et al*., 2017). Furthermore, from 30 to 55% of an application of 250 Kg/ha of urea-N is leached as NO-3 (Cannavo. *et al*., 2013). Such significant net loss of N causes important environmental concerns such as water contamination, soil acidification, greenhouse gas emissions or N volatilization, as well as economic impacts that threaten functionality of the soil and the coffee farmer’s livelihood (Bisht & Chauhan, 2020). Therefore application of organic fertilizers could increase micro and macro nutrients such as Calcium and Potassium that could increase water use efficiency by coffee and act as a promising strategy to adapt to climate change (Ramirez-Builes & Kusters, 2021).Therefore, provision of balanced nutrients to coffee as well as preventing detrimental effects of waterlogging in the soil which affects the growth and physiological performance of coffee under floods due to climate change is important (Leon-Burgos *et al*., 2022).

Studies have also indicated that coffee farmers apply little or no external inputs to their coffee because of financial constraints and price fluctuations of coffee prices at the market (AGRA, 2017); (Amrouk, 2018). This has resulted into low crop productivity exacerbated by high poverty levels in rural areas and farmers fail to buy inorganic fertilizers because of unaffordable high prices on the market in Malawi (Komareka *et al*., 2017). It is therefore paramount to maintain soil health for sustainable coffee production because farmers can integrate farm products of crop residues and animal manure to tackle production constraints like soil degradation (Yang *et al.,* 2022; Afzal, 2007). The combined application of organic and inorganic fertilizers decreased soil bulk density, increased soil moisture, soil fertility and improved maize grain quality (Ezea *et al.*, 2020). However, such studies have not been tested on coffee productivity and quality attributes in Malawi.

Past studies have indicated that coffee is a heavy feeder crop, removing on average 130 kg K, 120 kg N, 30 kg P, 30 kg Mg and 20 kg S per hectare when 1.5 tons per hectare of clean beans are harvested (Pohlan & Janssens., 2015; Fenilli *et al*., 2007; Zake *et al.*, 1996). Worse still, on average 30% of soil nutrients remains to mother fields hardly exists. The combined use of organic and inorganic nutrient sources could support the crop's productivity and therefore support the farmers' livelihood. According to Yang *et al*. (2022), the main role of organic matter is promoting microbial activity, improving soil structure, aeration and water holding capacity, thereby allowing the soil to respond better to fertilizers (Schroeder *et al*., 2022). The combined effect of the use of both organic and inorganic fertilizers does not only reduce the bulk density of the soil, but also improves the Cation Exchange Capacity (CEC) and soil porosity, hence improving water holding capacity, allowing nutrients to be available throughout the growing period (Ezea *et al*., 2020).

It is noted that when previous fertilization is considered in nitrogen balance, most coffee cropping systems are already N saturated, leading to N use efficiency lower than 25% during the reproductive stage (Cannavo *et al*., 2013). Therefore, it is apparent that inorganic fertilizers quickly release the major nutrients while the organic fertilizers release both the major (NPK) and micro-nutrients and other growth promoting substances slowly over long period for crop growth (Afzal, 2007). The organic substances bind the soil particles together, improving soil structure, retain soil moisture and improve water infiltration thereby improving groundwater sustainability and the soil productivity (Ezea *et al.*, 2020). On the contrary, inorganic fertilizers alone in most cases increase soil acidity, nutrient leaching, nutrient imbalance and degradation of soil physical properties (Cannavo *et al*., 2013).

1.2. Problem Statement

Coffee productivity and quality in Malawi has declined, production level estimated at 1.43 Mt/Ha which is often below the break-even point 1.88 Mt/Ha (EU-ACP project survey, 2017). Most capable factors for this uneconomic productivity have been thought to be low level of fertilizer-application. If balanced application of organic and inorganic fertilizers can be developed productivity would be elevated towards doubling or trebling the current decimal production level and the effects of price fluctuations would be rarely felt even at small scale level. The use of external inputs such as organic and inorganic fertilizers is seen to increase coffee productivity and quality (Komareka *et al*., 2017).

Low level of external inputs has also resulted into soil degradation which also contribute to low quality of coffee produced. Consequently low quality of coffee leads to low market prices of coffee (Amrouk, 2018). Fertilizer use at farmer level is very low estimated at 18 kg/ Ha for SSA, compared to World level, 119.9 kg/Ha, South Asia at 149.3 Kg/Ha, primarily on (AGRA, 2017). Farmers who manage to get mineral fertilizers are also faced with the continued depletion of soil fertility such that they have to increase the amount of inorganic fertilizers every year (Raimi *et al*., 2017). Under this condition, good soil management becomes crucial for maintaining and improving soil productivity (Bamirez-Builes & Krusters, 2021).

This has been exacerbated by high poverty levels in the country both in rural and semi-urban areas where 80% of the population lives and mostly engaged in agriculture (GoM, 2017). Farmers often desire to use more of inorganic fertilizers but face cash constraints in purchasing it (Komareka *et al.*, 2017) and this is due to low market prices and unpredictable international price fluctuations of coffee (Amrouk, 2018).

The realization of site-specific management recommendations is elusive in Malawi as it is in other parts of SSA (Heerwaarden, 2022). Coffee production in Malawi is still characterized by low productivity due to high levels of nutrient mining, low use of external inputs and traditional farm management (GoM, 2017). Consequently, the combined use of organic and inorganic fertilizers could reduce the high cost of chemical fertilizers but their application rates vary from farmer to farmer due to low technology utilization.

The use of organic manure may offer agronomic benefits in increased organic matter, moisture, beneficial soil microbes, maintain soil fertility/health and improved soil structure but farmers are hampered by low knowledge on application rates of organic manure (Ezea *et al*., 2020; Derbile *et al*., 2016). Improved varieties from breeding work are available but are on the threat due to degraded soils, pests and diseases, dry spells, floods etc (Derbile *et al.*, 2016).

The soil fertility status of most arable land has been further worsened by upland catchment deforestation by charcoal business people and farmers are also hampered with lack of knowledge of proper use of compost to maintain soil structure and essential micro-organisms in the soil (GoM, 2012). Therefore, organic fertilizer can improve the soil and soil water and nutrient use efficiency by the field crops, however, farmers have limited knowledge in soil conservation measures as a natural capital (Bamirez-Builes & Krusters, 2021).

Soil fertility decline is a major constraint in sub-Saharan Africa contributed by climate change and poor agronomic practices (Cuni-Sanchez *et al.*, 2022; GoM, 2012). Improved soil fertility management in coffee production system through combined use of organic and inorganic nutrient sources and other crop residues can contribute to, among others, sustainable groundwater and coffee production and this depends on both technological development and socio-economic factors (Mnthambala, 2021; Ezea *et al.*, 2020). Hitherto, multiple options for the management of nitrogen in cropping systems exist and they include use of compost manure and crop residues (Chali *et al.*, 2021) and these have their own advantages and constraints. Although studies indicated that enzyme-mediated decomposition for the release of nitrogen is controlled by soil organic matter; there is a paucity of knowledge on the levels of nitrogen produced and effect on crop production and quality. These may have implications to soil fertility (Leon-Burgos *et al*., 2022; Ezea *et al.*, 2020).

Therefore, in an attempt to determine effect of different combinations of in-organic and organic fertilizers on coffee growth, a study of effect of organic and inorganic fertilizers on yield and quality of coffee was conducted and also to determine the relationships of yield and yield components under organic and inorganic fertilizer application regime of the coffee plants at Lunyangwa, in Mzuzu City in Malawi.

1.3. Objectives

The overall objective of the study was to determine the effect of organic and in-organic fertilizer on coffee on yield and quality of coffee for development of low-cost alternative fertilizer application technology.

1.4 Specific Objectives

1. To analyze the effect of different combinations of N-levels obtained from organic and inorganic fertilizers on coffee yield and yield components of coffee
2. To analyze the effect of different combinations of inorganic and organic fertilizers on coffee quality index and attributes.
3. To determine the relationships between growth parameters of coffee and yield of the crop.
4. To identify the most rewarding treatment combination through economic analysis

1.5 Hypotheses

1. Different combinations of organic and inorganic nutrient sources have a significant effect on yield and yield components of coffee.
2. Different combinations of organic and in-organic fertilizers have a significant effect on the quality of coffee.
3. There is a significant relationship between growth parameters of coffee and yield.
4. Treatment combinations have an effect on net revenue and benefit cost ratio.

1.6. Justification

This research of organic and inorganic coffee production is in line with integrated soil fertility management ISFM for sustainable coffee production and quality. Soil fertility decline has resulted into low coffee yields despite the scientific evidence of nitrogen requirement by the coffee plants (Njoloma *et al*., 2016; Afzal, 2007). Farmers and experts face difficult decisions of what technologies to use to support the vulnerable farming communities who are resource poor (GoM, 2012). This is because few coffee farmers apply fertilizers on their coffee in Malawi due to fluctuation prices of coffee and uncertain for future coffee prices compounded by high fertilizer costs (Amrouk, 2018) and application rates vary from farmer to farmer (Amrouk, 2018). This is because of unaffordable high prices of inorganic fertilizers on the market by smallholder coffee farmers. Soils have become degraded due to poor agronomic practices (Ezea *et al.,* 2020) and there is need to develop low-cost fertilizer application technologies through use of organic and inorganic fertilizers. Therefore, use of different combinations of organic and inorganic nutrient sources is expected to have a significant effect on yield and quality of coffee and the performance of growth parameters through improved nutrient availability to coffee. Different combinations of organic and in-organic fertilizers are also expected to have a significant effect on the quality of coffee and net revenue in this research.

Modern analytical technologies, knowledge and skills are available in Malawi to develop and continually improve fertilizer recommendations to help cope with nutrient demands of the emerging elite coffee varieties from coffee breeding work in the country. Therefore, with technology backed soil fertility management and mass production of the elite high yielding disease resistant coffee varieties, productivity can be upturned and incomes per unit area will widely undermine the production costs and thus maintain wide gross margins (Komareka *et al*., 2017). The technology backed fertilizer application rates will be a major input towards enhancing coffee production in Malawi in short and medium term.

Therefore the combinations of organic and inorganic fertilizer application could not only reduce production costs of fertilizers by poor resource farmers but also enable the coffee plants to respond better to fertilizers due to increased level of organic carbon in the soil (Chipomho *et al.,* 2021) and therefore could be an alternative technology to sustain coffee yields and therefore a coping mechanism under climate change policy for improved farmers' livelihoods in Malawi, hence the need for this research study (Komareka *et al*., 2017).

CHAPTER 2: LITERATURE REVIEW

2.1 Theoretical Background

The study is inclined on the general theory as observed by (Vitousek *et al*., 2014); (Vitousek *et al*., 1997) that sustainability of agricultural practices is centralized on the need for continuous technology development and adoption for competitive advantage in the market place and that great progress in agricultural productivity are strongly increased by fertilizers, ground water sustainability, irrigation water, agricultural machinery, pesticides and land, and that there are always relationships with their use and methods (Raimi *et al*., 2017). Furthermore, new approaches are needed that will integrate biological and ecological processes into food production and to minimize the use of those non-renewable inputs that can cause harm to the environment (Stewart *et al.*, 2020) or to the health of farmers and consumers while making productive use of the knowledge and skills of farmers thereby substituting human capital for costly external inputs, and make productive use of people's collective capacities to work together to solve common agricultural and natural resources problems, such as pests, watershed degradation which contribute to groundwater unsustainability, irrigation water, forest and credit management (Vitousek *et al.*, 1997).

2.2. Theoretical premise of soil fertility

Past studies demonstrated soil quality or health as a fuzzy concept officially defined as " the continued capacity of the soil to function within ecological and land use boundaries, to sustain productivity, promote the quality of air and water, and maintain plant, animal and human health (Rousseaua *et al.*, 2012).The concept of soil quality includes assessment of soil properties and processes as they relate to the ability of soil to function effectively as a component of a healthy ecosystem (Bünemann *et al.*, 2018). Specific functions and subsequent values provided by ecosystems are variable and rely on numerous soil physical, chemical and biological properties and processes, which can differ across spatial and temporal scales (Bünemann *et al*., 2018)

The concept has been vigorously criticized (Rousseaua *et al.*, 2012) as it is considered non-objective mainly because no absolute reference to an optimal soil quality could be identified. This is a consequence of extreme soil variability and the difficult of linking soil indicators to sustained productivity, air or water quality or health (Rousseaua *et al.*, 2012). It has been emphasized that determining soil quality requires long-term experiments with indicators from the soil, the crops, the environment and the society that lives from this soil (Rousseaua *et al.*, 2012). This study follows this idea to determine the best agronomic practice through evaluation of coffee plants using yield and yield components of coffee as indicators for soil quality for sustainable coffee production in Malawi through experimentation.

Soil quality is a concept that has deeply divided the soil science community. It has been institutionalized and advocated without full consideration of concept weaknesses and contradictions (Letey *et al.*, 2003). Past studies highlighted its dis-functional definition, flawed approach to quantification, and failure to integrate simultaneous functions, which often require contradictory soil properties and/or management (Letey *et al.*, 2003). While the concept arose from a call to protect the environment and sustain the soil resource, soil quality indexing as implemented may actually impair some soil functions, environmental quality, or other societal priorities (Letey *et al.*, 2003). The study offered an alternative view that emphasizes on known principles of soil management as a better expenditure of limited resources for soil stewardship than developing and deploying subjective indices which fail to integrate across the necessary spectrum of management outcomes.

It was argued that if the soil quality concept could be retained, they suggested to precisely specify it as soil use, not function or capacity, as the criteria for attribute evaluation. Other studies considered soil quality concept to be directed toward using available technical information to motivate and educate farmers on management practices that optimize the combined goals of high crop production, low environmental degradation, and a sustained resource (Njoloma *et al.*, 2016). This study also supports this idea by developing different management options and combinations of organic and inorganic fertilizer combinations so that the technical information is transferred to coffee farmers and put into practice of the technical message for sustainable coffee production. Furthermore, ecologists have developed terminology to distinguish ecosystems based on the degree of human alteration (Brereton *et al.*, 2014; Morse *et al.*, 2014). To this end, ecosystems can be characterized as "novel ecosystems," "impacted ecosystems," or "designed ecosystems," depending on the role of human management in ecosystem development and effects on ecosystem properties through technology development (Brereton *et al.*, 2014).

Therefore this study was designed to improve soil quality, transform coffee agro-ecosystem practices through evaluation of organic and inorganic fertilizers on yield and quality of coffee thereby developing low cost and climate resilient technologies for continued soil ecosystem productivity considering the role of smallholder management of coffee agroecosystems in Malawi which is intended as a management practice for mitigation of climate change (Bamirez-Builes & Krusters, 2021) and for sustainable development of the agricultural sector for competitiveness of rural communities in the market place. Organic fertilizers can be crucial in promoting sustainable agricultural development, but they are not used in a wide-ranging way among smallholder farmers in many developing countries (Liu *et al.*, 2022) Soil fertility decline is a major challenge in sub-Saharan Africa where agriculture is an important engine for economic growth especially among smallholder farmers as it provides critical means of income and livelihood (Stewart *et al.*, 2020). Based on a comprehensive survey conducted by (Stewart *et al.*, 2020), with the aim of understanding barriers to enhancing soil fertility in sub-Saharan Africa and providing evidence-based recommendations, which focused in West Africa, East Africa, the Great Lakes region, and Ethiopia, overall recommendations were developed with four emerging themes: (1) strengthening inorganic fertilizer-based systems, (2) access to and use of quality organic inputs, (3) capacity building along the entire knowledge-transfer value chain, and (4) strengthening farming systems research and development across biophysical and socio-economic factors. This study compliments recommendations by (Stewart *et al.*, 2020) through technology development of low cost and resilient farming options of inorganic and organic fertilizer use, capacity building of coffee farmers through technology transfer and strengthening farming system research.

Soil fertility decline has led the agricultural sector to remain underdeveloped and uncompetitive from global markets, leaving rural populations without opportunities for employment and improved living standards (Amrouk, 2018; Njoloma *et al.*, 2016). An important prerequisite to produce high quality crops, among others, coffee with good growth, is to add nutrition. The crop extracts nutrients from the soil and it is important to combine a broad variety of nutrition in the right quantity to get a good yield (Kihara *et al.*, 2017). When growing crops on the same plot year after year, it is necessary to add extra nutrients to the soil to restore the nutrient level (Kiharaa *et al.*, 2020). This study was designed to address these issues through determination of different combinations of organic and inorganic fertilizers to produce high quality coffee for high prices at the market for the benefit of the resource need farmer within fragile ecosystems due to climate change impacts such as soil nutrients being over mined, deficient in both macro and micro-nutrients in Malawi (GoM, 2017).

A fertilizer is any material of natural or synthetic origin other than liming materials that is applied to soils or to plant tissues to supply one or more plant nutrients essential to growth of plants (Njoloma *et al.*, 2016) and there are many types of fertilizers The combined use of organic and inorganic fertilizers support this idea as nitrogen support is crucial at vegetative and productive stage to coffee plants (Sadeghian, 2008). Fertilizers contain nutrients for plants and are used to strengthen and maintain the soil's ability to improve the fertility (Kihara *et al.*, 2017). Fertilizers often include nutrients such as phosphorus, potassium and nitrogen, which are three nutrients that help to restore the soil fertility (Tonitto & Ricker-Gilbert, 2016). Fertilizer is also used to achieve a sustainable and profitable production (Heerwaarden, 2022). Therefore, combined use of organic and inorganic fertilizers could supply broad range of micro nutrients to restore the soil fertility status within the farming communities for sustainable coffee production.

2.3. Emperical evidence

2.3.1 Coffee Production Levels and Soil Fertility Status of the Coffee Sector in Malawi

The Department of Agricultural Research Services through Lunyangwa Research Station started implementation of a project, Grant contract identification number: FED/2013/330-219, entitled "Boosting coffee productivity in Kenya and Malawi through better access to and use of modern technologies and innovations" whose main objective was to increase coffee productivity and therefore income/food security among stakeholders in Malawi and Kenya. This project was being funded by ACP-EU Co-operation in Science and Technology (S&T II). One of the major activities in the project was to make fertilizer recommendations on coffee based on soil and leaf analysis taken from the project sampled areas. Through the soil survey conducted in this project, it was noted that coffee productivity in Malawi and Kenya has fallen below 3kgs cherry per coffee tree (Fanuel & Ngungi, unpublished, 2018).

However, findings by Benson et al. (2016) which indicate coffee productivity per hectare of 2.5 Mt/ha with good farming management on average which is higher than productive level on farm revealed by the survey funded by the EU-ACP project. The most capable factors for this uneconomic productivity have been thought to be frequent coffee price fluctuations, poor agronomic practices, negative social dynamics fueled by corrupt practices and low level of modern technology utilization (Gather & Wollni, 2022; Amrouk, 2018; Holden & Lunduka, 2012). If modern precision technologies were embraced; productivity would be elevated towards doubling or trebling the current decimal production level and the effects of climate change and price fluctuations would be rarely be felt even at small scale level (Bamirez-Builes & Krusters, 2021). With such guidelines, it is possible to target fertilizer applications to specific agro-ecologies and soil fertility problems and to increase economic returns for fertilizer investments (Tamene *et al.*, 2017).

Declining soil fertility and limited farmer access to inorganic fertilizer frequently cause sub-optimal crop yields throughout sub-Saharan Africa (Njoloma *et al.*, 2016). Farm productivity is also at risk from extreme weather and future climate change. Significant uncertainty remains in predicting climate in Africa, increasing the challenge of planning for climate change adaptation (Tonitto & Ricker-Gilbert, 2016). Soil fertility management and water supply are important for successful crop production in all agricultural commodities. The use of inorganic fertilizers has been a competitive in the global trade against oversupply and price fluctuations that in some years result into coffee price crisis (Chemura, 2014). Reliance on inorganic fertilizers may not be sustainable in the long term given that soils may lose microorganisms and become acidic, having unstable aggregates leading to erosion and general degradation, and this may explain yield decline with time despite the consistent use of inorganic fertilizers (Bisht & Chauhan, 2020).

Land degradation characterized by soil erosion, nutrient depletion, loss of biological diversity and decreasing quality and quantity of water is a major problem facing many countries in sub-Saharan Africa (Kiharaa *et al.,* 2020; Njoloma *et al*., 2016). Sub-Saharan African soils are largely degraded [e.g. limited organic matter (OM) and organic nutrient pools], a focus on inorganic fertilizer use alone has had limited success in improving soil fertility. Soil organic Carbon pools, as an indicator for soil health, have been depleted across SSA, resulting in reduced nutrient-use efficiency and water-holding capacity (Kihara *et al*., 2017). Long-term solutions, such as approaches that build OM and organic nutrient pools, in addition to inorganic fertilizer applications would likely be an essential component to achieving sustainable soil fertility in SSA (Heerwaarden, 2022; Ichami *et al*., 2019).

This study was therefore initiated following observations by the researcher from farmers that coffee farmers apply organic fertilizers but their application rates vary from farmer to farmer during the EU-ACP project survey which was implemented from 2014-2018, coordinated by the scientist through soil and leaf sampling survey showed soil nutrient deficits in Calcium, Phosphorus, Potassium for all the sampled project areas. It was noted that farmers apply very far below minimum sufficient levels of

Calcium (Minimum sufficient level for Calcium is 1.6 me/100g soil), very low levels Phosphorus, (Minimum sufficient level for Phosphorus is 20 ppm or µg/g) and very low levels of Potassium (Minimum sufficient level for Potassium is 0.4 me/100g soil) (Fanuel & Ngungi, 2018 unpublished). Soils in Malawi and other sub-Saharan African countries are unhealthy, largely due to years of crop nutrient-mining and limited organic or inorganic resupply (Stewart *et al.*, 2020). The technical report emphasized need to apply both organic and inorganic nutrient sources to supply broad nutrients to coffee plants for sustained production as indicated by (Raimi *et al*., 2017).

Low fertility and inefficient management of sub-Saharan African soils have been the major challenges facing productivity among smallholder farmers (Roland *et al.*, 1997). Unfortunately, inorganic fertilizer used as a major soil nutrient management is unsustainable, causing soil degradation and environmental pollution (Ezea *et al.*, 2020). Therefore, smallholder farmers may only realize their maximum potential if a more sustainable, low-cost and efficient integrated nutrient management system compatible with their socioeconomic status is practiced (Raimi *et al.*, 2017).

2.3.2 Relationships of Nitrogen to growth parameters and yield

Nitrogen uptake is essential for coffee growth and development, resulting in important effects on the biomass and final crop yield. Thus, like most nutrients, nitrogen is absorbed by the roots using water as a mean of transport, so that water stress and nitrogen can directly and indirectly affect various physiological processes. The water deficit WD promoted an increase on the proline concentration in the roots. With low N dose, the activity of glutamine synthetase GS presented linear increases in response to WD. According to a study conducted by Racha *et al.* (2023), it was concluded that in young coffee nitrogen can directly and indirectly affect various physiological processes plants under WD, proline can be involved in the osmotic adjustment, having its synthesis in the roots increased. Under WD, plants with good nitrogen nutrition presented larger leaf concentration of soluble amino acids and total soluble proteins (Rocha *et al*., 2023)

According to research conducted by Ramirez-Builes *et al*. (2024)**,** Nitrogen (N) is the most important nutrient in coffee, with a direct impact on productivity, quality, and sustainability. N uptake by the roots is dominated by ammonium ($NH4^+$) and nitrates ($NO3^-$), along with some organic forms at a lower proportion. From the perspective of mineral fertilizer, the most common N sources are urea, ammonium (AM), ammonium nitrates (AN), and nitrates; an appropriate understanding of the right balance between N forms in coffee nutrition would contribute to more sustainable coffee production through the better N management of this important crop. The aim of this research was to evaluate the influences of different NH4-N/NO3-N ratios in coffee from a physiological and agronomical perspective, and their interaction with soil water levels. Over a period of 5 years, three trials were conducted under controlled conditions in a greenhouse with different growing media (quartz sand) and organic soil, with and without water stress, while one trial was conducted under field conditions. N forms and water levels directly influence physiological responses in coffee, including photosynthesis (Ps), chlorophyll content, dry biomass accumulation (DW), nutrient uptake, and productivity. In all of the trials, the plants group in soils with N ratios of 50% NH4-N/50% NO3-N, and 25% NH4-N/75% NO3-N showed better responses to water stress, as well as a higher Ps, a higher chlorophyll content, a higher N and cation uptake, higher DW accumulation, and higher productivity. The soil pH was significantly influenced by the N forms: the higher the $NO3^-$-N share, the lower the acidification level. The results allow us to conclude that the combination of 50% NH4-N/50% NO3-N and 25% NH4-N/75% NO3-N N forms in coffee improves the resistance capacity of the coffee to water stress, improves productivity, reduces the soil acidification level, and improves ion balance and nutrient uptake. (Ramirez-Builes *et al.,* 2024**).**

2.3.3 Studies conducted on organic and inorganic fertilizer interventions on coffee

Effect of organic and inorganic fertilizer interventions was conducted on coffee by Chemura *et al.* (2010) in Pakistan conducted. The results showed that organic manure was economically viable. It was noted that although some studies have shown that organic manure are important for maintaining soil organic matter and supplies broad variety of nutrients to the coffee systems, they may not be enough for balanced plant nutrient flows and for achieving profitable yield levels (Chemura *et al*., 2010).

This is justified by (Van der Vossen H, 2005) in the sense that common organic manure can contribute maximum Nitrogen content of <10%, P<2%, K<10% of dry matter compared with high nutrient outflows of up to 105 kg per hectare of Nitrogen, 13 kg per ha P, and 107 kg per ha K to achieve yield levels of 1 tonne/ha per year resulting in serious negative nutrient balances (Van der Vossen, 2005). Given that the negative apparent yielding potential of coffee, it may be significant that organic manures is at least integrated to provide a positive nutrient balance when the coffee has not reached bearing age (Chali *et al*., 2021).

Recently, a study carried by Rahmah *et al.* (2022) which aimed at assessing the comprehensive sustainability evaluation of coffee production nurtured by an organic fertilizing system (OFS), chemical-organic fertilizing system (COFS), and chemical fertilizing system (CFS) that focused on the energy–environment–economic nexus., entitled "A life cycle assessment (LCA), life cycle cost analysis (LCC), and energy analysis were performed as methods to evaluate the environmental impact, economic performance, and energy requirement analysis" whose results indicated that the OFS had superior performance in two sustainability aspects: resulting in the lowest environmental damage and generating the highest economic benefit (Rahmah *et al.*, 2022). Simultaneously, COFS shows the highest sustainability performance as it consumes the least energy. In contrast, CFS indicated the lowest sustainability performance in all aspects: highest environmental impact, lowest economic benefit, and highest energy consumption. Therefore, OFS was strongly recommended to be applied broadly, considering its environmental and economic superiority. Consequently, massive OFS application was followed by higher energy consumption (Rahmah *et al*., 2022). Alternatively, COFS can be considered for application due to its higher energy performance, even though it can potentially result in higher environmental damage and lower economic benefit (Rahmah *et al.*, 2022). However, the government should explicitly provide some effort for the broad application of OFS in financial and assistance support since the shifting process needs more time to adapt (Rahmah *et al*., 2022).

In California, studies were conducted on soil chemical properties during transition from conventional to organic and low-input farming practices were studied over 8 years in California's Sacramental Valley to document changes in soil fertility status and nutrient storage (Clark *et al.*, 1998). Four farming systems differing in crop rotation and external inputs were established on land previously managed conventionally. Fertility in organic system depended on animal manure applications and winter cover crops; the two conventional systems received synthetic fertilizer inputs; the low-input system used cover crops and animal manure during the first 3 year and cover crops and synthetic fertilizer for the remaining 5 year. At 4 and 8 year after establishment, most changes in chemical properties were consistent with predictions based on nutrient budgets. Inputs of C, P, K, Ca and Mg were higher in organic and low-input systems as a result of manure applications and cover crop incorporations. After 4 yr, soils in the organic and low-inputs systems had higher soil organic matter, C; soluble phosphorus, P; and exchangeable potassium, K (Clark *et al*., 1998).

Various studies have shown that integrating organic and inorganic fertilizers is competitive in terms of growth and economic returns for crops (Chemura *et al*., 2010) and other cultures (Afzal, 2007). Therefore, the combination of both fertilizer interventions is probably a promising nutrient management option from the economic perspective taking into account that the soils in sub-Saharan Africa are being depleted at an annual rate of 22 kg/ha for nitrogen, 2.5 kg/ha for phosphorus, and 15 kg/ha for potassium (Smaling *et al*., 1997).

In Japan, (Poudel *et al*., 2009) presented an international conference paper on capital budgeting analysis of organic coffee production in Gulmi District of Nepal with the objective of examining the condition of organic coffee farming in the rural mid-hill of Nepal in the background of financial viability. The financial indicators showed economic profit and sustainable venture in income generation to the rural marginal people. The financial indicators administered were Benefit-Cost ratio (B/C), Net Present Value

(NPV), Internal Rate of Return (IRR), and Payback Period (PP) and the value were 2.12 (at 12 % opportunity cost of capital), 67763.58, 43.47% and 6 year respectively. This was shown to be an economically very sound business scenario. Sensitivity analysis was also done to predict the evolution of the aforementioned indicators under various circumstances subjected to variability in output and input price. The results showed that marketing channel was very short and having only two routes. Marketing margin of Rs. 225 and producers share was found to be 50%. Farmers were experiencing soil conservation, better health and better livelihood. Such studies are applicable in Malawi and therefore need to be exploited.

In Uganda studies on robusta coffee were also conducted where experiments were laid in various parts of the country to study the effects of inorganic and organic fertilizers on robusta coffee yields (Stewart et al., 2020; Zake *et al.*, 1996). Such studies have not been conducted in Malawi since the beginning of coffee research despite the differences in soil types and climatic conditions. Much work has been concentrated in maize and rice commodities.

Similar studies were also conducted on coffee to maintain soil fertility/functions. A study of effect of organic and in-organic fertilizers on *Coffee arabica L* by Chemura (2014) in Zimbabwe which revealed that inorganic fertilizers are the most effective at high irrigation levels while organic manure performs better than inorganic fertilizers under low irrigation water levels. In this regard, use of both organic and inorganic fertilizers could certainly put the coffee farmer on a safe side under different prevailing situations or when hit by climate change effects. Such studies have not been conducted on coffee in Malawi. Furthermore, the quality of coffee beans was not done to find the effect of organic fertilizers on coffee attributes.

Since the introduction of coffee in Malawi by the missionaries, coffee research technologies were provided by the Tea Research Foundation, in Mulanje in order to assist the coffee growers with support from the Zimbabwe Coffee Growers Association. It was until 1969 when Lunyangwa was handed over to the Malawi government from the Tung estate owners. However fair-trade organic coffee research needs to be conducted considering that several improved coffee varieties have been developed.

2.3.4 Efforts by Government to assist smallholder famers to access farm inputs

Over the past decade, government input subsidy rose from 70% to over 90%. Government clearly recognized that farmers would never be able to cope with the escalating fertilizer costs without Fertilizer Input Subsidy Programme (FISP). In recent years, Malawi's agricultural input subsidy program has increased access of improved inputs for many smallholder farmers by providing vouchers that enable access to agricultural inputs, primarily modern maize varieties and fertilizer (Holden & Lunduka, 2012). However, farmers of the most marginal agricultural lands received few benefits because of leakages of coupons and fertilizers and the targeting efficiency of the program. While the program enhances food production and food security, it does not target the poor better than a program that distributes inputs randomly and corruption, and targeting errors lead to local frustration and conflicts (Holden & Lunduka, 2012).

Furthermore, there have been no complementary investments in extension education to support sustainable use of inputs, and farmer access to extension services in Malawi remains poor (Chipomho *et al.*, 2021). Increasing returns to rural agricultural investments in Malawi for resource poor farmers is a core goal of the Africa RISING program and related agricultural development initiatives. Despite the government efforts in this program,

2.3.5 Constraints of the coffee sector in Malawi

Although coffee is an important cash crop, Malawi is failing to fully reap from the current high global demand for coffee due to production capacity constraints (Cuni-Sanchez *et al.*, 2022; Tonitto & Ricker-Gilbert, 2016; Cannavo *et al*., 2013). The major constraint experienced by smallholder farmers is decline in soil fertility and this is widespread in Sub-Saharan Africa (Mnthambala, 2021). While proper fertilizer regimes are recommended in coffee production, very few farmers apply adequate inorganic fertilizers on coffee and other crops due to high fertilizer prices on the domestic market (Bünemann *et al.*, 2018; AGRA, 2017).

According to (Bünemann *et al.*, 2018), farmers do not apply required fertilizer rates due to escalating fertilizer input prices on the market. Majority of farmers lack access to alternative technologies that can allow them to sustain coffee yields and income. It is noted that to maintain soil fertility in our soils, fertilization must first and foremost be organic particularly in highly weathered soils in order to increase soil organic matter and improve soil structure (Chipomho *et al.*, 2021). The organic matter supplies nutrients, buffers the soil pH-value and regulates the balance of nutrients thereby reducing the risk of leaching. Organic matter also improves the water holding capacity of soil (Ezea *et al*., 2020). Furthermore, the combination of organic sources of nutrients and inorganic fertilizer could reduce the cost of production (Mnthambala, 2021). From these observations, it is apparent that smallholder coffee farmers lack a low-cost technology of how much organic manure and inorganic fertilizer that could be applied in coffee production.

2.3.6 Opportunities of the Coffee Sector in Malawi and the ongoing challenges

Although Malawi is endowed with diverse agro-climatic zones and with plentiful fresh water, land is becoming severely degraded due to climate change, increasing population pressure and agricultural intensification (GoM, 2012; GoM, 2010). The reliance on rain fed cultivation coupled with the potential effects of climate change presents vital challenges to the sustainability and resilience of the sector (Derbile *et al*., 2016). Other major challenges include: fuel shortages, declining foreign exchange earnings, declining investments, lack of direct access to sea ports, and high HIV/AIDS prevalence rates (GoM, 2017). According to Nsabimana & Tirkaso (2019), coffee importing countries from Africa include Europe which imported 61% of the total coffee produced in Africa, USA and Canada, 12%, Algeria 7%, Japan 5%, Switzerland 3% and others 12%. It is also noted that certified coffee trebled in 2011 (Nsabimana & Tirkaso, 2019) and Asia is set to become increasingly an important market for certified coffee.

CHAPTER 3: MATERIALS AND METHODS

3.1. Study area

The study was conducted at Lunyangwa Agricultural Research Station (LARS) and is located 6.7 km north east of the Mzuzu City Centre on latitude 11°11´ South and Longitude 34°03´ East. The mean annual temperature for the 2019/2020 season was 20℃ and maximum temperature was 32℃. It is situated on the Viphya plateau at 1342m above sea level, representing high altitude ecological zone. Design in 2014/15 season. Data collection was done in 2019/2020 season on yield and yield components. Processing of cherry yield and quality analysis data was done at Mzuzu Coffee Planters Cooperative Union Limited.

Rainfall data was also collected using a rain gauge per month for the 2019/20 season, Figure 1.

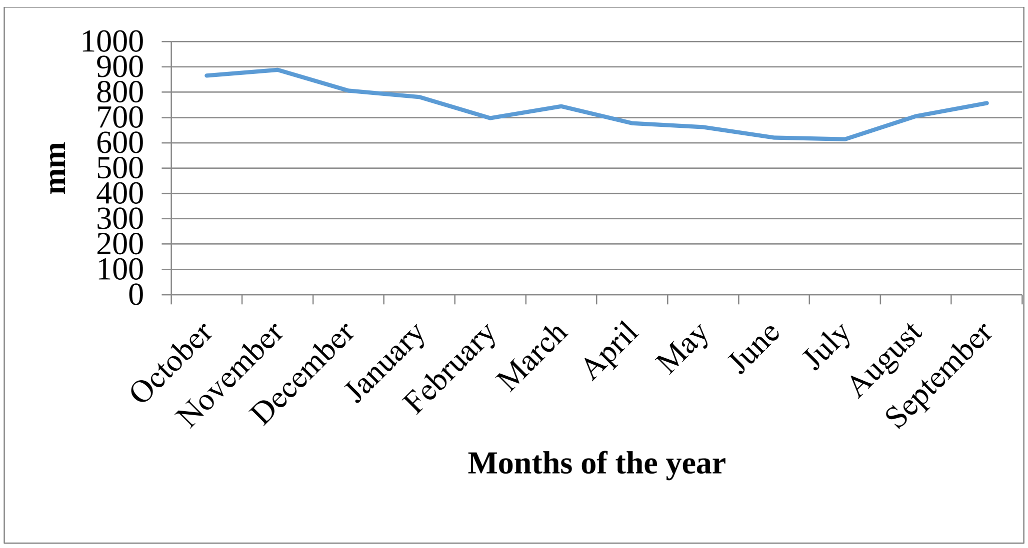

Figure 1: Rainfall data for the season 2019/2020 for Lunyangwa Research Station.

3.2. Research design

The experiment was laid out in a Randomized Complete Block Design with six treatments and three replicates. The soil fertility gradient and slope of the experimental site were considered as factors for blocking. One-way ANOVA was used because it is a short-cut method where a single factor (Nitrogen level) is considered, and its effect on yield, yield components and quality of coffee and that it is a commonly used technique as it is a more convenient method.

3.3. Coffee variety

Cutimor 129 variety was the genotype used in the experiment due to its resistance to Coffee Leaf Rust. In addition to being resistance to Coffee Leaf Rust, it is a released coffee variety in the Department of Agricultural Research Services recommended for coffee farmers in Malawi.

3.4. In-organic fertilizer formulation

Urea (46% Nitrogen), straight fertilizer and D Compound (8:18:15 N: P: K) fertilizers were used in the experiment. This was formulated in a mixture of 1:1, to come up with inorganic fertilizer with 27:9:7.5 N: P: K. Fertilizer recommended rates based on coffee age, Appendix 2. Urea was selected as fertilizer for crop yielding as well as fertilizer with high Nitrogen percentage content, while D Compound was selected as supplies adequate Phosphorus and Potassium.

3.5. Compost preparation

Materials in making compost manure included cattle dung, maize stover, good soil and water. Maize stover was chopped to 15cm length. The compost manure was prepared underneath tree canopy. 20 litres of water was thoroughly spread on a well cleared place 1 m x 1 m. This was followed by a layer of cattle dug to a depth of 15 cm, followed by maize stover layer of 10 cm and then a layer of top soil from a depth of 5 cm. Two 40 litres of water were used to moistened the materials. The process was repeated until the heap reached 2 m high. The prepared heap was covered by black plastic paper for decomposing. The layers were turned so that the top layer was put at the bottom every week to facilitate decomposing of the maize stover till the compost was fully decomposed while watering the heap every week. The compost was ready after two months when the sample was taken for nutrient analysis (Appendix 3) for Nitrogen computation in the soils laboratory in order to obtain the intended nitrogen levels.

After the compost analysis in the soils laboratory, the treatments consisted of 100, 75, 50 and 25% rates of inorganic fertilizers and 100, 25, 50 and 75% organic fertilizers giving various combinations of organic and inorganic fertilizers.

Table 1**:** Treatments description and combinations

Treatment combination	Compost Manure (%N)	In-Organic Fertilizer
1	100%N	0%N
2	0%N	100%N
3	25%N	75%N
4	50%N	50%N
5	75%N	25%N
6	0%N	0%N Control

3.6. Quality analysis of coffee

Parchment samples per treatment application were processed and dried in a glasshouse per parchment harvested per plot and was separately put in bags with labels for identification. The yield samples were processed at Mzuzu Coffee for green beans. Cup testing was done in the Mzuzu Coffee Laboratory using Specialty Coffee Association of American Cupping (SCAA) standard.

3.7 Determination of yield and yield components relationships

To determine relationships of yield and yield component, the data collected on plant heights, stem diameter, number of primary branches, number of bearing branches, canopy radius and yield were used in order to identify yield components which can guide the farmers to predict the coffee yield under organic and inorganic fertilizer application. This was analyzed using R-4.44 Version software.

The regression model building from this study was as follows:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$$

Where: Y is cherry yield in Kg, β_o is constant , X_1 is Canopy Radius in Cm, X_2 is Plant height in Cm, β_1, β_2 are model coefficients and ε is the error term.

3.8. Data Collection

Growth parameter data was collected on plant heights using a ruler, number of primary branches, number of bearing branches, stem diameter using a caliper, canopy radius using a ruler. Cherry yield was harvested per plot and weighed using a digital scale and yield per plot was put separately in bags with labels for identification. The cherry was processed using a hand pulpery, washed with water, fermented for three days, rewashed and dried. The parchment was further dried in a glass house. The samples were taken to MZCPU for cupping testing.

Soil data was also collected and analyzed at Lunyangwa soil laboratory using a soil cores for top soil and sub-soil to further determine nutrient change due to organic and inorganic fertilizers combinations. (Appendix 3 and 4).

3.9. Data Analysis

Data were analyzed using one way Analysis of Variance (ANOVA) to determine effect of Nitrogen levels on yield, yield components and quality attributes of coffee using the model below:

$$Yij= \mu + Ti + \varepsilon ij$$

Where Yij represents the j-th observation (j=1, 2………ni) on the -i th treatment (i=1, 2………k). Where ever there were significant difference, a follow up post hoc multiple comparison of least significance difference (LSD) was used to separate the means at a 5% level of significance.

Correlation and regression analysis were performed on yield and yield components of coffee using R-4.4.4 Version software to determine their relationships and also to identify yield components that can guide stakeholders predict yield of coffee.

Partial analysis was done to determine net revenue and benefit cost for treatment combinations (Penot. *et al.*, 2021). The yield components were adjusted by 15% to accommodate 10% for management differences and 5% for plot size differences in order to reflect the differences between the experimental yield and the yield that the coffee farmers can expect (Schrama *et al*., 2018). The average farm gate price of cherry yield per kilogram Nitrogen fertilizer price, labour per person-day for coffee and field management were used to determine revenues and costs (Penot. *et al.*, 2021). The net revenue and benefit-cost ratio were both used to determine rewarding treatment combination.

3.10 Ethical Consideration

The research study was carried out after the approval from the Mzuzu University Research Ethical Committee (Appendix 6).

CHAPTER 4: RESULTS

4.1. Growth and yield parameters

The results for performance of treatment combinations on growth parameters included plant heights, primary branches, number of bearing branches, canopy radius and cherry yield, (Table 2).

Table 2**:** Performance of treatment combinations for 2019/2020 season of coffee plants at Lunyangwa Research Station

Treatment combination	**Plant heights**	**Number of primary branches**	**Number of bearing branches**	**Canopy radius**	**Stem diameter**	**Yield in kg/hectare**
100% OF	125.10^{c}	18.48^{b}	0.78^{b}	23.30^{b}	3.72^{a}	1440^{b}
100% IF	148.20^{ab}	24.87^{a}	3.10^{a}	32.42^{a}	4.12^{a}	2383^{a}
75%IF +25% OF	152.70^{a}	27.72^{a}	4.69^{a}	35.14^{a}	4.09^{a}	1601^{b}
50% OF+50% IF	164.60^{a}	26.31^{a}	5.17^{a}	32.92^{a}	4.13^{a}	2033^{a}
25%OF+75%IF	139.60^{b}	26.95^{a}	2.02^{b}	33.67^{a}	3.53^{ab}	1564^{b}
0%OF+0% IF	116.90^{c}	17.22^{b}	1.49^{b}	19.86^{b}	3.27^{ab}	612^{c}
Grand Mean	142.90	23.71	3.10	29.76	3.85	1634
SED	8.02	2.62	1.50	2.93	0.24	272.60
LSD	15.91	5.20	2.97	5.80	0.48	540.40
CV%	17.08	33.58	146.99	29.92	19.09	50.72
P-Value	<0.001	<0.001	0.011	<0.001	<0.001	<0.001

Means in the same column connected with the same letter are not significantly different. CV%= coefficient of variation percent; LSD= Least significant difference and SED= Standard error of the difference; IF=In-Organic Fertilizer ; OF= Organic Fertilizer

4.1.1. Plant heights

Results on plant heights, primary branches, number of bearing branches, canopy radius, stem diameter and cherry yield are presented in Table 2. The results for plant heights for 2019/20 season showed significant differences among the treatments at Lunyangwa ($p<0.001$) compared to control treatment for treatment combination 50% OF + 50% IF. The treatments performance was further separated by LSD and there were significant differences by LSD for treatment combinations. The combination of 50% organic + 50% inorganic fertilizer was superior in plants heights compared to the control treatment but there were no significant differences by LSD with the 100% in-organic fertilizer and 75% OF + 25% IF combinations.

4.1.2. Primary branches

The results for 2019/20 season showed significant differences in number of primary branches ($p<0.001$) compared to control treatment. The combination of 75% OF + 25% IF was superior but there were no significant differences by LSD with the 50% OF organic +50% inorganic fertilizer, 100% IF and 25% OF +75% IF combinations~~.~~

4.1.3. Bearing branches

The results for the season showed significant differences in number of bearing branches, treatment 50% IF + 50% OF being superior ($p<0.011$) compared to control treatment combination but there were no significant differences by LSD with treatment combinations of 100% IF and 75% OF + 25% IF. The combination of 50% organic and 50% inorganic fertilizer was superior to all treatments in number of bearing primaries.

4.1.4. Canopy radius

The results for canopy radius showed no significant differences among the treatment combinations ($p<0.001$) compared with the control treatment.

4.1.5. Stem diameter

The results for stem diameter showed significant differences among the treatment combinations ($p<0.001$) compared with the control treatment. Treatment combination of 50% OF +50% IF was superior among treatment combinations compared with the control treatment. The means were further separated by LSD and treatment 50% OF + 50% IF showed no differences by LSD

4.1.6. Cherry yield

The results for 2019/20 season showed highly significant ($p<0.001$) differences with treatment combination 100% IF being superior compared to the control treatment but there were no significant differences between treatment combination 50% in-organic fertilizer + 50% OF and 100% IF.

4.2. Coffee quality analysis results

Results on quality analysis are presented on Table 3. There was no significant difference of coffee quality for Lunyangwa research station.

Table 3**:** Quality analysis for coffee at Lunyangwa Research Station

Treatment	**Percentage rating**	**Remarks**
100% OM	83	Floral, caramel, sweet, long after taste, Slightly winery, sour, herbal, musty after taste
100% IF	83.67	Floral, caramel, sweet, good acidity, medium sweet, clean cup, Floral, sweet, medium body
75% IF + 25% OM	83.67	Floral, caramel, sweet, smooth body, balanced, medium acidity and sweet, sweet cup
50% IF + 50% OM	83.50	Floral, citric, sweet, long after taste, medium acidity and sweet, Floral, sweet cup
25% IF + 75% OM	84.17	Floral, citric, sweet, long after taste, good acidity, clean cup, acidity, sweet cup
0% IF + 0% OM	83.50	Floral, citric, sweet, sweet acidity, clean cup, Grassy, musty after taste
Mean	83.58	
SED	0.43	
LSD	0.95	
CV%	0.6	
p-Value	0.26	

4.3. Regression analysis results for yield and yield components

There were correlations among growth parameters and yield with strong and significant correlations in yield and canopy radius, 0.9884713, yield and plant heights; 0.92355, with adjusted R-squared of 0.1850 (Table 4).

Table 4**:** Correlation coefficients of yield and yield components

Growth and yield parameters	Height (cm)	Stem diameter (cm)	No. of primaries	Bearing primaries	Canopy radius (cm)
Height (cm)	1.000				
Stem diameter (cm)	0.667	1.000			
No. of primaries	0.698	-0.068	1.000		
Bearing primaries	0.699	0.100	-0.025	1.000	
Canopy radius (cm)	0.8554	0.184	0.968	0.226	1.000
Yield (kg)	0.924	0.330	0.919	0.371	0.988

Therefore, model building from this study was as follows:

$$Y \ = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \text{ Is equal to } Y = -11122.36 + 269.77\, X_1 + 25.72 X_2 + \varepsilon$$

Where: Y is cherry yield in Kg, β_o is a constant , X_1 is Canopy Radius in Cm, X_2 is Plant height in Cm, β_1, β_2 are model coefficients and ε is the error term

4.4. Economic analysis results of fertilizer interventions

The results for economic analysis of treatment combinations are presented in Table 5. The results show that combined application of organic and inorganic fertilizers has more benefits. This study has showed 100**%** IF with the Benefit-Cost Ratio of 2.76 and 50% IF + 50% Organic Fertilizer benefit cost ratio of 3.846. The net revenue of 100% IF was MK1, 937,897 while 50% IF + 50% OF net revenue was MK1, 918,271. This was followed by 100% Organic Fertilizer with Mk1, 588,820, and 25% IF + 75% OF with Mk1, 353,608.

Table 5**:** Cost benefit analysis for fertilizer treatment combinations 2019/20

Treatments	Average yield (kg/ha)	Adjusted yield-15%	Price/kg cherry (MK)	Gross Benefit	IF Cost (MK)	OF Cost (MK)	Labour	Total cost	Net Revenue	Benefit-Cost Ratio
100% OF	1440	1224	1500	1,836,000	-	199,980	47,200	247,180	1,588,820	7.42778
100% IF	2383	2025.55	1500	3,038,325	1,053,228	-	47,200	1,100,428	1,937,897	2.76
75% IF + 25% OF	1601	1360.85	1500	2,041,275	789,921	49,995	47,200	887,116	1,154,159	2.30
50% IF+50%OF	2033	1728.05	1500	2,592,075	526,614	99,990	47,200	673,804	1,918,271	3.8469
25%IF+75%OF	1564	1329.4	1500	1,994,100	263,307	149,985	47,200	640,492	1,353,608	3.11
0%IF+0%OF	612	520.2	1500	780,300	0	0	42,200	42,200.00	738,100	17.49

CHAPTER 5: DISCUSSION

5.1. Superiority of treatment combinations in performance of yield components

The combination of 50% organic and 50% inorganic fertilizer was superior in plants heights compared to the control treatment but there were no significant differences by LSD with the 100% in-organic fertilizer and 75% OF + 25% IF combinations. This implies that balanced application of organic manure and inorganic fertilizers provided balanced nutrients for coffee plant growth. This suggest that application of 50% Organic manure and 50% In-Organic fertilizer sustained plant growth. The combination of 75% OF + 25% IF was superior in number of primary branches compared to control treatment but there were no significant differences by LSD with the 50% OF organic +50% inorganic fertilizer, 100% IF and 25% OF +75% IF combinations. This is due to well distributed rainfall for the season (Figure 1) and also due to better coffee response to fertilizers as noted by past studies by (Bamirez-Builes & Krusters, 2021) that organic carbon improves fertilizer and water use efficiency by the plants.

The combination of 50% organic and 50% inorganic fertilizer was superior to all treatments in number of bearing primaries~~.~~ This is probably due to relatively balanced and broad availability of both macro and micro nutrients from organic and inorganic nutrient sources compared to the control treatment as noted by Chemura (2014) that organic fertilizers buffers the soil than sole application of mineral fertilizers which may increase soil acidity and depletion of essential nutrients, while Organic fertilizers serve as a source of soil organic matter; improve buffering capacity of the soil; release nutrients gradually over the crop growth period and excellent supplier of balanced nutrients to plants. However, it was observed that some coffee plants were affected by die bark due to insufficient nitrogen levels which is is suggested to have contributed to high CVs. The slow release of nitrogen and low levels of nitrogen in organic fertilizers also contributed to high coefficient of variations for bearing branches for treatment 100% OF fertilizer as observed by Mnthambala (2021).

Treatment combination 75% OF +25% IF was superior in canopy radius compared with the control, the means were further separated by LSD. Treatment 75% OF + 25% IF showed no significant differences by LSD with treatments 100% IF, 50% OF + 50% IF and 25% OF + 75% IF. The results implies that application of more of organic matter is important for plant vigour as nutrient release to coffee is sustained, water and soil preservation is maintained with minimal nutrient loss through leaching. The four treatments performed equally and this suggest the need for area specific recommendations, hence need to be tested on farm. Similarly, in terms of stem diameter, treatment combination of 50% OF +50% IF was superior compared with the control treatment. The means were further separated by LSD and treatment 50% OF + 50% IF showed no significant differences by LSD with treatments 100% IF and 75% IF + 25% OF combinations. The results suggest different combinations of organic and inorganic fertilizers as the best strategies to climate change adaptation for farmers as noted by Cuni-Sanchez *et al.* (2022).

5.2 Superiority of treatment combinations in performance on cherry yield

The yield results for this research showed significant differences in yield/ha (p<0.001) for 100% IF fertilizer and 50% IF +50% OF (p<0.001) being superior treatments compared with the control treatment. Compared with the current coffee production level of 1.43Mt/Ha, the performance of the two treatment combinations is on the higher side (EU-ACP, 2017). The two treatment combinations revealed no significant differences by LSD. Therefore, it is important to apply 50% OF + 50% IF to reduce fertilizer costs by farmers. The results agree with past studies conducted by Ghosh *et al.*, 2022; Wang *et al.*, 2024 that combination of organic and inorganic fertilizers increases crop productivity and soil fertility. Demand for organic products, including coffee, is continuously increasing due to the rising concern of the consumers for sustainable products and a healthy lifestyle without chemical residues (Hasibuan *et al.*, 2022). At present, both types of coffee farming are seen to be economically viable. It would be worthy to pay attention towards organic as noted by Rahmah *et al.*, 2022. Farmers can fetch the good revenue and its long-term financial suitability permits to go for organic coffee. Rural poverty can gradually be addressed by the sustainable income from the coffee production and selling to cooperative despite the effects of climate change. The financial analysis of organic coffee is significant for the cooperatives and its members and to the policy makers in the future and further support to the government climate mitigation policy as observed by Gruter *et al.* (2022).

5.3 Relationships of yield and yield components

Yield and yield components showed significant relationships 0.9884713, for canopy radius. Based on the recorded yield and yield components and analysis results, yield of cherry can be determined by plant height and canopy radius with adjusted R-squared of 0.1850. The plant height and canopy radius are able to explain approximately 18.50% of cherry yield attributes (adjusted R-squared 0.1850). This simply means that yield of the cherry is influenced by other factors of which were not recorded. These other factors of which were not recorded are biotic and abiotic factors such as chlorophyll content, number of leaves per plant, pests and diseases scores per treatment combination. Therefore, one has to focus much on plant heights and canopy radius for yield prediction and it is important to consider tall coffee plants with big canopy radius to have high yield. The residual sum of squares was zero.

5.4. Economic analysis of treatment combinations organic and inorganic fertilizers

From economic point of view, the Benefit-Cost Ratio of 50% IF + 50% OF is greater compared to 100% IF (2.76) despite net revenue of 100% IF MK1, 937,897 being higher than the 50% IF + 50% OF, MK1, 918,271. This means that the economic efficiency of 50% OF + 50% IF is greater than 100% IF. However, pure organic coffee farmer could get more benefits (7.43) and a combination of 25% IF + 75% OF (3.11) than 100% IF.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

This research was carried out with the objective of determining the effect of organic and in-organic fertilizer combinations on yield and quality of coffee for development of low-cost alternative fertilizer application technology. The results show that combined application of organic and inorganic fertilizer has significant effect on yield and growth parameters. This implies that resource constrained farmers can increase coffee yields by combining organic and inorganic nutrient sources with reduced cost. However, there are no significant effect on coffee quality using organoleptic test. It is also suggested to test coffee quality using artificial intelligence advanced tools as organoleptic test fails to detect spectral similarities like sour test. The combined application of organic and inorganic fertilizers improves the growth performances of coffee demonstrating the important roles of combined application of organic and inorganic fertilizers in soil fertility management and thus improvement of coffee growth and yield. The treatment combination of 50% organic and 50% inorganic fertilizer and treatment 100% in-organic fertilizer are both economically viable. The 50% Organic fertilizer + 50% IF is seen as an alternative low-cost technology for resource need coffee farmers and has a greater economic efficiency than 100% IF. There were also significant relationships of growth parameters and yield under organic and inorganic fertilizer application on coffee. Through model building, canopy radius and plant height are the yield components which can be used to predict coffee yields under organic and inorganic fertilizer application in coffee production.

6.2. Recommendations

This work recommends the 50% IF +50% OF as a low-cost alternative technology for resource need farmers due to high costs of inorganic fertilizers on the market and this could reduce cost of production. Therefore smallholder coffee farmers could save costs by using the 50% organic fertilizer + 50% in-organic fertilizer as a low cost technology as an alternative technology to 100% inorganic fertilizers in order to sustain coffee yields because very few farmers use inorganic fertilizers in the coffee sector as reported in the past studies by AGRA, (2017) that farmers in Africa apply very low in-organic fertilizer to crops per hectare estimated at 18 kg/ Ha for SSA due to poor access to inorganic fertilizer inputs on the market compared to World level, 119.9 kg/Ha, South Asia at 149.3 Kg/Ha (AGRA, 2017).

Organic agriculture is rapidly gaining importance on the global markets, even though in it still accounts for a small proportion of on farm production. Therefore, there is need for technology transfer and evaluation of the 50% IF + 50% OF combination technology as an alternative low-cost technology and to test the four treatment combinations, 100% OF, 100% IF, 75% IF + 25% OF and 25% IF + 75% OF on farm for area specific technology recommendations of organic and inorganic fertilizer application on coffee. Catimor 129 was the variety used in this study, it is also strongly recommended to test the fertilizer combinations on other improved and introduced varieties especially varieties provided by the World Coffee Research Organization (WCR), which can yield up to 4 kilograms of cherry per tree like Catigar MG.

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APPENDICES

Appendix 1. : Initial soil fertility status at Lunyangwa Research Station

No.	Soil Depth (cm)	p H (H_2O)	N %	OM %	K (cmol/Kg)	Ca (cmol/Kg)	P (mg/kg)
1	0-20	5.60	0.08	1.70	0.33	0.75	7.00
2	20-40	5.20	0.04	0.90	0.05	0.60	5.40
3	0-20	5.40	0.06	1.20	0.10	1.52	5.90
4	20-40	5.10	0.03	0.70	0.23	1.25	4.50
5	0-20	5.00	0.08	1.70	0.59	0.77	6.80
6	20-40	4.70	0.06	1.20	0.46	1.52	6.10

Appendix 2: The fertilizer regimes and plant spacing:

		Trees/Ha	**Spacing (meters)**
Density		3333	2*1.5
Fertilizer rates	**Nitrogen**	**Phosphorus**	**Potassium**
Year 1.	75	50	75
Year 2.	100	60	100
Year 3.	175	60	200
Year 4+	200	60	250

Appendix 3: Initial soil and compost analysis result

Soil	Soil Depth(cm)	Soil colour	pH	EC	%N	NO_3 (mg/L)	P (mg/100g soil	K (ppm)	Na (mg/100g soil)	Fe (ppm)	Ca (mg/100g soil)	Mg (mg/100g Soil)	Mn (ppm)	%C	OM %	CEC me/100g
Top	0-20	Red	5.60	54.00	0.08	6.00	7.00	13.00	8.00	7.00	30.00	38.00	20.00	0.96	1.70	7.5-13.1
Sub	20-40	Red	5.20	52.00	0.04	5.00	5.40	2.00	2.00	5.00	24.00	38.00	20.00	0.51	0.90	6.7-13
Top	0-20	Red	0.40	48.00	0.06	5.00	5.90	4.00	2.00	4.00	61.00	38.00	20.00	0.68	1.20	6.3-13.3
Sub	20-40	Red	5.10	46.00	0.03	5.00	4.50	9.00	3.00	1.00	50.00	38.00	20.00	0.38	0.70	4.0-9.6
Top	0-20	Red	5.00	49.00	0.08	6.00	6.80	23.00	5.00	7.00	31.00	38.00	20.00	0.96	1.70	7.5-13.1
Sub	20-40	Red	4.70	47.00	0.06	5.00	6.10	18.00	2.00	4.00	61.00	38.00	20.00	0.68	1.20	6.3-13.3
			4.35	49.33	0.06	5.33	5.95	11.50	3.67	4.67	42.83	38.00	20.00	0.70	1.23	
Compost			7.60		0.05	19.00		120.00	19.00					5.81	10.31	

Appendix 4: Top soil nutrient status results of effect of treatment application for 2019/20 season

Treatment	**%OC**	**%OM**	**%N**	**P (µg/g)**	**K (Cent moles/kg)**	**Mg (µg/g),**	**Ca (Cent moles/Kg)**
100% OM	0.96	1.65	0.08	86	0.53	0.62	8.91
100% IF	0.69	1.19	0.06	93	0.33	0.94	7.51
75% IF+25%OM	0.88	1.52	0.07	118	0.54	0.91	6.42
50% IF+50%OM	0.66	1.13	0.06	120	0.38	0.94	7.53
25% IF+75% OM	1.36	2.34	0.12	96	0.27	0.87	5.83
0% IF+0% OM	0.84	1.45	0.07	77	0.23	0.91	7.78
Mean	0.89	1.55	0.08	98.33	0.38	0.87	7.33
SED	0.49	0.86	0.04	37.5	0.14	0.28	1.17
CV%	33.1	33.2	33	17.6	25.3	11.4	5.3
P-Value	0.74	0.74	0.75	0.82	0.2	0.85	0.22

Appendix 5: Sub soil nutrient status results of effect of treatment application for 2019/20 season

Treatment	**%OC**	**%OM**	**%N**	**P (µg/g)**	**K (Cent moles/kg)**	**Mg (µg/g),**	**Ca (Cent moles/Kg)**
100% OM	0.64	1.09	0.05	24.2	0.29	1.1	8.11
100% IF	1.23	2.12	0.1	38.7	0.38	1.12	7.32
75% IF+25%OM	1.6	2.76	0.14	73.1	0.5	1.22	8.21
50% IF+50%OM	1.22	2.11	0.1	66.8	0.43	0.9	6.61
25% IF+75% OM	1.05	1.82	0.09	54.4	0.43	0.94	6.72
0% IF+0% OM	1.72	2.96	0.15	56.8	0.51	0.85	7.23
Mean	1.24	2.14	0.11	52.33	0.42	1.02	7.37
SED	0.32	55	0.03	30.2	10	0.35	2.54
CV%	7.5	7.3	7.4	22.3	0.12	15.9	6.4
P-Value	0.06	0.06	0.07	0.62	0.52	0.87	0.98

Appendix 6.: Ethical clearance document of the research proposal

MZUZU UNIVERSITY

DIRECTORATE OF RESEARCH

Mzuzu University
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MALAWI
TEL: 01 320 722
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MZUZU UNIVERSITY RESEARCH ETHICS COMMITTEE (MZUNIREC)

Ref No: MZUNIREC/DOR/24/101 **03/09/2024.**

Fanuel Josiah Matawale,
Mzuzu University,
P/Bag 201, Luwinga,
Mzuzu 2.

Email: fanuelmatawale@gmail.com

Dear Fanuel,

RESEARCH ETHICS AND REGULATORY APPROVAL AND PERMIT FOR PROTOCOL REF NO: MZUNIREC/DOR/24/101: IMPACT OF ORGANIC AND IN-ORGANIC FERTILIZER ON COFFEE ON YIELD AND QUALITY (COFFEE ARABICAE L) AT LUNYANGWA RESEARCH STATION IN MALAWI.

Having satisfied all the relevant ethical and regulatory requirements, I am pleased to inform you that the above referred research protocol has officially been approved. You are now permitted to proceed with its implementation. Should there be any amendments to the approved protocol in the course of implementing it, you shall be required to seek approval of such amendments before implementation of the same.

This approval is valid for one year from the date of issuance of this approval. If the study goes beyond one year, an annual approval for continuation shall be required to be sought from the Mzuzu University Research Ethics Committee (MZUNIREC) in a format that is available at the Secretariat. Once the study is

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finalised, you are required to furnish the Committee with a final report of the study.

The Committee reserves the right to carry out compliance inspection of this approved protocol at any time as may be deemed by it. As such, you are expected to properly maintain all study documents including consent forms.

Wishing you a successful implementation of your study.

MZUZU UNIVERSITY
RESEARCH ETHICS COMMITTEE

[illegible]3 SEP 2024

PRIVATE BAG 201 LUWINGA
MZUZU 2

Yours Sincerely,

Wanangwa K. Msowoya

MZUNIREC Secretariat
FOR: MZUNIREC CHAIRPERSON

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