EVALUATING ALTERNATIVE ISFM PRACTICES ON SOIL FERTILITY, CROP PRODUCTIVITY, SOIL CARBON STOCK, AND NUTRIENT BALANCE IN HUMID HIGHLAND OF CENTRAL ETHIOPIA

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Evaluating Alternative ISFM Practices on Soil Fertility, Crop Productivity, Soil Carbon Stock, and Nutrient Balances in Humid Highland of Central Ethiopia

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BY

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February, 2025

DECLARATION

I hereby declare that the research reported in this PhD thesis is original and have been completed independently by myself (Meseret Habtamu Cheru), under the supervision of Prof. Eyasu Elias Prof. Mekuria Argaw and Prof. Teshome Soromessa. This PhD thesis has not been submitted for the award of any other degree or professional qualification, where other sources are quoted and full references are given.

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Meseret Habtamu, PhD Dissertation, Addis Ababa University, February 2025

ABSTRACT

Smallholder farmers in the Dire and Legedadi watersheds face challenges with declining soil fertility and crop productivity exacerbated by limited adoption of integrated soil fertility management (ISFM) practices. Therefore, the main objective of this PhD work was to explore the effect of ISFM practices on crop yields, soil fertility, soil C stock and soil NPK balance. The study included eight treatments (sole wheat, sole faba bean, wheat with 100% recommended NPS, wheat with 100% recommended VC, wheat with 50% recommended rate NPS and 50% VC, wheat and faba bean intercropping with 50% recommended NPS and 50% VC, wheat and faba bean intercropping with 50% NPS, and wheat and faba bean intercropping with 50% VC). In NPS added treatments Urea fertilizer was applied as a supplemental dose to satisfy the N recommendation. The treatments were tested in two farmers' fields using a randomized complete block design with three replications for two consecutive rain-fed cropping years (2021-2022). Crop productivity was evaluated by grain yield and biomass yield explained by partial budget/economic analysis using marginal rate of return (MRR). Intercropping indices, including the land equivalent ratio (LER), crowding coefficient, and system productivity index, were assessed. Selected soil physicochemical properties were determined following standard protocols, and soil carbon stock, nitrogen stock, and carbon sequestration were calculated according to Donvan's equation. The MonQI toolbox was used to analyze full and partial nutrient balances. The data were subjected to analysis using SAS/STAT software. The highest mean wheat grain yield (4000 kg ha^{-1} at Dire and 4151.7 kg ha^{-1} at Legedadi and straw yields (8827.7 kg ha^{-1} at Dire and 8548.3 kg ha^{-1} at Legedadi) were obtained from the application of a full dose mineral fertilizer. Wheat faba bean intercropped treatments exhibited the highest net benefits of (USD 5598.1ha^{-1}, 5690.8 ha^{-1}) at Dire and Legedadi sites, respectively. The combined application of VC and NPS fertilizers resulted in higher agronomic efficiency of N (40% and 42%), and LER 1.89 and 1.76 at Dire and Legedadi sites, respectively. These treatments also significantly ($p< 0.01$) increased total nitrogen (TN), available phosphorus (Pav), exchangeable bases (Ca^{2+}, Na^{+}, and Kexc), and Cation exchange capacity. The results revealed significant variations of soil chemical properties between Dire and Legedadi sites for the TN ($p=0.003$), Pav ($p=0.0001$), Kexc ($p=0.0001$), and SOC ($p=0.001$). The application of a full dose of VC resulted in the highest soil carbon stock and carbon sequestration at both sites. Wheat-faba bean intercrop showed a greater NPK deficit, attributed to the higher nutrient uptake by both the wheat and faba bean crops. Combined fertilizers application had better PK balances than the sole application of mineral fertilizer.

Key words*: Crop productivity, ISFM, Intercropping, Nutrient Balance, MonQI toolbox, Soil Fertility, Soil carbon and Nitrogen stock*

DEDICATION

I dedicate this thesis to my parents, whose unwavering support and encouragement have been my greatest source of strength throughout my life.

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ABBRIVATIONS AND ACRONYMS

AP	Available Phosphorus
AAWSA	Addis Ababa Water and Sewerage Authority
BD	Bulk Density
CSA	Central Statistical Agency
DAP	Di Ammonium Phosphate
EIAR	Ethiopian Institute of Agricultural Research
GDP	Gross Domestic Product
FAO	Food and Agricultural Organization
FYM	Farmyard Manure
GIS	Geographical Information System
GHG	Green House Gases
GPS	Geographical positioning System
GMV	Gross Monetary Value
ISFM	Integrated soil fertility management
LER	Land Equivalent Ratios
MA	Monetary Advantage
MoA	Ministry of Agriculture
MONQI	Monitoring for quality improvement
NutMON	Nutrient Monitoring
OC	Organic Carbon
OM	Organic Matter
RCBD	Randomized Complete Block Design
SD	Standard Deviation
SDG	Sustainable Development Goals
SAP	Sustainable Agricultural Practices
TN	Total Nitrogen
USDA	United States Department of Agriculture

Chapter one

1. Introduction

1.1. Background

The African continent is facing increasing challenges with food insecurity. Around 30% of the population in SSA remains food insecure and economically poor partly due to low agricultural productivity (FAO, 2012). Decreasing soil fertility and poor land management practices have been major problems to productivity for smallholder farmers in Africa (Bationo et al., 2015). Mono-cropping, failure to adopt soil-conserving practices, erosion and negative nutrient balances, deforestation, unbalanced fertilization, excessive use of groundwater for irrigation, and improper pesticide use are recognized as key factors contributing to soil fertility decline in Africa (Lewoyehu et al., 2020). Soil fertility decline reduce annual agricultural productivity by nearly 3%, resulting in an estimated loss of approximately USD 68 billion per year in the Sub-Saharan Africa (SSA) region (Zingore et al., 2015). This has caused stagnation or even declines in the yield levels of cereal and legume crops (Kihara et al., 2016).

Agriculture is the mainstay of the Ethiopian economy, contributing 41.4% of the country's gross domestic product (GDP), 83.9% of the total exports, and 80% of all employment in the country (Matouš et al., 2013). However, the agricultural sector is characterized by low productivity caused by declining soil fertility expressed by serious soil nutrient depletion in the highland areas of Ethiopia (Sigaye et al., 2020). Causes for the low agricultural productivity can be many and diverse, but declining soil fertility, and nutrient and organic matter depletion are among the major causal factors for low agricultural productivity generally in SSA specifically in Ethiopia (Mattete et al., 2010, Kihara et al., 2016, Elias et al., 2019). This decline in soil fertility is attributed to factors such as severe soil erosion, extensive nutrient depletion, and limited use of external inputs, all of which contribute to poor crop yields (Tamene et al., 2017).

Ethiopia's highly rugged topography, coupled with suboptimal land-use practices, has resulted in one of the most severe rates of soil erosion in SSA. This process leads to substantial nutrient depletion from agricultural lands, thereby contributing to a persistently negative soil nutrient balance and exacerbating soil fertility decline during each cropping cycle (Biyensa et al., 2015).

In response, soil fertility enhancement strategies have been implemented, predominantly relying on a standardized fertilizer application regime, which since 2015 has consisted of 100 kg per hectare of NPS (19% N, 38% P_2O_5, 7% S) and 100 kg per hectare of urea. Historically, prior to this shift, a blanket recommendation of 100 kg per hectare of diammonium phosphate (DAP: 18% N, 46% P_2O_5) alongside 100 kg per hectare of urea (46% N) was widely used (Elias et al., 2019).

However, tailored soil fertility management strategies, incorporating both organic amendments such as compost and site-specific mineral fertilization, have remained largely absent in Ethiopia's agricultural system (Seifu et al., 2022). Given the heterogeneity of agroecological conditions, integrated soil fertility management (ISFM) has been proposed as a more scientifically robust and sustainable approach to mitigating soil nutrient depletion, enhancing agricultural productivity, and reducing poverty across SSA nations (Teklewold et al., 2013).

Numerous ISFM field trials have been conducted across various regions of Ethiopia, yielding promising results. Notable studies include an investigation into *the effect of plant density of sweet lupine intercropping on tef crop yield in Northwest Ethiopia* (Hunegnaw et al., 2022), an assessment of *the adoption of intercropping and ISFM practices by smallholder farmers in Northwestern Ethiopia* (Nigussie et al., 2017), and an evaluation of *intercropping legume cover crops with maize for soil moisture improvement in Southern Ethiopia* (Bekele et al., 2021). Collectively, these studies indicate that implementing ISFM strategies significantly enhances the agricultural productivity of smallholder farmers.

The utilization of organic fertilizers and soil amendments, such as agricultural lime for ameliorating soil acidity, presents a highly promising strategy for enhancing soil fertility, increasing food production, and simultaneously mitigating land degradation (Guo et al., 2019). The incorporation of organic fertilizers, including composting, conservation agriculture, and crop residue restitution, plays a crucial role in counteracting negative nutrient balances while also reducing the risk of groundwater contamination from nitrate leaching, a common consequence of excessive mineral fertilizer use (Silva et al., 2016). Vermicomposting, adopted in various agricultural systems, has been shown to improve soil fertility, enhance crop yields, and positively influence soil physicochemical properties, all while being cost-effective and environmentally sustainable (Piya et al., 2018, Jemal and Abebe, 2020).

Soil organic carbon is one of the largest carbon reservoirs in terrestrial ecosystems and plays a crucial role in the global carbon cycle. Sink of carbon from atmosphere to either plant into soil or from atmosphere into soil is called soil carbon sequestration. It offers a "win-win" solution by lowering greenhouse gas concentrations in the atmosphere and simultaneously improving soil quality for agricultural purposes (Melenya et al., 2015).

Unsustainable agricultural practices affecting organic matter have significant impacts on soil fertility, agricultural productivity, food security, the terrestrial carbon cycle, and climate change (Abegaz et al., 2020). Understanding the effects of ISFM practices on soil carbon stock is essential for addressing climate change, improving soil health, boosting agricultural productivity, and promoting sustainable soil management practices. The effects of ISFM practices on soil carbon stock are essential for enhancing soil carbon levels, which in turn improve soil fertility, stimulate microbial activity, and increase nutrient availability. However, such strategies are not adequately available in the study areas, highlighting the need for improved implementation and awareness.

Within the MonQI toolbox framework, biological nitrogen fixation (BNF) is recognized as a key nutrient input contributing to field-level nutrient equilibrium (Elias, 2005b). Consequently, sustainable agricultural practices advocate for intercropping cereals with legumes, offering multiple agronomic advantages: (1) improving soil fertility through BNF, thereby fostering nutrient balance at the field level; and (2) enhancing soil quality by increasing organic matter content via enzymatic activities in the root zone (Wang et al., 2015).

Soil nutrient status is vital for the appropriate soil management practices, which are not adequately available in the study areas. Monitoring soil nutrient flows and balance in smallholder farming serves as a valuable tool for the sustainability of agricultural systems. Establishing links between nutrient input and output flows and soil nutrient reserves, thereby providing crucial indicators for the effective management of soil fertility (Bahr et al., 2015).

Research on soil nutrient balance in Ethiopia remains limited; however, existing studies consistently indicate a severely negative nitrogen and phosphorus balance at both field plot and farming system scales (Elias et al., 1998a, Gebresamuel et al., 2021, Mesfin et al., 2021,

Lewoyehu et al., 2020, Van Beek et al., 2016, Haileslassie et al., 2005). Ethiopia is rated as one of the countries with the highest rates of nutrient depletion in SSA with national average nutrient balances of -41 kg N, -6 kg P, and −26 kg K per hectare per year (Jayne and San- chez 2021). More alarming are field-level nitrogen and phosphorus depletion rates observed in Nitisols, which range from -60 to -102 kg N/ha and -23 to -45 kg P/ha in the southern and southwestern highlands (Elias et al., 1998a). These findings underscore the high rate of nutrient depletion, highlighting the unsustainable nature of Ethiopia's agroecosystems. Addressing this challenge necessitates the adoption of Integrated Soil Fertility Management (ISFM) practices that ensure a balanced nutrient input-output cycle (Sanginga and Woomer, 2009). Among the ISFM strategies, the intercropping of wheat with faba bean, combined with the application of vermicompost (VC) and NPS fertilizer supplemented with urea fertilizers has been identified as a promising approach.

The Dire and Legedadi watersheds serve as the primary water reservoirs for the residents of Addis Ababa. However, these critical water sources are increasingly threatened by a range of environmental challenges. Research indicates that extensive land use and land cover changes over recent decades, coupled with unsustainable land management practices, inadequate resource utilization, and ecosystem degradation at the catchment level, have accelerated sedimentation and siltation in the Legedadi and Dire reservoirs (Anteneh et al., 2018). Over a 30-year period (1986–2016), the average annual soil loss in the Legedadi watershed escalated from 3.93 to 21.74 t/ha/year, while in the Dire watershed, it surged from 18.1 to 77.15 t/ha/year (Awraris, 2017). The prevailing land use practices have significantly altered key soil physical and chemical properties, leading to a decline in overall soil quality and reduced agricultural productivity within the affected cultivated areas (Habtamu et al., 2023).

The decline in agricultural productivity per unit of land, primarily driven by soil fertility depletion, poses an increasing challenge for smallholder farmers in these regions. Achieving sustainable agricultural growth hinges on enhancing productivity, which can be realized through the efficient utilization of existing technologies, such as legume-based systems, intercropping, and agroforestry (Mamuye et al., 2021). Without the adoption of ISFM practices, substantial improvements in food production remain unlikely (Aticho et al., 2011). However, ISFM approaches have not been widely implemented in the study areas. Farmers traditionally rely on

cereal-legume rotation and chemical fertilizers. The integration of cereal-legume intercropping, particularly in farming systems characterized by minimal external inputs and fragmented land use, is crucial for establishing sustainable food production frameworks.

Extensive research has consistently demonstrated the superior benefits of legume intercropping compared to monocropping systems (Bekele et al., 2021, Hunegnaw et al., 2022, Kherif et al., 2021, Biruk et al., 2021, Temeche et al., 2022). The study areas are well recognized for cultivating cereals (wheat and barley) being the dominant field crops and faba bean from legumes. Due to its adaptability, stability, and ease of production, faba bean was selected as the primary legume for intercropping with wheat in these regions. Legume-cereal intercropping plays a crucial role in enhancing sustainable food production, particularly in agricultural systems characterized by low external inputs and fragmented land use. Additionally, vermicompost (VC) was chosen among various organic fertilizers for its multiple agronomic benefits, including its ability to enhance soil fertility and improve crop yields.

This study aims to promote and facilitate the adoption of VC in the target areas. Therefore, it serves as a fundamental resource for sustainable land and soil management strategies in the Dire and Legedadi watersheds. The primary objective of this research is to assess the impacts of intercropping and the combined application of NPS and VC on soil fertility, crop productivity, soil carbon, and farm-level soil NPK nutrient balances within the cereal-based farming systems in the humid mid-highlands of Ethiopia.

1.2. Statement of the problem and justification

The cultivation of annual crops is the predominant land use type accounting for 64% and 78% of the total area in the Legedadi and Dire watersheds, respectively. Soil erosion rates of up to 77.15 t/ha/year at Dire site have been considered one of the highest in Ethiopia (Awraris, 2017). Low agricultural productivity in the area is attributed to declining soil fertility as a result of soil erosion and unbalanced fertilization and mono-cropping of cereals, mainly wheat and barley in the area. Integrated soil fertility management practices such as legume-based technologies, intercropping and balanced nutrient management are largely lacking (Mamuye et al., 2021).

Integrated soil Fertility Management (ISFM) practices have not been effectively integrated with the farming systems. The adoption of cereal and legume intercropping is crucial for establishing sustainable food production systems, especially in areas with limited external inputs and dispersed land use. Numerous studies have confirmed the significant advantages of legume intercropping over sole cropping (Bekele et al., 2021, Hunegnaw et al., 2022, Kherif et al., 2021).

However, rigorous empirical research is required to guarantee the sustainable adoption of technologies and their beneficial impacts on productivity, soil physiochemical properties, soil carbon and nitrogen stock and soil nutrient balance. This is because information on soil fertility assessment helps to design appropriate soil fertility management practices (Abate et al., 2016), but particular information is lacking in the study areas. The soil nutrient status, essential for devising appropriate land use systems and soil management practices, is insufficiently accessible in the study areas. In addition, the effects of intercropping and combined fertilizers application on crop productivity and soil physico-chemical properties and soil carbon stock have yet to be studied. Smallholder agricultural production in the Dire and Legedadi watersheds faces challenges from declining soil fertility, caused by soil erosion, low nutrient application, and mono-cropping.

Therefore, taking into account the importance of the areas for the metropolitan and sensitivity of the watershed and nationwide crop productivity decline problem, it is important to investigate the impacts of ISFM practices on soil fertility, crop productivity, soil carbon stock and soil nutrient balance. Thus, this research will investigate the effects of intercropping and VC application on crop productivity, soil fertility, and soil carbon. Additionally, it will assess the nutrient balance in the study areas and provide valuable information for local and government agencies, research institutes, and stakeholders that would help improve soil management practices to enhance productivity.

1.3. Research objectives

1.3.1. General objective

The overall objective of this study is to investigate the effects of ISFM practices on soil fertility, crop productivity, soil carbon stock and nutrient balance at Dire and Legedadi watersheds located in the humid mid-highlands of Ethiopia.

1.3.2. Specific objectives

- To explore the effects of integrated soil fertility management practices on wheat yield at Dire and Legedadi watersheds;
- To investigate the effects of integrated soil fertility management practices on soil fertility at Dire and Legedadi watersheds;
- To examine how soil organic carbon stock is affected by integrated soil fertility management practices at Dire and Legedadi watersheds;
- To examine how integrated soil fertility management practices affect field level soil NPK balances at Dire and Legedadi watersheds.

1.4. Research questions

The following research questions were developed and tested in order to verify the research hypothesis and achieve the study's stated objectives:

- What are the effective integrated soil fertility management practices to enhance soil fertility and nutrient supply?
- What are the effects of intercropping and combined application of vermicompost and NPS blended fertilizers on soil carbon stock?
- What are the impacts of legume intercropping and combined application of vermicompost, and NPS fertilizer on the yield of companion crops – i.e., wheat (main crop) and faba bean (intercropped legume)?
- How do field-level nutrient balances respond to legume intercropping and the combined application of vermicompost and mineral fertilizer?

1.5. Significance of the study

Scientific studies on the role of integrated soil fertility management practices for degraded soil rehabilitation and crop production are important, especially for Ethiopia where the majority of the population economy relies on agriculture and production is much below world average. The key to a prolonged increase in agricultural production is to improve productivity, which can be achieved through better and effective use of sustainable agronomic practices. Among the available sustainable agronomic practices ISFM practice is promising one including cereal intercropping with legumes and integrated application of organic fertilizers (vermicompost) with inorganic fertilizers (NPS); which were selected for this PhD study to examine their effect on crop productivity, soil fertility, soil organic stocks and soil nutrient balance.

ISFM increases crop productivity, maintains soil health, and shows promising potential for soil physicochemical improvement with low-cost and environmentally friendly. In addition, soil nutrient balance data are important for the design of appropriate land use systems and soil management practices. Therefore, this study is significant for establishing baseline information and data that would help improve management practices to enhance crop productivity and sustainable soil management initiatives at Dire and Legedadi watersheds.

1.6. Outline of the dissertation

The research is structured into six chapters. The first chapter serves as an introduction to the study. Chapter Two provides a review of related literature on the research topic. Chapter Three outlines the study's methodology, including sampling and data analysis methods. Chapter Four presents the results, focusing on data analysis. Chapter Five is the discussion, where key findings are analyzed and interpreted. Finally, Chapter Six summarizes the research, presenting the conclusions and recommendations.

2. Literature Review

2.1. Crop Productivity in Ethiopia: An Overview

In Ethiopia 60% of farmers, cultivate plots of land that are smaller than 0.90 ha in landscapes characterized by significant fragmentation (Rapsomanikis, 2015). Small-scale farming plays a crucial role in contributing to a substantial portion of food production. Total area under crop and more than 90% of its yield are the results of small-scale farming. Ethiopia serves as a hub for the origin and diversity of multiple crop varieties (Tadesse et al., 2021).

The crop yields on smallholder farms are significantly below their capacity and notably less, accounting for less than 50% of the yields achieved in experimental farms and research stations (Taffesse et al., 2012). Cereal production holds a prominent position in agricultural activities when compared to the production of other crops. Cereals occupy 81.19% of the total grain crop area, contributing to 88.36% of the total grain production in the country (Table 1). This percentage is significantly higher than the share of other crops like pulses (12.9%) and oilseeds (5.9%) (CSA, 2021).

Table 1: Average area of cereal production for 2007-2018

Year	Teff	Barley	Wheat	Maize	Sorghum	Millet	Oats	Rice
2007	2404674	1019314	1473917	1694522	1464318	374072	32798	39377
2008	2565155	984943	1424719	1767389	1533537	399268	30556	24434
2011	2761190	1046555	1553240	1963180	1897734	408110	30859	2966
2012	2731112	951993	1437485	2054724	1923717	432561	30568	30649
2013	2730273	1018753	1627647	2013045	1711485	431507	26514	41811
2014	3016522	1019478	1605654	1994814	1677486	454662	35618	33820
2015	3016063	993939	1663846	2114876	1834651	453909	27899	46832
2016	2866053	944401	1664565	2111518	1854711	465508	22106	45454
2017	3017914	959273	1696083	2135572	1881971	456172	24041	48418
2018	3023284	951993	1696907	2128949	1896389	456057	25896	53107

Source (Gizaw and Assegid, 2021)

Wheat and faba bean

Wheat (*Triticum aestivum* L.) is one of the globally produced and marketed cereal crops which covers 15% of the total sowing areas of cereal crops in the world (Kiss, 2011). Wheat ranks fourth after teff, maize and sorghum in area coverage and third after maize and teff in total production in Ethiopia (Minot et al., 2019), but, the production of wheat is tremendously of a subsistence nature and dominated by smallholder farmers that cultivate more of wheat for consumption and less of it for the market (Matouš et al., 2013). Ethiopia, with the potential to expand its wheat cultivation to 1.3 million hectares, stands as the second-largest wheat producer in Sub-Saharan Africa, following South Africa (Haregewoin et al., 2018).

According to the report of (CSA, 2017), the total cereal production of wheat was 267.8 million quintals and 277.7 million quintals in the 2017/2018 and 2018/2019 production seasons, respectively. The central, southeastern and northwest highlands are the main wheat and pulse crops growing areas of Ethiopia (Fekadu et al., 2018).

The report of FAOSTAT indicates that the average wheat yield of Ethiopia is 28 quintals per hectare in 2017 (Figure 1), but the Ethiopian wheat yield is lower than other African countries.

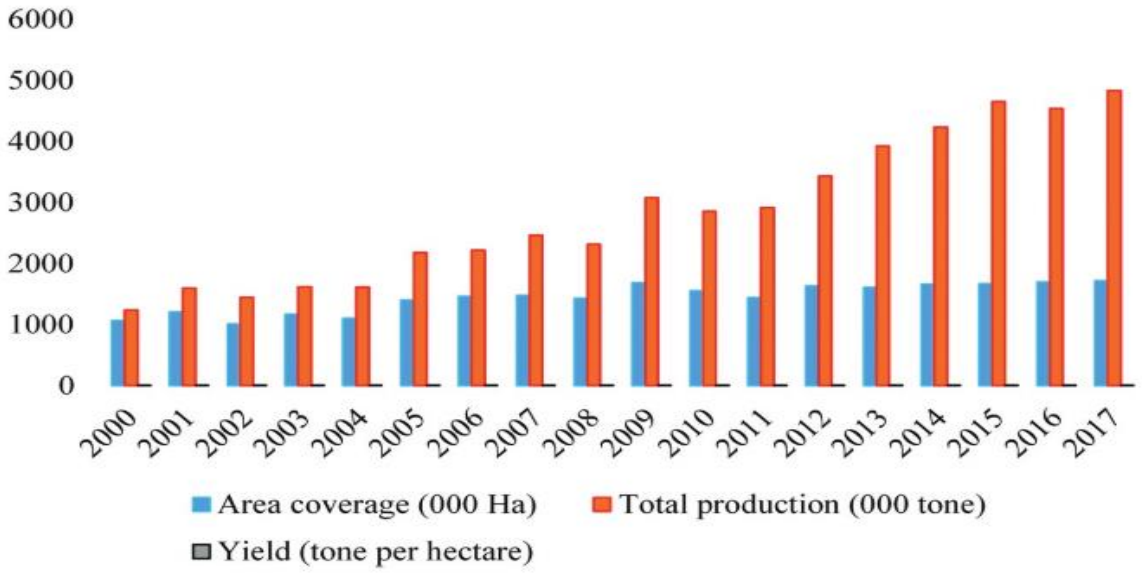


Figure 1: Status of wheat production, area coverage and productivity from 2000 to 2017 (source: (FAOSTAT, 2017)

The limited progress in wheat development is hindered by a range of natural and human-induced challenges, encompassing factors such as drought, soil acidity, erosion, soil fertility issues, water-logging, pre-harvest sprouting, farmers' low input utilization, limited irrigation, soil degradation, soil erosion, and insufficient agricultural research (Tadesse et al., 2019).

Faba bean

Faba bean is a significant pulse crop in Ethiopia, serving as a vital protein source, covering a substantial cultivation area, and contributing significantly to the annual production volume (Dobocha and Bekele, 2021). The primary faba bean producers include China (1.64 million tons), Ethiopia (0.92 million tons), Australia (0.34 million tons), France (0.27 million tons), and Sudan (0.16 million tons) (Semba et al., 2021). Faba bean plays a key role in improving food security and soil fertility. It usually grows in Nitisol and Vertisol dominated areas of Ethiopia.

In the country, the cultivation of faba beans encompasses 31% of the total area allocated for pulses, covering 1,863,445 hectares (CSA 2019). Nonetheless, the crop's production remains low at 2.12 t/ha, which is lower than the average yield of 3.7 t/ha observed in leading faba bean-producing countries across the globe (FAOSTAT, 2017). In Ethiopia, the annual cultivation area for this crop spans 492,271.60 ha, resulting in a total production of 1.04 million t ha^{-1} and a productivity rate of 2.1 t ha^{-1} (Ojiewo et al., 2020). Faba bean gives various benefits in Ethiopia. It is mainly used as food and feed. It is also has high economic value (Jensen et al., 2010).

Ethiopia also earns foreign currency through the export of faba bean, with major destinations including Sudan, South Africa, Djibouti, Yemen, Russia, and the USA (Dobocha and Bekele, 2021). Faba bean is also valuable for its role in replenishing soil fertility and its contribution to crop rotation by facilitating the fixation of atmospheric nitrogen (Tedone et al., 2023). Climatic conditions, soil-related factors, disease challenges, and agronomic practices all pose limitations to faba bean production in Ethiopia (Dobocha and Bekele, 2021).

2.2. Soil fertility issues in Ethiopia

Ethiopia's designation as a "Soil Museum of the World" underscores its unique and diverse soil resources, offering vast agricultural potential. However, due to centuries-old, traditional, and unsustainable cropping systems, the country is experiencing severe soil fertility depletion, threatening food security and rural livelihoods. Addressing this challenge requires a fundamental shift toward sustainable, climate-smart agricultural practices that restore soil health while maintaining productivity for future generations (Ali et al., 2022).

Most soils in Ethiopia are highly weathered and infertile due to their low organic matter content and open nutrient cycling systems. The loss of soil fertility results from soil erosion and excessive nutrient mining due to the complete harvest of crops for food, animal feed, and fuel, without adequate replenishment (Hörner and Wollni, 2021). These factors have led to soil fertility depletion and a reduction in crop productivity, driven by various soil degradation agents. Low soil fertility and inefficient soil management have been significant challenges to productivity among smallholder farmers in Ethiopia. It is estimated that over 1.5 billion tons of soil are lost annually due to erosion and flooding in the country. This loss of fertile soil could have potentially added about 1.5 million tons of grains to the country's agricultural production (Lebeda et al., 2010). This has led to a decline in the productivity of crop and livestock systems and a high level of food insecurity (Mebrate et al., 2022). Addressing these challenges requires a combination of sustainable agricultural practices, improved land management techniques, and increased access to fertilizers and organic amendments. The current global scenario firmly emphasizes the need to adopt eco-friendly agricultural practices for sustainable food production. Collaborative efforts between the government, researchers, and local farmers are essential to restore and maintain soil fertility in Ethiopia.

2.3. Basic problems associated with Ethiopia's Agriculture

2.3.1. Declining soil fertility and negative nutrient balances

Soils have played pivotal roles in sustaining the Earth's life-support system by offering a wide array of indispensable ecosystem services to benefit both humans and the environment (Schwilch et al., 2016). Nevertheless, human interventions driven by economic interests have

resulted in the rapid and extensive deterioration of soils over the last fifty years, posing a significant threat to their capacity to supply essential services to society (Brevik et al., 2015). Soil fertility decline has emerged as a significant global concern. This represents a grave agricultural issue that poses a threat to both current and prospective food production and the well-being of humans (Tsegaye, 2019).

Soil fertility has been declining due to low fertilizer use, poor land management practices, and soil erosion. Soil fertility decline leads to a negative nutrient balance by depleting essential nutrients in the soil faster than they can be replenished. As fertility decreases, nutrients like nitrogen, phosphorus, and potassium are continuously extracted by crops, while insufficient inputs such as fertilizers or organic matter fail to restore them (Rawal et al., 2022). This imbalance results in reduced soil productivity, degraded agricultural potential, sustainability, and food security (Kiros et al., 2014, Koch et al., 2020). The depletion of soil fertility in East Africa, including Ethiopia, is primarily due to continuous cropping with minimal nutrient replenishment, coupled with nutrient losses through leaching, gaseous emissions, and erosion (Van Beek et al., 2016). For example, erosion rates of up to 42 $Mg\,ha^{-1}$ $year^{-1}$ have been observed on cultivated lands throughout Ethiopia (Haregeweyn et al., 2015) and (Hurni et al., 2015) reported that erosion rates of 20 $Mg\,ha^{-1}year^{-1}$ on presently cultivated lands and 33 $Mg\,ha^{-1}year^{-1}$ on lands that were previously cultivated degraded lands in the country.

These findings indicate a high rate of soil fertility decline, which contributes to a negative nutrient balance. The significant loss of soil through erosion depletes essential nutrients faster than they can be replenished, further degrading the soil's productive capacity.

2.3.2. Soil erosion as a negative driver of nutrient balances

Soil erosion is a major factor leading to soil nutrient loss and a decline in soil fertility. It is also a major contributor to global food insecurity, reducing nutrient nitrogen, phosphorus, and potassium supply capacity in the global harvested area (Gebrehiwot, 2022). Nutrient removal through plant harvests (yield and crop residues), combined with nutrient loss from erosion, poses significant threats to soil nutrient depletion in sub-Saharan Africa and shapes the overall condition of soils in the region (Bashagaluke et al., 2018). The East African highlands have been observed to lose 130 kg N, 5.0 kg P, and 25.0 kg K ha^{-1} yr^{-1} due to soil erosion (Braun et

al., 1997). Soil erosion is a major agricultural problem in Ethiopia, posing a serious threat to food production and livelihoods. It has caused significant economic losses and environmental damage, with the country losing around $106 million annually due to soil and nutrient depletion (Tsegaye, 2019).

The pressing on-site consequence of soil erosion for farmers is the decrease in both present and potential crop and livestock yields, leading to income losses. Erosion significantly reduces the size of grazing lands, effective soil depth and ground water availability thus hindering the free movement of moisture within the soil system and the sizes of farmlands. The effects of soil erosion can also be observed in the necessity to apply additional inputs to sustain soil productivity and achieve the same level of yield (Gebreselassie et al., 2016).

According to, (Assefa, 2014) report approximately 50% of Ethiopia's highlands were already classified as "significantly eroded," with 4% of this land considered irreclaimable. The Ethiopian highlands experience a depletion of 1.5 million tons of soil annually, resulting in a substantial decrease in the total annual grain yield (Gashaw et al., 2018). The external effects of soil erosion are caused by sedimentation of hydroelectric dams, and pollution of municipal water reservoirs, and ponds. This sedimentation adversely impacts the storage capacity of water reservoirs, consequently diminishing agricultural productivity due to a decrease in the availability of irrigation water (Mekonnen et al., 2017).

2.4. ISFM a solution for sustainable agriculture approach

2.4.1. Integrated soil fertility management practices

The application of technological innovations is believed to increase agricultural productivity, for example, the Green Revolution (CSA 2019), the introduction of integrated soil fertility management practices (Teklewold et al., 2013), and favorable policy environments (Niragira, 2016). Sustainable agriculture can be described as farming methods that employ minimal chemical inputs, locally accessible resources, and farmers' knowledge, and skills to increase production, strengthen local systems' resilience, maintain the environment's quality, and increase household food security (Kaczan et al., 2013, Hamid Reza et al., 2014, Khatri-Chhetri et al., 2016, krall, 2015, Hobbs and Powell, 2011).

Integrated Soil Fertility Management (ISFM) practices is defined as: “A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions to maximize the agronomic use efficiency of the applied nutrients and improve crop productivity” (Roobroeck et al., 2015). ISFM practices focus on techniques and procedures that increase soil productivity while reducing negative effects on the environment, including the soil, water, air, biodiversity, and climate (krall, 2015). The general objectives of ISFM practices are to ensure environmental sustainability through enhancing farm productivity (Piñeiro et al., 2020).

ISFM practices encompass a range of strategies such as crop rotation, intercropping with legumes, conservation tillage, retention of crop residues, adoption of improved crop varieties, the complementary application of organic fertilizers, and the implementation of soil and stone bunds to conserve soil and water resources (Manda et al., 2016, Branca et al., 2011), irrigation, agroforestry systems, integrated pest management, biological controls, improved livestock breeds (Figure 2) (FAO, 2013). The sustainable use of agricultural practices is an important issue for SSA development policy agenda, especially as a way to tackle land degradation, boost agricultural productivity, and eradicate poverty. Allocating resources to agricultural research and extension programs is a fundamental factor in elevating agricultural productivity and enhancing food security (Teklewold et al., 2013).

The productivity of agriculture relies on accessibility and the use of better agricultural technologies and practices. The government of Ethiopia has given priority to agricultural development, productivity and natural resource management (Sime and Aune, 2018).

Although ISFM approaches offer many advantages, they are not widely used in Ethiopia (Teklewold et al., 2013). The eradication of hunger and poverty in Ethiopia depends on investments in ISFM techniques that boost and sustain agricultural productivity.

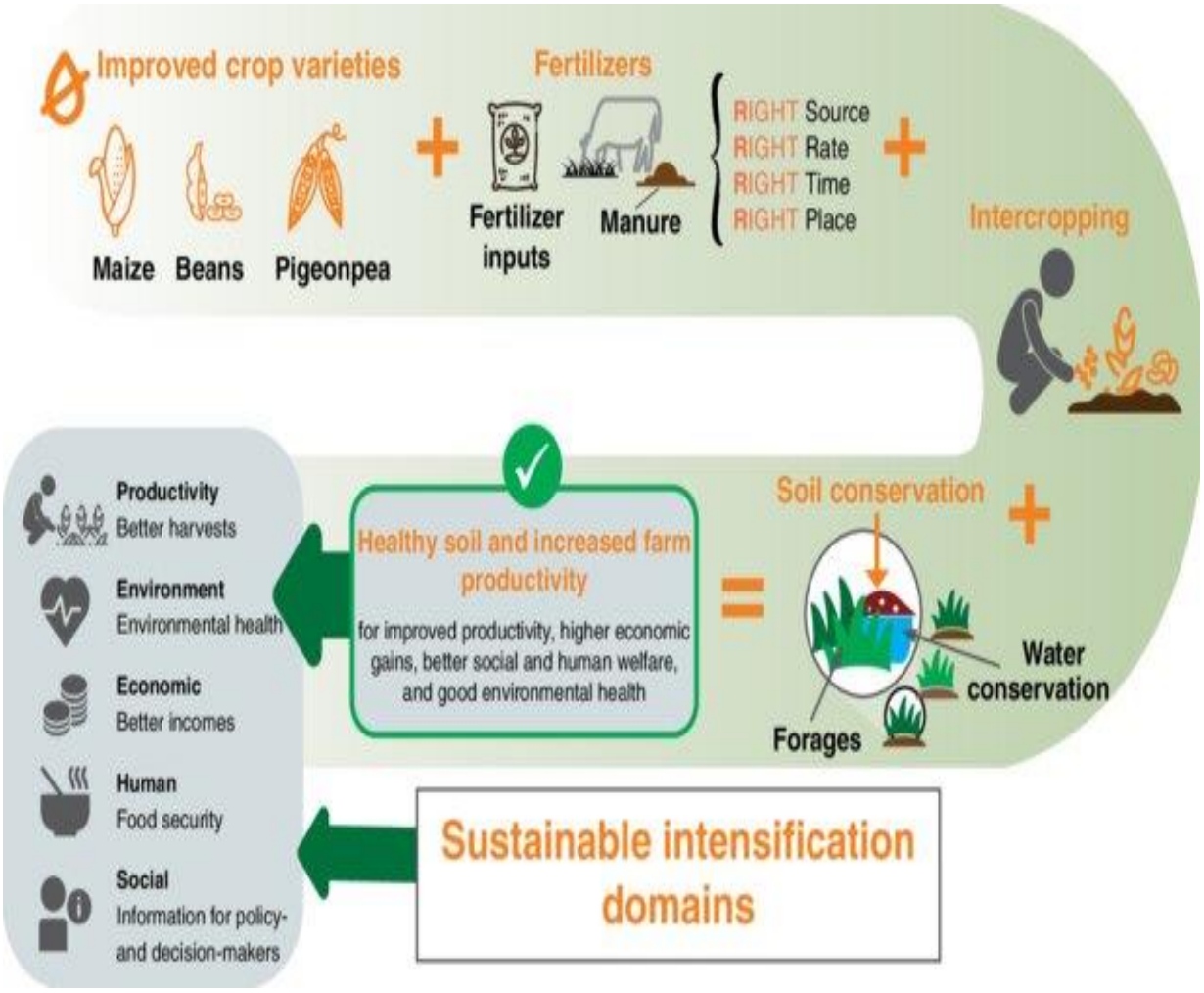


Figure 2. ISFM: combining different soil fertility management practices for sustainable farming systems. Adapted from: (Kizito et al., 2016)

2.4.1.1. Combined use of organic with inorganic fertilizers

When there is significant nutrient depletion and turnover in the soil-plant system, neither organic manure nor chemical fertilizers alone can achieve sustainable yields across different cropping systems. Continuous use of inorganic fertilizers reduces soil quality (Agegnehu et al., 2014). To tackle this problem, the combined use of organic manure and inorganic fertilizers can enhance grain yield and soil properties without imposing environmental costs (Iqbal et al., 2019).

Integrated nutrient management entails reducing the reliance on synthetic fertilizers by integrating them with organic materials such as animal manure, crop residues, green manure, and composts (Selim and Al Jawhara, 2017, Khoshgoftarmanesh et al., 2010).

It has a significant role in improving soil properties (Tehulie and Tola, 2020, Bolan et al., 2013), enhancing nutrient-use efficiency, decreasing nutrient loss, minimizing the crop nutrient requirement, and increasing the Cation exchange capacity, water storage capacity, and service in sustaining higher yield (Figure 3). For instance, in Kenya, the combination of inorganic inputs with mineral fertilizers led to an increase in both maize yield and profitability, as demonstrated in an on-station experiment (Mucheru-Muna et al., 2014).

Similarly, (Chivenge et al., 2011) also reported that utilizing a combination of both inorganic and organic fertilizers resulted in a maize yield boost of 60% to 114% compared to exclusively using either inorganic or organic sources. Therefore, it is crucial to employ both organic and inorganic fertilizers together to combat soil fertility loss, sustainably boost crop yields and sustain soil Productivity (Zelleke et al., 2019, Agegnehu and Amede, 2017, Meresa et al., 2016).

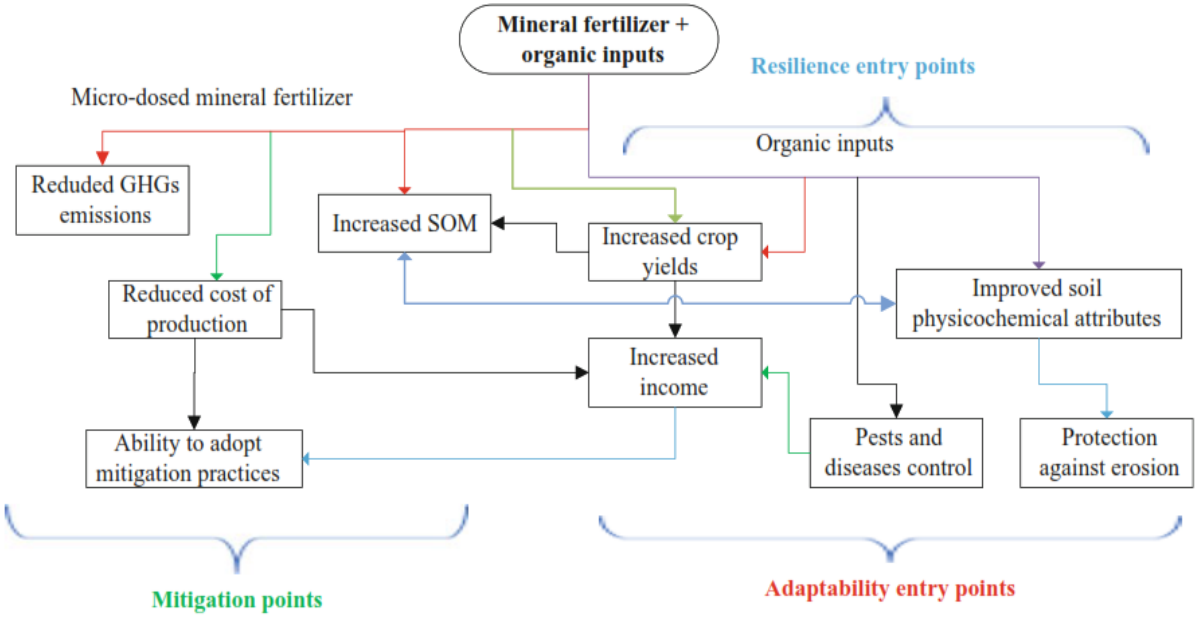


Figure 3: Conceptualized relationship between mineral fertilizer and organic input integration and productivity, adaptation, and mitigation (Mugwe and Otieno, 2020)

2.4.1.2. Intercropping

Different types of ISFM approaches are adopted in various countries. Intercropping is one of ISFM practices widely used in Botswana, Kenya, Nigeria, Ghana, Egypt and South Africa. Cultivation of two or more crop species concurrently as they coexist for a significant part of the crop cycle is known as intercropping (Anil et al., 1998). Intercropping adds value to the cropping system by potentially boosting income, ensuring higher productivity, and optimizing resource utilization (Maitra et al., 2021, Manasa et al., 2018).

Intercropping systems, have developed in response to increasing land pressure and agro-climatic risks in Ethiopia (Mekonnen et al., 2020). The natural relationship to common agro-ecological adaptations of partner crops determines the intercrops' selection (Fikre, 2016). A cereal-legume intercropping is commonly practiced in Ethiopia (Kebebew et al., 2014). It is one strategy to increase crop diversity and productivity while enhancing the food security of smallholder farmers (De Jager et al., 2019). It can also increase soil water use efficiency and reduce evaporation from the soil which increases the diversity of the farming system (Huss et al., 2022).

Research confirmed that intercropping significantly increases grain yield. For instance, intercrops with maize in China had greater yield gains than intercrops without maize (Li et al., 2020), intercropping maize-cowpea, in Egypt (Alla et al., 2015), maize-soya bean in Ethiopia (Kebebew et al., 2014), sorghum-cowpea in Ethiopia (Sibhatu et al., 2015), provided greater yield.

Similarly, studies showed that farmers who used cereal-legume intercropping had yields that were 70% higher than those who used either sole wheat or faba bean (Latati et al., 2016). In addition, it helps to maximize the use of available resources and space. For example, the finding of (Ayele, 2020) reported that the land equivalent ratio (LER) for maize and lablab grain yield was 1.7, whereas intercropping maize with cowpea yielded a LER of 1.9. The benefits of incorporating legumes into the cropping system can be attributed to various factors, including direct nitrogen transfer, residual fixed nitrogen, improved nutrient availability and uptake, positive effects on soil properties, disruption of pests' life cycles, and the promotion of other soil microbial activities. To maximize these advantages, integrating legumes into cropping systems is essential (Kebede, 2021).

The presence of N_2-fixing legumes in intercrops could also solve the problem of N fertilization (Salinas-Roco et al., 2024). This enhanced N-retention could even be accompanied by a greater potential for carbon sequestration in soils (Cong et al., 2015). Furthermore, micronutrient malnutrition, also called the 'hidden hunger', is one of the failings of the Green Revolution (Pingali, 2012), a problem to which many regions of the world are still susceptible (McGuire, 2015), particularly under ongoing atmospheric change. Hence, natural bio fortification of food products through the mobilization of P, Fe and Zn by cereals in intercrops is another example where intercropping could be of great utility (Xue et al., 2016).

All of this suggests multiple win-win trade-offs between productivity and ecosystem services (Iverson et al., 2014), but much effort is still required to determine which other services are improved by intercropping (Brooker et al., 2015). Intercropping has also been observed to inhibit weed growth, decrease pest or disease prevalence, mitigate the risks associated with drought and secure food (Kuwornu and Owusu, 2012).

Generally, intercropping reduces the likelihood of crop failure, provides a way to diversify the products produced with a higher combined yield, and contributes to soil and water conservation. Hence, in countries like Ethiopia, where fragmented landholding and subsistence farming are dominant in cropping regions, cereal legume intercropping has many benefits to exploit (Belachew et al., 2022).

2.4.1.3. Application of compost

The continual use of mineral fertilizers results in the degradation of soil, affecting its chemical, physical, and biological attributes, as well as overall soil health (Bhatt et al., 2019). The adverse effects of chemical fertilizers have spurred increased interest in utilizing organic fertilizers as a nutrient source (Abebe et al., 2022). Organic matter plays several crucial roles in soil, including enhancing its physical structure, serving as a medium for biological activity, and contributing significantly to soil productivity. It also supplies nutrients to the soil, enhances its water retention capacity, and contributes to maintaining optimal soil structure, improving aeration for the germination of seeds and the development of plant roots (Edwards and Hailu, 2011). The use of organic fertilizers is also known for its capacity to improve crop growth by supplying essential plant nutrients, including micronutrients thus fostering a more conducive environment

for root development through enhancements in soil structure (Mengistu and Mekonnen, 2011). Among the available organic fertilizers, the benefits of compost and vermicompost will be discussed below.

Compost

It can be made using locally available materials, like grass clippings, leaves, weeds, vegetable peels, and animal dung (Waitt and Rankin, 2022). It supplies essential nutrients and improves soil quality and benefits soil fauna and flora (Cerda et al., 2018). It is an important source of nutrients, to manage soil fertility for small holder farmers. The utilization of composts led to a decrease in soil pH, an augmentation of soil organic carbon, an elevation in soil Cation exchange capacity, an increase in available phosphorus concentration, an enhancement of macroaggregate stability, and raised availability of nitrogen (Duong, 2013). According to (Roghanian et al., 2012), following the application of compost, there was a notable increase in the availability of nitrogen (N), phosphorus (P), potassium (K), along with increased concentrations of micronutrients and heavy metals in the soil as shown on Table 2.

Table 2: The effects of compost on selected soil properties (Roghanian et al., 2012)

					Available (mg Kg^{-1})			
	pH	EC (dsm^{-1})	OC (%)	N (%)	P	K	Fe	Mn
Control	6.83^{a}	0.9^{d}	0.16^{d}	0.05^{c}	14^{d}	111^{d}	2.2^{d}	2.3^{c}
15	6.89^{a}	1.2^{c}	0.24^{c}	0.06^{bc}	33^{c}	123^{c}	2.4^{c}	2.4^{c}
30	6.71^{a}	0.43^{b}	0.43^{b}	0.07^{ab}	53^{b}	143^{b}	2.5^{b}	2.5^{b}
60	6.94^{a}	0.65^{a}	0.65^{a}	0.08^{a}	69^{a}	192^{a}	2.7^{a}	2.7^{a}

Means with common letters do not exhibit statistically significant differences at $p< 0.05$

However, compost contains less amount of nutrients compared to chemical fertilizers and releases the nutrients slowly; it doesn't provide all the NPK nutrients which are highly required by crops unless applied in very large amounts (Goldan et al., 2023).

Moreover, the prices of inorganic fertilizers are on the rise, rendering them unaffordable for smallholder farmers with limited resources. The most efficient approach to achieve cost-effectiveness and effectively manage soil fertility involves utilizing a combination of both mineral and organic fertilizers.

Mineral fertilizers supply essential nutrients, while organic fertilizers primarily enhance soil organic matter, improve soil structure, and enhance buffering capacity (Hammad et al., 2020). Research findings also indicated that sustainable productivity cannot be achieved through the use of either mineral fertilizers or organic sources alone (Alzamel et al., 2022, Godara et al., 2012). According to (Bekele et al., 2018) the optimal economic strategy for improving nutrient availability for maize in strongly acidic soils in Ethiopia involves the combined application of 2.5 t ha^{-1} of VC and 20 kg ha^{-1} of chemical P, along with 4 t ha^{-1} of lime. This approach has been found to enhance both grain yield and yield components of maize plants.

Similarly, (Hadis et al., 2018) indicated that the joint use of vermicompost and NPK fertilizers has significantly boosted nutrient uptake, as well as improved yield and various yield components in wheat. Consequently, researchers recommend the combined application of organic and inorganic fertilizers as an effective approach to increase crop yield and enhance soil productivity in a sustainable manner (Agegnehu et al., 2016, Baghdadi et al., 2018).

Vermicompost

Vermicomposting is the practice of employing vermi-worms to convert organic materials into a humus-like substance referred to as vermicompost. It is, essentially the excrement of earthworms, possesses the ability to enhance soil health and nutrient levels (Adhikary, 2012). VC is a stabilized, finely divided organic fertilizer known for its low C: N ratio, exceptional porosity, and high water-holding capacity. Most of its nutrients exist in readily available forms for plants (Tilahun et al., 2013).

A number of researches proved that VC can enhance soil fertility physically, chemically and biologically. Physically, VC-treated soil has better aeration, porosity, bulk density and water retention. Chemical properties such as pH, electrical conductivity and organic matter content are also improved for better crop yield (Lim et al., 2015), reduce exchangeable acidity in acidic

soils, promoting the release of plant nutrients (Agegnehu et al., 2016), enhance soil aggregation, strengthens its structure and fertility, promotes an increase in microbial diversity and populations, and improves the soil's water-holding capacity (Pathma and Sakthivel, 2012). Furthermore, it can be employed to raise the pH levels in acidic soils and alleviate the toxicity of aluminum (Al) and manganese (Mn) under its alkaline nature (Nada et al., 2011).

Furthermore, VC enhances the provision of readily assimilable nutrients, including micronutrients, to plants, in addition to mobilizing previously inaccessible nutrients into forms that are now available for uptake (Amanolahi-Baharvand et al., 2014). Research also demonstrated that applying VC at a rate of 6 t ha^{-1} resulted in the highest nutrient uptake. This application increased grain uptake of nitrogen, phosphorus, and potassium by 51%, 110%, and 89% respectively, compared to the control (Hadis et al., 2018).

VC also accelerates plant growth. The findings of (Sinha et al., 2010) indicated that VC can boost growth by 50% to 100% compared to conventional compost and by 30% to 40% when compared to chemical fertilizers to conventional compost. Another study of (Kenea and Gedamu, 2018) also reported that the highest total garlic bulb yield, 12.9 t ha^{-1}, was achieved with the application of 7.5 t ha^{-1} of VC and 130 Kg ha^{-1} of mineral fertilizer resulted in a yield of 12.69 t ha^{-1}.

2.5. Effects of ISFM

2.5.1. Effect of ISFM practices on crop yields

Low crop yields are a common problem in most African countries (Ngwira et al., 2012). Approximately 30% of the population continues to experience food insecurity, with over 60% live in rural areas of Sub-Saharan African countries (McGuire, 2015). Food insecurity and poverty largely stem from low agricultural productivity, a consequence of limited utilization of enhanced inputs in rain-fed systems and heavy dependence on subsistence farming (Norton et al., 2021). ISFM practices hold promise as a potential solution to address certain issues by enhancing soil fertility, decreasing land degradation, increasing crop yields and incomes, enhancing soil organic matter, and supporting natural resources (Manda et al., 2016, Teklewold et al., 2013, Zeweld et al., 2020, Hobbs and Powell, 2011). They safeguard the ecosystem through more effective use of natural resources and improved ability to adapt to climate change

and climate variability, which is very favorable for the environment (Wheaton and Kulshreshtha, 2017).

Five key characteristics of sustainable agriculture include resource conservation, environmental protection, technical suitability, economic viability, and social acceptability (Zoveda et al., 2014). Sustainable agriculture has the potential to contribution to several of the United Nations Sustainable Development Goals for 2030, including those relating to poverty (SDG 1), hunger (SDG 2), decent work and economic growth (SDG 8), reducing inequalities (SDG 9), responsible consumption and production (SDG 12), climate action (SDG 13), and life on land (SDG 15) (Piñeiro et al., 2020). Additionally, ISFM practices enable sustainable agriculture, which would help to reduce poverty and increase food security by achieving more resilient and productive agricultural systems (Teklewold et al., 2013, Zeweld et al., 2020).

For example, the Cambodian ministry of agriculture reported that the "system of rice intensification," a novel method of producing rice, has helped farmers improve yields from an average of 2.5 tons per hectare to 3.7 tons per hectare while using less water and agrochemicals (Hobbs and Powell, 2011). Similar to this, a five-year study in the central highlands of Ethiopia reported that combining a half dose of inorganic fertilizer and a half dose of organic fertilizer consistently provided higher yields than treatments that used a full dose of either inorganic or organic fertilizer alone (Bedada et al., 2012). Key benefits of these technologies are increasing productivity, and income and solving pest challenges (Asfaw et al., 2012, Kassie et al., 2013, Manda et al., 2016, Negassa and Sileshi, 2018).

2.5.2. ISFM practices in Ethiopia

Agriculture comprises nearly 46% of the GDP, 73% of labor employment and 80% of foreign export earnings in Ethiopia (Degaga and Angasu, 2017). Unsustainable land use practices, a lack of proper plant nutrition, the depletion of organic matter in the soil, and soil erosion have all damaged this sector. The finding of (Wolde, 2016) indicated that soil loss due to erosion in the Ethiopian highlands is between 42 and 175.5 t ha^{-1} $year^{-1}$. Other studies on crop fields have also confirmed that declining soil fertility and limited water availability resulted in low crop yields in Ethiopian highlands (Laekemariam et al., 2016, Teklu et al., 2018). There is also a high rate of population growth. Extensive farming is becoming unattainable due to the high

demand for food and limited opportunities for area expansion (Agazhi, 2016) cited in (Neda, 2020). Therefore, it is imperative to prioritize agricultural research and technological advancements to enhance agricultural productivity, meet food demands, and consequently alleviate poverty (Asfaw et al., 2012).

Through the national agricultural extension system and different technology scaling programs, smallholder farmers have access to a variety of improved varieties and legume technologies (Kassa et al., 2017). Accelerating agricultural growth which mainly comprises strengthening legumes production and contributing to better food security and more sustainable and profitable farming systems remains one of the most urgent goals in Ethiopia. ISFM practice is part of the nationwide 'Soil Health and Fertility Improvement Strategy,' aimed at boosting soil fertility, productivity, and rural livelihoods in a sustainable manner (MoANR, 2017).

Various ISFM practices are implemented across different regions of Ethiopia, including the utilization of organic fertilizers, the production of compost with effective microorganisms, vermicomposting and bio-slurry, adoption of technologies like bio-fertilizers, intercropping of major cereal crops with legumes, and the implementation of small-scale mechanization for minimal tillage (Leta et al., 2020). Research findings showed the advantage of implementing ISFM approaches in different regions of the country. For example, the finding of (Sibhatu et al., 2015) showed that the land equivalent ratio and gross monetary value of sorghum-cowpea intercropping were more advantageous over sole cropping in Kobo, Northern region of Ethiopia, (Kebebew et al., 2014) also reported that the gross monetary value of intercrops was greater by 41.05% over sole cropped maize in Bench-Maji zone, and the highest yield advantage of 71%, with a net benefit of 24,320 Ethiopian birr ha^{-1} was obtained in cassava/maize intercropping in the south region of Ethiopia. Similarly (Ejigu et al., 2021) reported that plots that received 10 t ha^{-1} of compost and 100/100 kg ha^{-1} of urea/NPSB recorded the highest maize dry biomass at 18.62 t ha^{-1} and the highest grain yield at 6.07 t ha^{-1}.

Application of organic fertilizers either alone or in combination with chemical fertilizers is also one of ISFM practices in Ethiopia. Organic fertilizers (compost, manures, biochar, and vermicompost) application in adequate amounts and right time either in sole or combined with chemical fertilizers has the potential to serve as an effective strategy for managing nutrients and enhancing yields (Bedada et al., 2014, Agegnehu et al., 2016a), enhance soil fertility by

augmenting nutrient levels, increasing Cation exchange capacity, raising pH levels, and decreasing soil bulk density (Asaye et al., 2022, Wang et al., 2017) and improving soil structure and the formation of soil aggregates, by forming a conducive environment for root growth (Zhou et al., 2019).

2.5.3. Adoption challenges of ISFMs practices

Adopting agricultural technologies to boost productivity is an essential approach to increase production. Agricultural growth and development are not possible without yield-enhancing technological options. Research and adoption of technological improvements are crucial to increasing agricultural productivity and reducing poverty while sustaining the agro-ecosystems that support livelihoods (Kassie et al., 2011). Sustainable agriculture achieves the dual objectives of enhancing crop production and income while also adapting to climate change and mitigating greenhouse gas emissions. It accomplishes this by maintaining a balance among crop, livestock, fisheries, and agroforestry systems and by improving resource utilization efficiency, protecting the environment and maintaining ecosystem services.

Maximizing productivity to ensure food security while staying within the planet's safe environmental limitations is the aim of sustainable food production systems (Beddington et al., 2012). To enhance agricultural productivity, mitigate disaster risks, boost yields, and foster economic development, governments in Sub-Saharan African countries such as Ethiopia have prioritized the implementation of enhanced technologies and the adoption of sustainable agricultural practices. However, the general adoption and practice of sustainable agriculture and technologies remain below expectations.

This can be attributed primarily to factors such as the characteristics of household and village resources, institutional variables, socio-psychological factors, the availability of labor, knowledge, and the level of education, as well as infrastructure services (Abera et al., 2020b, Aweke, 2017), the shortage of funds, along with policy limitations, represents further essential aspects to consider (Ogato, 2014, Jaleta et al., 2016).

In addition, lack of available information for farmers, economic limits, social factors, farmers' characteristics, attributes of sustainable practices, and infrastructure conditions are also some of the barriers to adoption and practice of ISFM approaches (Serebrennikov et al., 2020). Efforts

to promote the widespread adoption of ISFM practices by smallholder farmers should focus on enhancing farmers' access to agricultural loans and off-farm income, through increased integration into the non-farm rural economy and addressing liquidity constraints through affordable rural financing schemes (Mutyasira et al., 2018). The adoption of ISFM can further be enhanced by raising farmers' general awareness and knowledge to change their perceptions and attitudes towards sustainable farming practices.

2.6. Integrated soil fertility management practices and climate change

Agriculture stands as a significant contributor to greenhouse gas emissions, stemming from livestock husbandry (related to enteric fermentation and manure management) and emissions originating from agricultural soils (resulting from the excessive use of nitrogen-based fertilizers and the breakdown of organic materials, Figure 4). As a global average, agriculture contributes to around 14% of the total greenhouse gas emissions (Parry, 2007). Inadequate land management, excessive cultivation, overgrazing, deforestation, peatland drainage, and rainforest burning are some of the contributing factors.

Agriculture is both a contributor and a potential solution for the effects of climate change. ISFM practices offer different benefits to mitigate GHG emissions from agricultural systems. Agricultural soils have the potential to sequester substantial amounts of carbon from the atmosphere and retain it in the soil, consequently mitigating emissions of CH_4 and CO_2 (Gaskell et al., 2007).

Organic inputs applied over an extended period of time reduce soil respiration, which lowers CO_2 emissions (Sun et al., 2019). These inputs prove soil resilience to climate change. Further, granulation of mineral fertilizers with nitrification inhibitors will ensure reduced N_2O emissions. Greater recovery of N fertilizers by crops, and retention of nitrate in soils, are two of the most important indicators for reduced emissions of nitrogen oxides in tropical farming systems (Hickman et al., 2011). This has the potential to mitigate the adverse impacts of climate change on agricultural yields at a comparatively lower cost (Mugwe and Otieno, 2020).

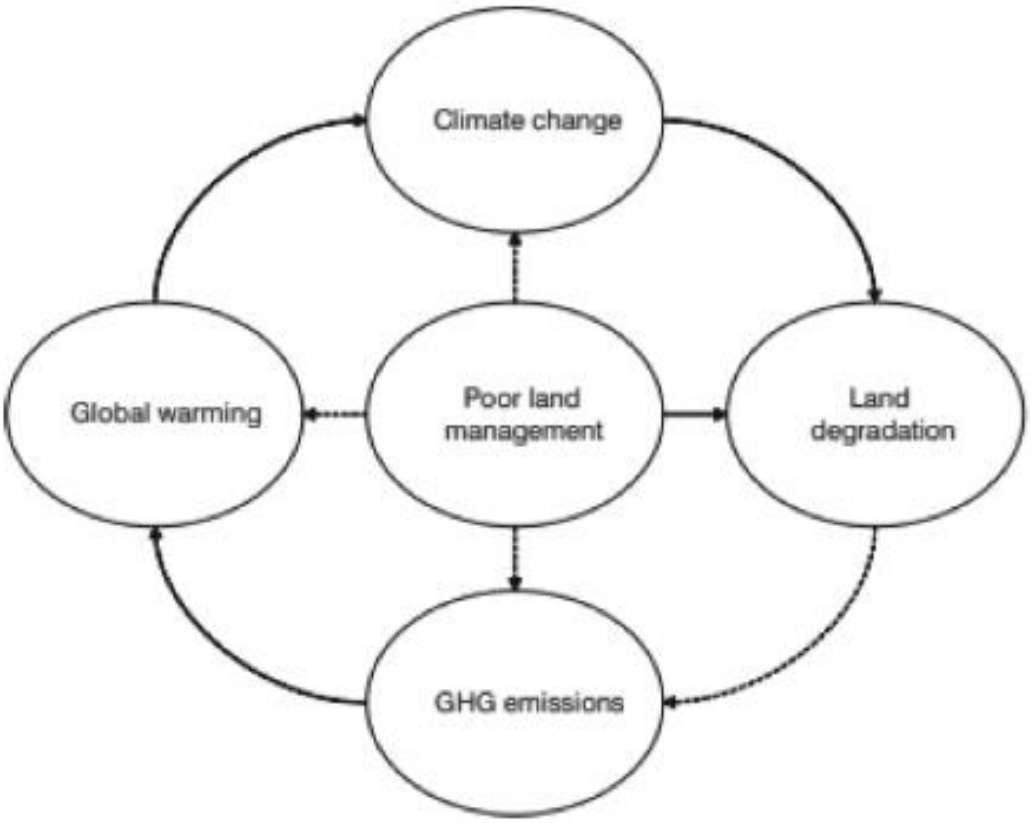


Figure 4: The link between climate change and soil management; Adapted from (Bayu, 2020)

2.7. Nutrient balance as an indicator of sustainable soil management

2.7.1. Soil nutrient balance

Securing food for the growing global population is intimately tied to the health and productivity of soils. Soil degradation and a decline in soil qualities, is becoming a universal ecological problem. SSA countries' soils are characterized by widespread negative nutrient balance and low productivity (Chianu et al., 2012). Despite the shallowness, extensive weathering, and minimal fertilizer content of these soils, they are cultivated intensively in these areas. The depletion of nutrient stocks is primarily attributed to various factors, including accelerated erosion, suboptimal agronomic practices, a decrease in soil's organic carbon, depletion of soil fertility, uneven nutrient levels, acidification, and salinization (Gedamu, 2020). Numerous strategies might be justified to reduce these issues.

To begin implementing viable management alternatives, it is essential to determine the soil's fertility level under the current system of management practice. The assessment of soil fertility decline can be accomplished through various methods, including professional experience, long-term monitoring of soil chemical properties (chronosequences), or at different locations (bio-sequences). Among these methods, calculating nutrient balances stands out as one of the most commonly employed and cost-efficient techniques (Cobo et al., 2010).

The nutrient balance for 35 sub-Saharan African (SSA) countries was calculated, highlighting the severe impact of nutrient depletion on future food production (Stoorvogel and Smaling 1990) and (Joost et al., 2015). Nutrient inputs and outputs of agricultural systems are measured by the nutrient balance. Positive balances would mean more nutrient additions into the system than losses.

A nutrient deficit (negative value) is an indication of more losses than gains which results to declining soil fertility and unsustainability of a farming system (Onwonga et al., 2015). When determining the need for fertilizer or the sustainability of the land use system, nutrient balances shouldn't be employed without taking soil nutrient stocks into account (Bahr et al., 2015).

2.7.2. Farm level nutrient balance in Ethiopia

Different studies were conducted to estimate the nutrient status of certain areas in Ethiopia. For example, "Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia" (Elias et al., 1998b), "Estimating soil nutrient balance of cereal lands of Tigray region, northern Ethiopia" (Assefa, 2014), "Soil nutrient balances under diverse agro-ecological settings in Ethiopia" (Van Beek et al., 2016), "Nutrient balance in Kecha and Laguna micro watersheds, Amhara Region, Northwestern, Ethiopia" (Lewoyehu et al., 2020), "nutrient balance of Farming Systems in Tigray, Northern Ethiopia" (Gebresamuel et al., 2021, Mesfin et al., 2021), and "The effects of land management on soil fertility, and Nutrient balances in smallholder farms in Northern Ethiopia" (Mesfin et al., 2021). The findings of all these studies showed that soil nutrient depletion proceeds at an alarming rate.

A study in Tigray, Northern Ethiopia (Gebresamuel et al., 2021) revealed that, on average, the nitrogen, phosphorus, and potassium balances in the highlands were -30.8 kg ha^{-1}, 4.08 kg ha^{-1},

and -42.75 kg ha^{-1}, respectively. Conversely, in the lowlands, the average nutrient balance stood at -19.5 kg ha^{-1} for nitrogen, 2.09 kg ha^{-1} for phosphorus, and -15.35 kg ha^{-1} for potassium. Likewise, a farm-level study in Northern Ethiopia in smallholder farms showed varied results.

Full nutrient balances, were -26.2 kg ha^{-1}, 6.7 kg ha^{-1}, and 2.9 kg ha^{-1} in Alaje, and -17.9 kg ha^{-1}, 11.1 kg ha^{-1}, and -5.3 kg ha^{-1} in Raya Azebo for nitrogen, phosphorus, and potassium, respectively (Mesfin et al., 2021). These results have substantiated the existence of variations in soil nutrient balances among socio-economic groups in different parts of northern Ethiopia.

Additionally, other studies have also validated the presence of such variability in soil nutrient balances among different socio-economic groups (Aticho et al., 2011, Assefa, 2014). The finding (Assefa, 2014) also reported that all macro nutrient balance for each zone of cereal lands of the northern region was negative. In a report by (Van Beek et al., 2016) the nutrient input flows and output flows were monitored over 3 years (2012–2014) stated that average nitrogen, phosphorus, and potassium balances were -23 ± 73, 9 ± 29 kg ha^{-1} and -7 ± 64 kg ha^{-1}, respectively across the high potential highlands of Ethiopia. This study has affirmed the presence of severe nitrogen depletion, with an average depletion rate of 0.2% of the soil's total nitrogen stock per year. This depletion rate is equivalent to 4.2% of the available soil nitrogen pool. All these findings confirmed that there is nutrient depletion in most regions of the country which needs immediate action to alter the situation and ensure sustainable agricultural productivity.

2.7.3. How ISFM improves nutrient balances

Integrated soil fertility management (ISFM) improves nutrient balances by combining the use of organic and inorganic fertilizers, improved crop varieties, and sustainable agricultural practices. ISFM can also help farmers in improving nutrient use efficiency (Bayu, 2020). The integration ensures that nutrients are supplied in a balanced manner, reducing deficiencies or excesses, which can harm soil health (Goda, 2019).

Practices like mulching, crop rotation, and cover cropping reduce nutrient leaching and erosion, keeping nutrients in the soil and available to plants (Mugwe and Otieno, 2020). Organic amendments improve soil structure, enhancing root development and nutrient uptake. This leads to better overall soil fertility and more balanced nutrient availability (Chen et al., 2018).

The use of both organic and inorganic fertilizers in ISFM creates a synergistic effect, where the strengths of each are enhanced, leading to improved nutrient use efficiency and better crop yields (Dunjana et al., 2023). By promoting sustainable nutrient management, ISFM improves the balance and availability of essential nutrients, contributing to long-term soil fertility and crop productivity.

2.7.4. Soil nutrient balance calculation

The augmentation of agricultural productivity and the enhancement of rural livelihoods are inextricably linked to investments in soil fertility. The constrained utilization of nutrient inputs places significant pressure on soil nutrient deficiencies among smallholder farmers. Nutrient imbalance, and application of fertilizers insufficiently or excessively can have a negative impact on yield and raise production costs (Abdulrahman et al., 2019).

The growing concern over soil nutrient depletion and low soil fertility has spurred the development of various integrated soil fertility management technologies in Africa. These innovations hold the promise of improving soil fertility across the continent (Mugwe et al., 2019). These approaches collectively contribute to addressing soil nutrient depletion and improving soil fertility in Africa. A popular method for determining soil nutrient balances was developed by (Stoorvogel and Smaling 1990). Such a fundamental technique was frequently used in later studies and adapted according to the objectives and area.

MonQI (formerly known as NUTMON) represents an integrated and multidisciplinary approach that engages various stakeholders in the management of natural resources, with a specific emphasis on soil nutrients. Through the MonQI methodology, farmers and researchers collaborate to assess the financial and environmental sustainability of farming systems. This approach promotes a holistic understanding of nutrient management, and its implications for agriculture and the environment.

The MonQI toolbox, which includes a handbook and supporting software, was created to integrate economic farm studies with nutrient stock and flow assessments. The MonQI approach distinguishes two phases: the diagnostic phase and the development phase. Both phases require a multidisciplinary approach and the integration of knowledge systems.

MonQI is the commonly used tool for the calculation of soil nutrient flow and balances (Cobo et al., 2010). It has found extensive application in numerous nutrient balance studies conducted in tropical farming systems (De Jager et al., 1998, van Beek et al., 2009, Van den Bosch et al., 1998). The fundamental approach to defining a soil nutrient balance involved utilizing a net balance of five inflows and five outflows (Figure 5).

The five inflows consisted of mineral fertilizer (IN1), organic inputs (IN2), atmospheric deposition (IN3), nitrogen fixation (IN4), and sedimentation (IN5), while the five outflows are crop products (OUT1), crop residues (OUT2), leaching (OUT3), gaseous losses (OUT4), and erosion (OUT5). The net balance was calculated by taking the difference between the sums of inflows and outflows. The use of NUTMON/MONQI at the farm level may provide a swift assessment of farmers' nutrient management techniques to assist nutrient use decisions (Abate et al., 2016).

The MonQI -toolbox is made up of four modules and two databases that combined make it easier to monitor nutrient levels in both individual farmers' fields and farms as a whole (Figure 6). The four modules consist of:

- A set of questionnaires that collects the required farm-specific information on, the farm environment, the farm household, soils and climate and management;
- A data entry module that facilitates entry of the data from the questionnaires into the computer;
- A background processing module that stores non-specific information on crops, crop residues, animals, inputs, and outputs;
- A data processing module that calculates nutrient flows, nutrient balances and economic indicators, based on the farm-specific data from the questionnaires and general data from the background database, using calculation rules and assumptions.

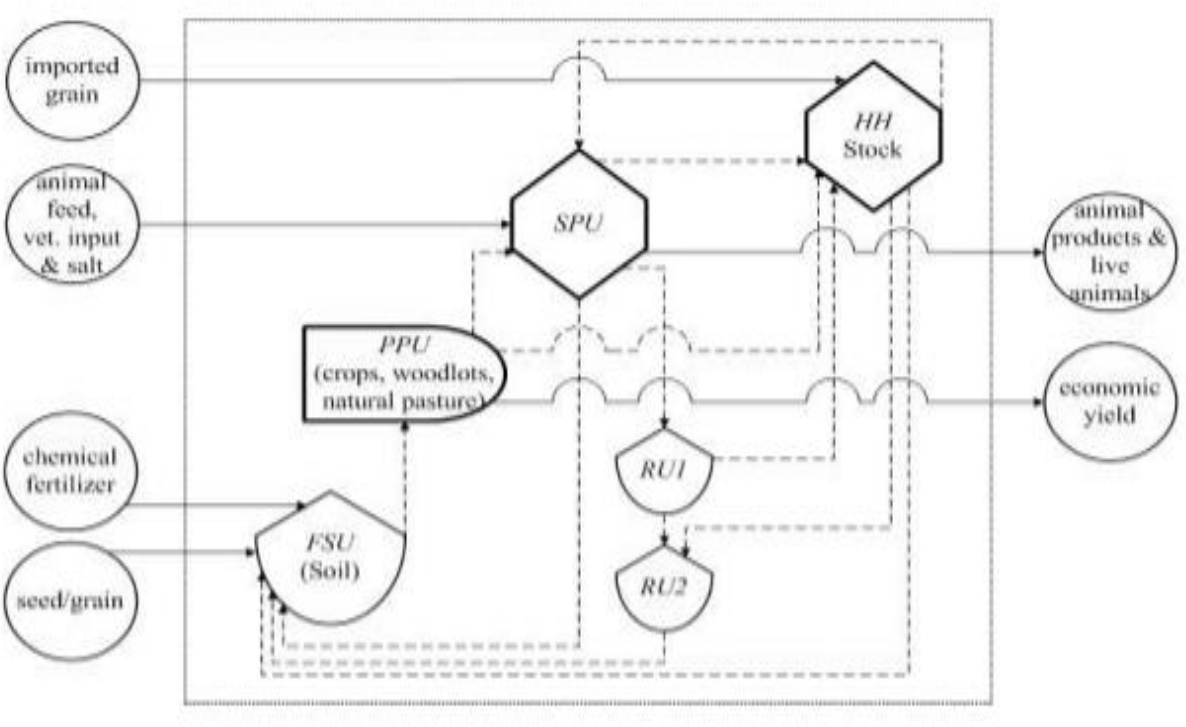


Figure 5 : Inflows and outflows over the farm; farm gate flows, (Solid lines) and farm scale internal flows (broken lines)(Assefa, 2005).

The two databases are:

- A background database, including information that is not specifically related to farming, such as data on crop and livestock parameters and calibration factors for local units of measurement
- A farm database, containing farm-specific information. Farm database that contains information on a set of farms that are part of a study (Abdulrahman et al., 2019).

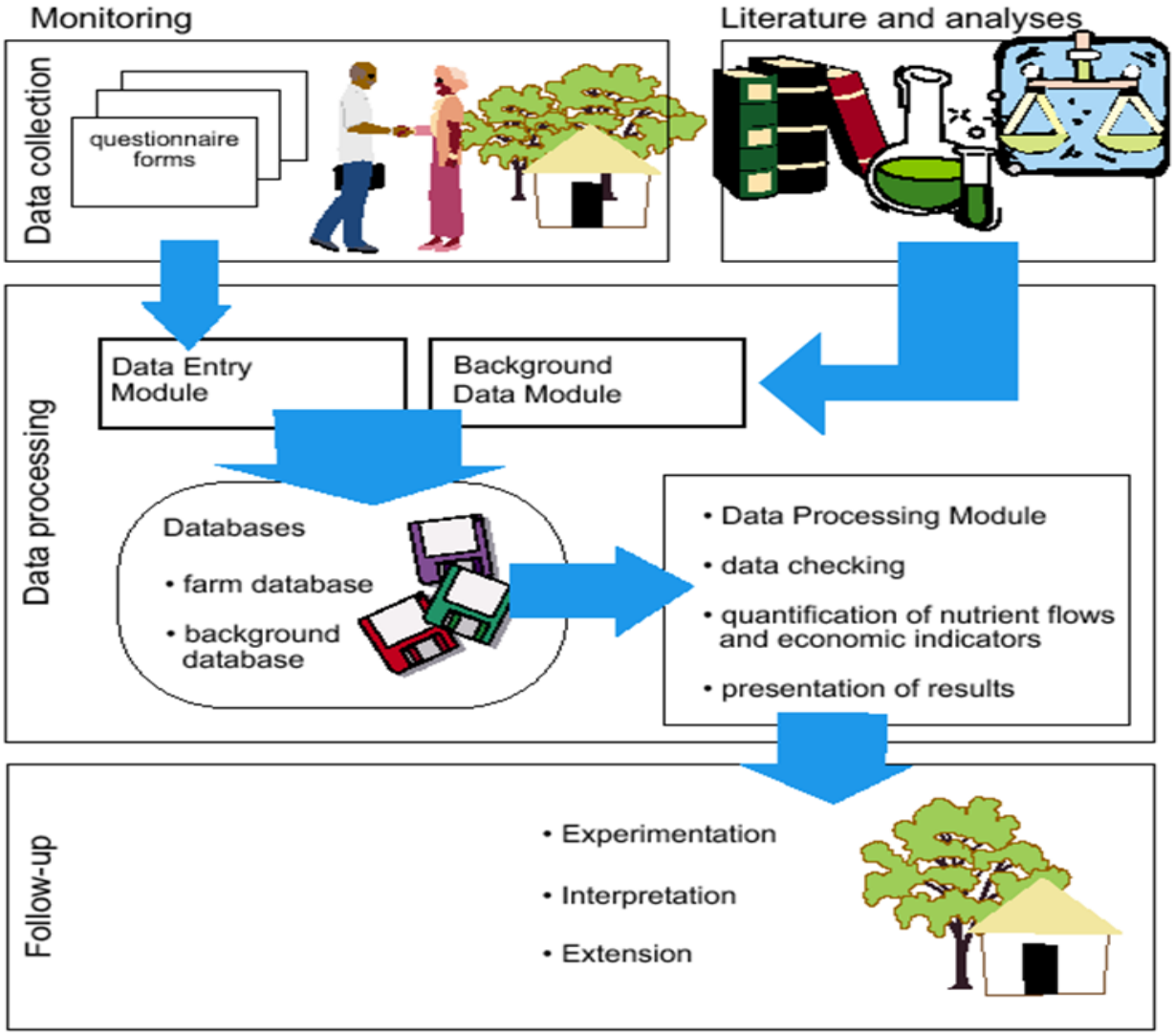


Figure 6: Flow chart of the steps procedure in MonQI (Joost et al., 2015)

2.7.5. Implications and uncertainties in soil nutrient balance calculations

Interpreting soil nutrient findings was closely tied to the scale of the study. These results played a crucial role in raising awareness about soil fertility concerns, pinpointing regions with nutrient depletion or accumulation, and laying the groundwork for identifying areas where soil fertility enhancement efforts are necessary. The MonQI -toolbox is a valuable tool that encompasses not only nutrient assessments but also incorporates a monetary component. The promotion of locally specific packages is a potential avenue for its application. Additionally, the interpretation of negative nutrient balances was closely linked to the assessment of nutrient

stocks (Surendran et al., 2005). Indeed, a negative nutrient balance on nutrient-rich soil may not immediately impact crop yield, whereas on nutrient-poor soil, it could lead to year-on-year yield declines due to nutrient depletion. As a result, nutrient depletion may not be immediately apparent but could pose significant challenges for future generations in terms of sustaining agricultural productivity and soil fertility. This underscores the importance of proactive soil management practices to prevent long-term soil fertility problems (Harden et al., 2018).

This study spans two years, and since nutrient balance is dynamic, it requires a model that accurately captures nutrient dynamics. The MonQI cannot simulate the long-term effects of farm management on soil fertility and productivity, as it does not account for nutrient dynamics over extended periods (van Beek et al., 2009). Although the model estimates nutrient flows and balances at the farm level and offers a genuine reflection of farmers' practices, it contains some uncertainty. The use of transfer functions has drawbacks due to an unknown level of uncertainty in the quantified flows. Additionally, the real losses from leaching are overestimated because some of the nitrogen leached into soil layers below 30 cm can still be available for plant growth.

Chapter Three

3. Materials and Methods

3.1. Description of the study areas

3.1.1. Location

Dire and Legedadi watersheds are located in Bereh Woreda, Oromia Regional State in Central Highland of Ethiopia (Figure 7). Legedadi and Dire are the two water reservoir sites located in the area that supply the bulk of drinking water for the Addis Ababa city inhabitants. Dire watershed is located 37 km North East of Addis Ababa city within the geographical bounds between 9°8.9″ to 9°13.7″N and 38°50″ to 38°57.9″E covering a total area of 7807 ha. Legedadi watershed on the other hand, is located 30 km East of Addis Ababa within the geographic bounds of 9°3′0″ to 9°13′30″N and 38°60′30″ to 39°02′30″ E, covering a total area of 20,318 ha. The altitude of the Legedadi watershed ranges from 2346 to 3216 m while the Dire watershed lies at the altitude ranges from 2491 to 3248 m.

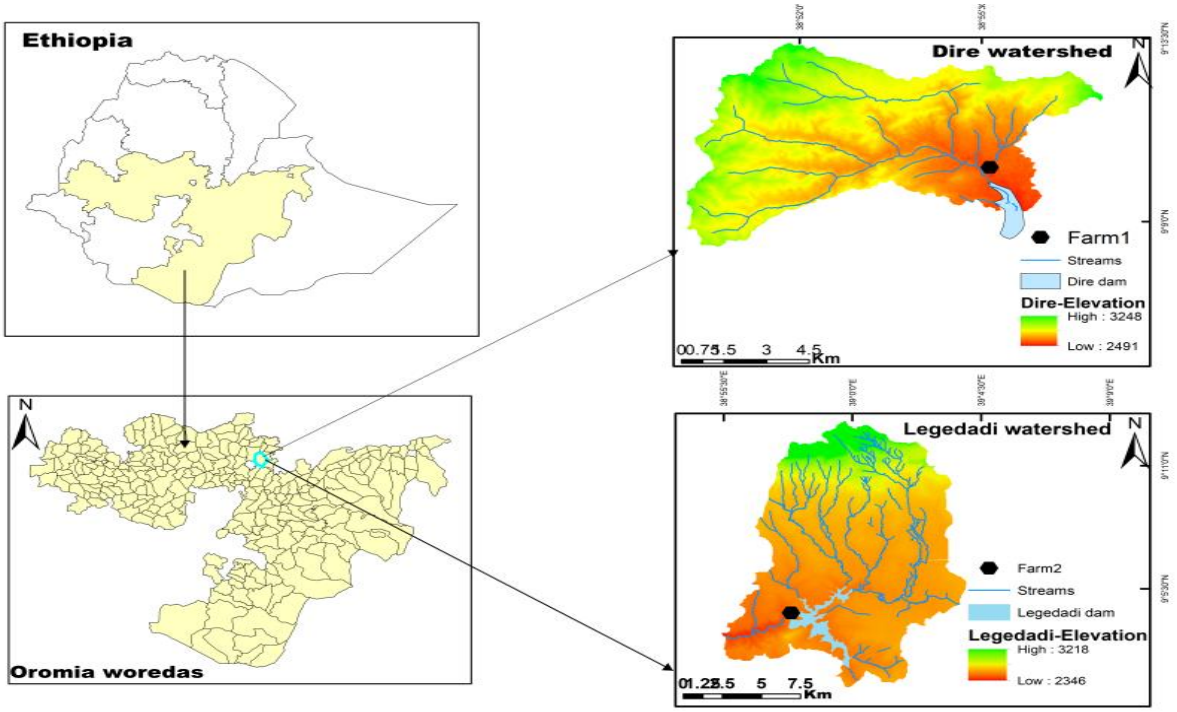


Figure 7: Map of the study areas-Dire and Legedadi watersheds

3.1.2. Geology and Climate

Geologically, the area falls in the Miocene-Pliocene and Middle Miocene periods. The geologic development ranges from late quaternary sediments to the relatively older pyroclastic basic rock. Colluvial deposits, residual soils, and river deposits are among the recent quaternary sediments. There are also pyroclastic rocks and simple lava flow exposures. Ignimbrite (welded buff), Tuff, volcanic ash, and Agglomeratic (pyroclastic) Basalt are among the pyroclastic rocks. The major rocks present in the study areas are conglomerate sandstone, siltstone with basalt, and sub alkaline Basalt with Rhyolite and Trachyte mixtures (Israel, 2011).

Both watersheds have moist Dega agro-climatic zones of Ethiopia, with long-term average rainfall (20 years of weather data from nearby stations) of 1,103 mm at Dire and 1,119 mm at Legedadi site (Figure 8). The mean annual maximum and minimum temperature of Dire watershed were 25.5^{o}C and 11.3^{o}C, respectively, while that of Legedadi was 25.5^{o}C and 16.1^{o}C, respectively. The rains fall during the main rainy season (June-October) with a monomodal peak in August. The study areas received more rain in July and August of 2021 and 2022 compared to the other months of the year.

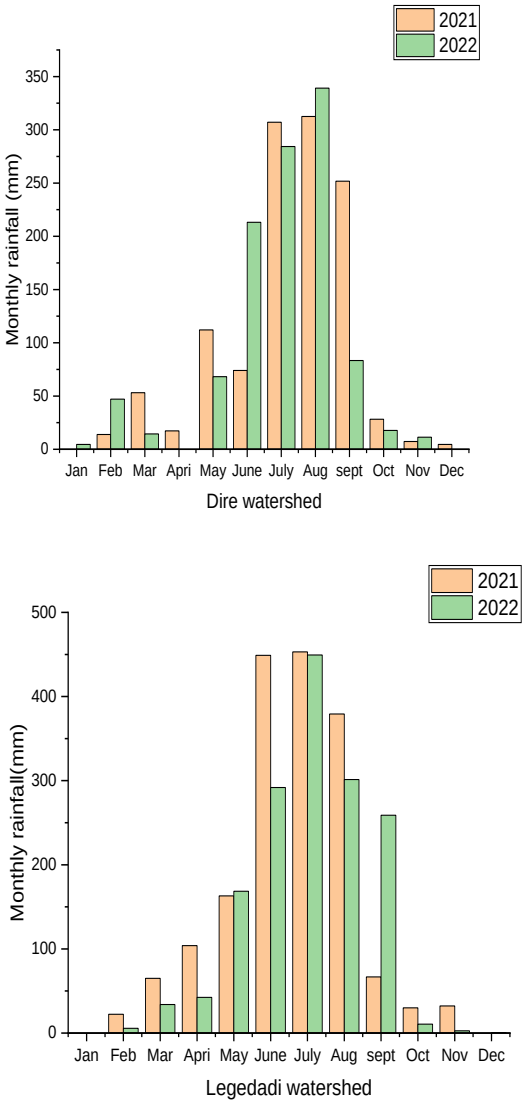


Figure 8: Monthly rainfall distribution at Dire and Legedadi site (data source: (NMSAE, 2021).

3.1.3. Soil types

The soil data for the study areas was obtained from Oromia Water Works Design, Construction, and Supervision Enterprise in a raster shape file format. The predominant soil types of the watersheds consist of Cambisol, Leptosol, Luvisol, and Vertisol (Figure 9). Vertisol and Leptosol are the most dominant soil in the study areas. In terms of landscape positions, Leptosol occupy extensive areas in the severely dissected high-relief mountains while Vertisol occupy the low-lying plains and foothills (OWWDCSE, 2015).

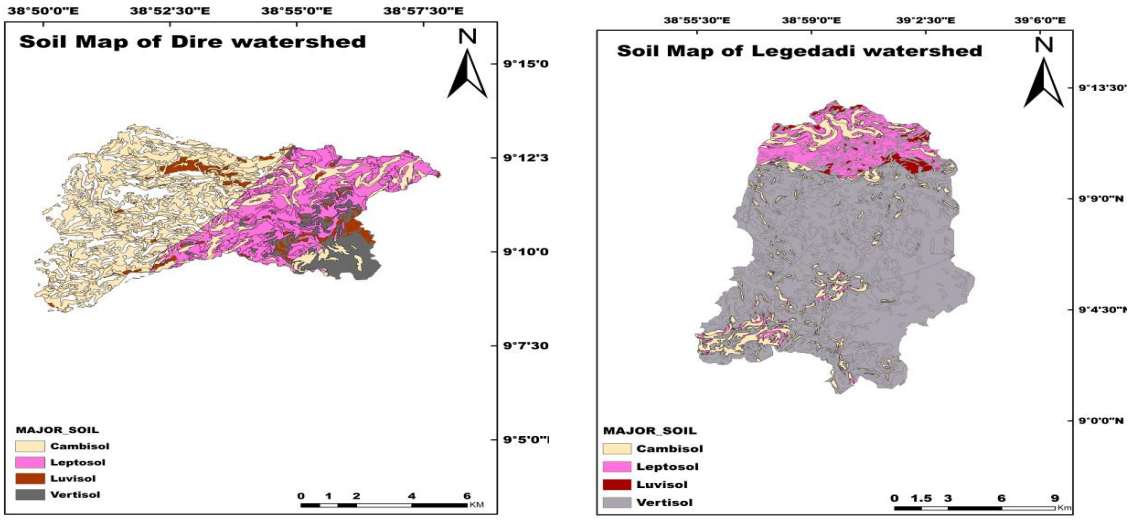


Figure 9: Soil type map of Dire and Legedadi watersheds (data source: OWWDCSE, 2015).

3.1.4. Land use types and Farming systems

The primary land use units within the study areas include settlements surrounded by Eucalyptus wood, cultivated land, Eucalyptus plantation, grassland, bare land, and water bodies. The farming system of the watershed is mixed farming with dominantly cereal crop production and livestock rearing. According to Bereh woreda Agriculture and Rural Development Office annual report of the year 2021, almost all cultivated lands in the areas are used for annual crop cultivation. Cultivation of annual crops is the predominant land use type accounting for 64% and 78% of the total area in the Legedadi and Dire watersheds (Awraris, 2017). The land use map of the study areas for the year 2015 are presented in the following figure (Figure 10).

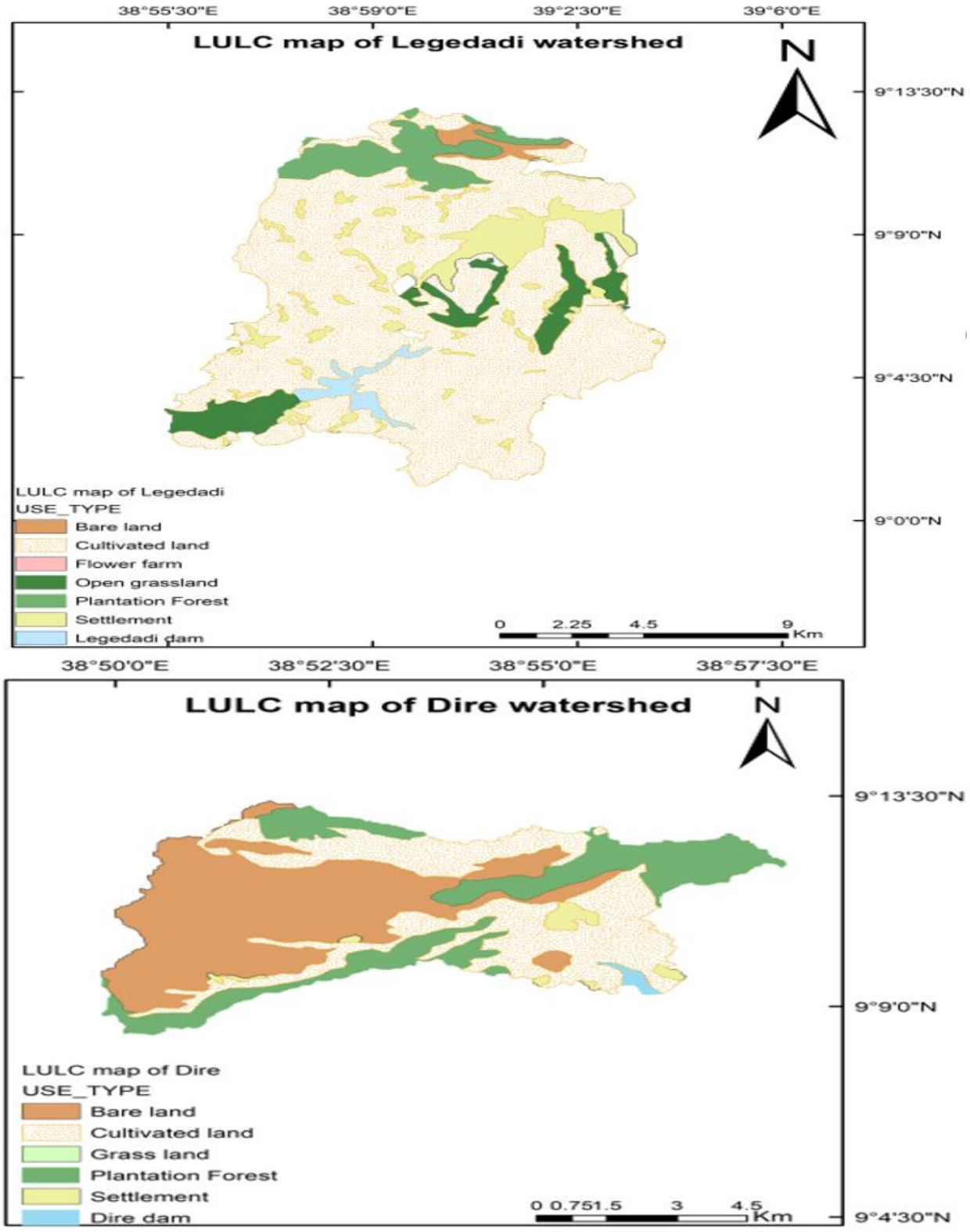


Figure 10: Land use map of Dire and Legedadi watersheds for the year 2015 (data source: OWWDCSE, 2015)

The study areas are known for the production of wheat, barley, oats and faba bean. Cereals (wheat and barley) are the most significant field crops in the study areas. Farmers practice mono-cropping of wheat-barley rotation in the main season while lentils and chickpeas are planted as catch crops.

3.2. Field Experiments I

Assessment of the effects of combined application of organic and inorganic fertilizers and legume intercropping on crop yield

The purpose of this experiment was to analyze the effects of integrated application of VC and mineral fertilizers, along with legume intercropping, on crop yield. Crop growth parameters, including plant stand counts at complete emergence, plant height (cm), spike length (cm), number of tillers, seeds per spike, number of pods per plant, and seeds per pod, were recorded from 10 randomly selected plants in the central rows at the crops' physiological maturity (Abera et al., 2020a).

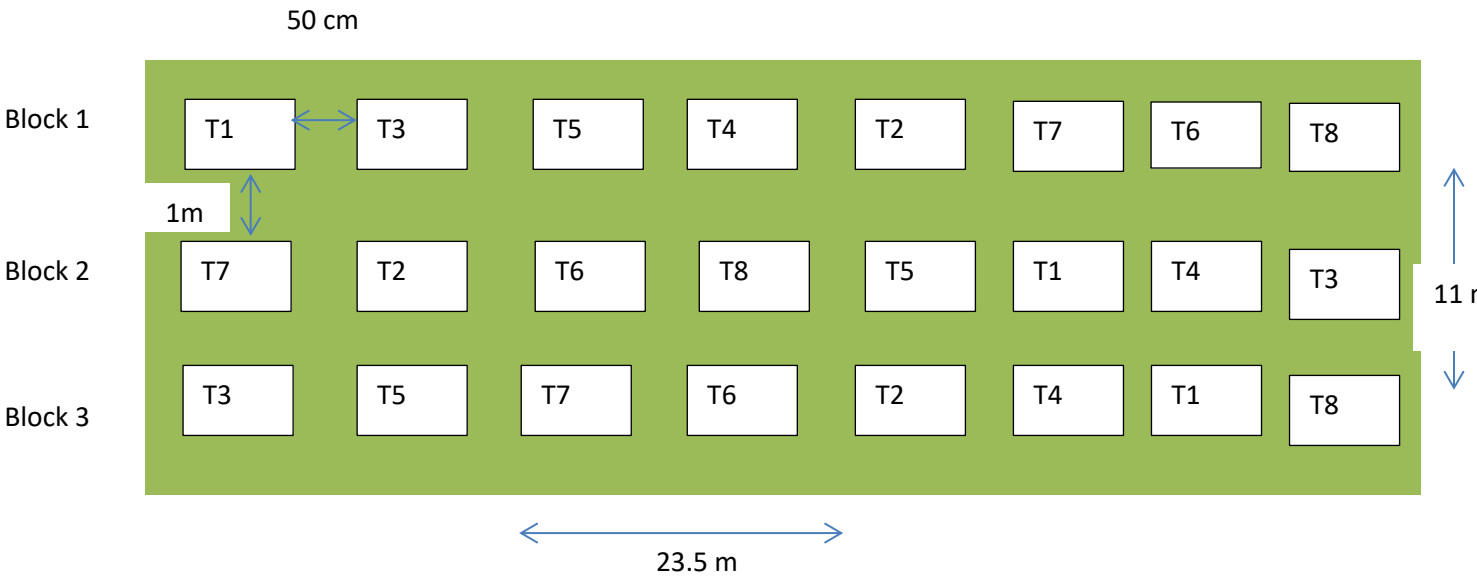
3.2.1. Treatments and experimental design

Intercropping, the application of VC and NPS blended, and their combinations were used as treatments in the field trials. Wheat (variety Danda'a) and faba bean (variety Gabelcho) without any soil amendment were used in the experiment. Two treatments included were 100% recommended blended NPS fertilizer versus 100% recommended VC application. One treatment was wheat with combined 50% recommended rate of NPS and 50% VC.

The three other treatments were wheat and faba bean intercropping with combined 50% recommended rate NPS and 50% VC, wheat and faba bean intercropping with 50% recommended rate NPS fertilizer, and wheat and faba bean intercropping with 50% recommended rate VC (Table 3). These eight treatments were arranged in a randomized complete block design (RCBD) with three replications planted in two farm fields at Dire and Legedadi sites (Figures 11 and 12).

Table 3: Treatments at Dire and Legedadi sites, central highlands of Ethiopia during 2021 and 2022 cropping seasons

Treatments Code	Description
T1	Sole wheat without fertilizer application
T2	Sole faba bean without fertilizer application
T3	Wheat with100% recommended NPS+ urea fertilizer rate
T4	Wheat with100% recommended VC rate
T5	Wheat with 50% recommended rate NPS fertilizer+ urea and half rate VC rate
T6	Wheat and faba bean intercropping with 50% recommended rate NPS+ urea and half rate VC
T7	Wheat and faba bean intercropping with 50% recommended rate NPS+ urea fertilizer
T8	Wheat and faba bean intercropping with 50% recommended rate VC



(A) RCBD layout for field application

(B) Field plot at Legedadi site

Figure 11: RCBD for field application at Dire and Legedadi sites

3.2.2. On-farm trial execution

Field trials were conducted on farmers' fields in the 2021 and 2022 main cropping seasons (June to December) at Dire and Legedadi sites. In each site, a farm field was selected to layout the trials. The same farm fields were used for both cropping seasons, for which the geographical locations are presented below (Table 4).

Table 4: Geographical location of the fields'

	Geographical location				
Farm site	Latitude	Longitude	Altitude	Crop history	Soil type
Dire	9.179504	38.927139	2635	Wheat	Luvisol
Legedadi	9.103820	38.98557	2742	Wheat	Vertisol

A row of faba bean was sown in the center of wheat rows at 20 cm intra-row and 40 cm inter-row spacing (Figures 12). Similarly, in sole planting faba bean was sown with a spacing of 40 cm between rows and 10 cm between plants. The space between the replications and the plots was 1m and 50 cm, respectively. The size of the plot was 2.6 m × 3 m (7.8 m^2) for all treatments at both study sites.

Figure 12: Field management of wheat-faba bean intercropping at Dire and Legedadi Sites

3.2.3. Vermicompost preparation and application

Vermicompost was prepared from *tef* straw, surface soil and farm yard manure. It was prepared at Debre Zeit Agricultural Research Center, Ethiopia. Earthworms *(Eisenia fetida)*, were used as decomposers for both the bedding and feeding materials. The earthworms were fed with cabbage and avocado leaves every 2 weeks except the last 2 weeks before vermicompost harvest. The compost reached maturity at 60 days.

Table 5: Mean values of selected chemical composition of vermicompost before application

Parameters	Result
Moisture content (%)	55
Total nitrogen (%)	1.35
Organic carbon (%)	9.7
Available phosphors (ppm)	1600
Exchangeable K (ppm)	6384.3
Cation exchange capacity ($cmol^{+}/kg$)	58.01

VC was applied a month before sowing at a rate of 5.3 t ha^{-1}, for both plants (MoA, 2016). Faba bean seeds were sown on June 17–18 in 2021 and 2022, while wheat seeds were sown on July

21–22 in the same years at the Dire and Legedadi sites, respectively. Wheat and faba bean seeds were sown by hand drilling. The chemical composition of VC was tested and analyzed at Debre Zeyit Agricultural Research Center soil laboratory (Table 5).

Wheat and faba bean seeds were sown at a rate of 150 kg ha^{-1}, and 350 kg ha^{-1}, respectively (EIAR, 2018). Blended NPS fertilizer (19 N-38 P_2O_5 + 7% S) was applied at the recommended rate of 100 kg ha^{-1}, it was applied at planting while 100 kg ha^{-1} urea (46% N) was split applied in two halves; the first half at planting and the remaining at tillering according to recommendation rate for wheat. Fertilizers were purchased from Bereh district Farmers' Cooperative Union. Throughout the growing periods of both cropping seasons, plants were hand-weeded three times and cultivated once. All agronomic procedures were applied uniformly throughout the treatments (EIAR, 2007).

3.2.4. Crop sampling and laboratory analysis

At physiological maturity, plants from the net area of a 1 m^2 central plot were hand-harvested using sickles. The harvested plants were sun-dried in the open air, and the above-ground biomass yield was weighed. The plants were then threshed and weighed to determine the grain yield for each treatment.

The straw yield was measured by subtracting the grain yield of wheat from the above ground biomass yield of the crop. Above-ground biomass yield was weighed using a hand-held balance in the field.

The intercropped crops were harvested separately from the entire plot. Wheat was the main crop and faba bean was an intercrop component. Crop growth parameters such as plant stand counts at complete emergence, plant height (cm), spike length (cm), number of tillers, seed per spike, number of pods per plant, and number of seeds per pod were recorded from 10 randomly selected plants in the central rows at physiological maturity of the crops.

A total of forty-eight samples of grain yields and crop residues were collected using $1m^2$ quadrants from each plot at both sites. These samples were analyzed for their nitrogen (N), phosphorus (P), and potassium (K) content. All collected plant samples were analyzed at Holeta Agricultural Research Center soil and plant analysis laboratory using standard procedures. Plant

samples were washed with 0.25% detergent solution following rinsing in distilled water to remove dust and other contaminants. Then the samples were dried in an oven at 105^{o}C for 24 hours. The N content was analyzed by Kjeldahl digestion, distillation and titration method. The concentrations of P and K were measured using a spectrophotometer and a flame photometer, respectively (Thomas et al., 1967).

3.3. Analysis of intercrop efficiency indices

Land equivalent ratio

The land equivalent ratio (LER) quantifies the amount of land needed in an intercropping system to attain an equivalent yield compared to that of sole cropping. The yields of both crops from the sole and intercropped plots were evaluated using the LER, as described by (Mead and Willey, 1980):

- **Land equivalent ratio =** $\frac{Ya}{YA} + \frac{Yb}{YB}$

Where Ya is the seed yield of the legume crop, in this case faba bean, in intercropped with wheat; YA is the seed yield (kg/ha) of sole faba bean; Yb is grain yield kg/ha of wheat in intercrop with faba bean; YB is grain yield (kg/ha) of sole wheat crop. A land equivalent ratio of 1.0 signifies an equal advantage for intercropping and sole cropping.

LER values greater than 1.0 indicate a greater advantage for intercropping over sole cropping, while values less than 1.0 suggest a lesser advantage for intercropping compared to sole cropping.

Crowding coefficient

The crowding coefficient (K) quantifies the relative dominance of one companion crop over another in an intercropping system, and each crop is designated a unique K value in the intercropping system (Willey, 1979b). Therefore, the crop component with a higher K value is dominant, while the yield component with a lower K value is dominated. The relative crowding coefficient was calculated as follow (Willey, 1979a):

- **K= K wheat * K faba bean**

$$\textbf{Crowding coefficient of Wheat} = \frac{\textbf{YIW} * \textbf{ZIF}}{(\textbf{YW} - \textbf{YIW})\textbf{X ZIW}}$$

$$\textbf{Crowding coefficient of faba bean} = \frac{\textbf{YIF} * \textbf{ZIW}}{(\textbf{YF} - \textbf{YIF})\textbf{X ZIF}}$$

Where K, total relative crowding coefficient; K-wheat, relative crowding coefficient of wheat; K- faba bean, relative crowding coefficient of faba bean; YIW, Wheat yield in intercropping system; YW, Wheat yield in sole planted; YIF, faba bean yield in intercropping system; YF, faba bean yield in sole planted; ZIW, proportion of wheat in intercropping system; ZIF, proportion of faba bean in intercropping system. If the value of K is greater than 1, there is a yield advantage; if K is 1, there is no yield advantage; and if it is below 1.00, the yield is at a disadvantage.

Aggressivity

Aggressivity (A) is frequently employed to signify the extent to which the relative yield increase in crop 'a' surpasses that of crop 'b' in an intercropping system (Dhima et al., 2007). It is used to determine the competitive relationship between the two companion crops in a mixture. This specification indicates that if A is 0, both crops are equally competitive; if A for cereal is positive, it signifies the dominance of the cereal crop over the legume, and if A for cereal is negative, it indicates that the cereal crop is the dominated by the legume crop in the intercropping system.

- $\textbf{Aggressivity of Wheat} = \frac{\textbf{YIW}}{\textbf{YW} * \textbf{ZIW}} - \frac{\textbf{YIF}}{\textbf{YF X ZIF}}$
- $\textbf{Aggressivity of faba bean} = \frac{\textbf{YIF}}{\textbf{YF} * \textbf{ZIF}} - \frac{\textbf{YIW}}{\textbf{YW X ZIW}}$

Where, YIW, Wheat yield in intercropping system; YW, Wheat yield in sole planted; YIF, faba bean yield in intercropping system; YF, faba bean yield in sole planted; ZIW, the proportion of wheat in intercropping system; ZIF, proportion of faba bean in intercropping system.

System productivity index

System productivity index (SPI), standardizes the yield of the secondary crop b relative to the primary crop, *a* (Odo, 1991).

- $\mathbf{SPI = \frac{Sa}{Sb} Yb + Ya}$

Where Sa and Sb, are the mean yield of wheat and faba bean in sole culture, and Ya and Yb, are the mean yield of wheat and faba bean in the intercrop, respectively.

Gross monetary value

The purpose of calculating the gross monetary value of crop yield is to quantify the total economic value of agricultural production in monetary terms (Penot et al., 2021). Gross monetary value (GMV) was calculated for wheat and faba bean as:

GMV = Grain yield (kg ha^{-1}) × unit price (Eth. Birr kg^{-1})

The market price for wheat and faba bean at the time of crop harvest around Sendafa (the common market center for Dire and Legedadi sites) was estimated at Eth. Birr 45 kg^{-1} (USD/kg 0.838) and Eth. Birr 60 kg^{-1}(USD/kg 1.118), respectively in 2022. The total gross monetary value (GMVt) was then estimated by the addition of the GMVw and GMVf.

Partial budget analysis

Partial budget analysis assists in evaluating the economic benefits of intercropping and different fertilizer applications in the context of grain and straw yields following the partial budget methodology (CIMMYT, 1988). The prices (USD/Kg) of wheat grain yield, faba bean grain yield, faba bean straw yield and wheat straw yield were 0.74, 0.92, 0.04 and 0.15, respectively. The cost of labor varies and was considered as a variable cost when considering other costs as constant for each treatment. The labor cost/man/day was 5.58 USD. The indices were calculated using the following formulae:

Gross average yield (kg/ha) (Yav): was computed by converting the average yield for each treatment into hectares.

Adjusted yield (AjY): was derived by reducing the average yield by 10% to align it with the difference between experimental and farmers' yields:

$$\textbf{A jY (t/ha)} = \textbf{Yav} \times \textbf{(1-0.1)}$$

Gross field benefit (GFB) (USD/ha): was calculated by the following formula.

$$\textbf{GFB} = \textbf{AjY} \times \textbf{field/farm gate price for the crop}$$

Total variable cost: covers labor cost, fertilizers cost (NPS, urea and VC)

Net benefit (NB) (USD/ha): was determined by deducting the overall costs from the gross field benefits

$$\textbf{NB} = \textbf{GFB} - \textbf{total cost}$$

Marginal rate of return (MRR %): calculated by dividing the change in net benefit by the change in cost (CIMMYT, 1988).

- $\textbf{MRR} = \frac{\textbf{Marginal benefit}}{\textbf{marginal cost}} \textbf{X 10}$

Nutrient use efficiency

1. Recovery Efficiency (RE): the quantity of nutrient absorbed per unit of nutrient applied

- $\mathbf{RE\% = \frac{Un-Uo}{n} \times 100}$

Where; Un, nutrient uptake by the rate of N and P fertilizer, Uo, nutrient uptake by unfertilized and n, for quantity of fertilizer applied.

2. Agronomic Efficiency (AE): assesses the economic production achieved per unit of nutrient applied

- $\mathbf{AE\ (kg/kg) = \frac{Gf-Gu}{QA}}$

Where; Gf and Gu, stand for grain yield of fertilized plots at 'n' rates of fertilizer and grain yield of unfertilized plots, respectively, and QA, stands for nutrient applied (Godebo et al., 2021).

3.4. Soil sampling and analysis for Objectives 2 and 3

Assessment of the effects of combined application of organic and inorganic fertilizer and legume intercropping on soil properties and soil carbon stock

The purpose of this experiment was to analyze the effects of the combined application of VC and inorganic fertilizers along with legume intercropping on selected soil properties and soil carbon stock and sequestration at Dire and Legedadi sites.

3.4.1. Soil sampling and analysis

Composite soil samples were collected before planting using Edelman soil auger from each experimental field at a depth of 0-20 cm to determine the initial soil condition. Similarly, after harvest soil samples were collected per experimental plot to determine treatment effects on the soil characteristics. Before the experiment, two composite soil samples were collected from each study site. After the experiment, a total of 48 soil samples were collected from each plot across both sites. Undisturbed soil samples were also collected before and after the experiment separately using a core sampler to determine the soil bulk density.

The soil samples were analyzed at Debre Zeyit Agricultural Research Center soil laboratory following standard soil laboratory procedures (Van Reeuwijk, 2006). Soil samples were air-dried and crushed before passing through a 2 mm sieve for physicochemical analysis.

Soil texture was analyzed using the hydrometer method (Bouyoucos, 1962); soil bulk density (BD) was measured from an undisturbed soil sample collected using a core sampler (Black, 1965).

The field capacity (FC) of the soil was determined at 1/3 bar, and the permanent wilting point (PWP) at 15 bars. The plant available water content (AWC) was determined as the difference between FC and PWP (Klute and Dirksen, 1986). Soil chemical properties such as soil pH was determined using a pH meter in water (H_2O) suspension in a 1:2.5 (soil: liquid), and electrical conductivity using an EC meter (Van Reeuwijk, 2006).

Soil organic carbon (SOC) was determined using the Walkley and Black method (Walkley and Black, 1934). Total nitrogen (TN) was assessed with the Kjeldahl method (Bremner and Mulvaney, 1982), and available phosphorus (Pav) was determined with the Olsen method (Olsen, 1954). To determine the Cation exchange capacity (CEC), the soil samples were first leached with 1 M ammonium acetate (NH4OAc), washed with ethanol, and the adsorbed ammonium replaced by Na (Chapman, 1965). Exchangeable Ca, Mg, K and Na were determined by the ammonium acetate method at pH 7 (Black et al., 1965). Then Ca and Mg were determined using atomic absorption spectrophotometry, while exchangeable Na and K were measured by flame photometer from the same extract (Chapman, 1965).

3.4.2. Soil Carbon and Nitrogen Stock Determination

Soil organic carbon stock, nitrogen (N) stocks and carbon sequestration (t ha^{-1}) were calculated according to the equation given by (Donovan, 2013).

$$\textbf{Soil C (or N) Stock (t ha}^{-1}\textbf{) = Soil OC (\%) or N (\%) * BD (kg m}^{-3}\textbf{) * V* 10}^{-3}$$

Where: BD = bulk density (kg m^{-3}) and V= Volume of the soil in cubic meters = depth of soil (m) X Area of soil (m^2)

Carbon sequestration (t ha^{-1}) quantifies the amount of carbon stored in the form of carbon dioxide (CO_2) within a given area of land. It is obtained by multiplying SOC by 3.67 (i.e., the molecular mass of CO_2/ atomic mass of C = 44/12=3.67).

$$\textbf{Carbon sequestration (t ha}^{-1}\textbf{) = SOC (t ha}^{-1}\textbf{) } \times \textbf{ 3.67}$$

3.5. Experimental Objective-4

Quantification of nutrients flows and balances at farm level

Nutrient input and output flow analysis were conducted to determine the effects of cereal-legume intercropping systems on farm level nutrient balances (N, P and K). Data on inputs and outputs at farm level were collected for each of the case study farms using the MonQI toolbox (Van Duivenbooden and Van Beek, 2015, Van Beek et al., 2016). MonQI toolbox had been calibrated and utilized in tropical regions for numerous years. Additionally, many researchers had employed it in Sub-Saharan African countries such as Ethiopia (Van Beek et al., 2016, Mesfin et al., 2021, Gebresamuel et al., 2021, Tadesse et al., 2018, Assefa, 2014).

Soil nutrient balances were computed by determining the net disparities between nutrient input and output flows within the soil system (Stoorvogel and Smaling 1990). The methodological approach used here to estimate nutrient depletion and requirements combines information on four input and five output processes (Elias, 2005a). The key input flows are provided in Table 6 including mineral fertilizer (IN1), organic matter (IN2), atmospheric deposition (IN3), and biological N-fixation (IN4). The major output flows quantified were: removal in harvested products (OUT1), removal in crop residue (OUT2), leaching (OUT3), gaseous losses (OUT4), and soil erosion (OUT5).

Data on the grain yields of the crops in the intercropping mix were collected through field measurements conducted for two-year period (2021-2022). Data on "hard to quantify" flows such as nutrient deposition, leaching and gaseous losses were determined through pedo-transfer functions (Lesschen et al., 2007).

Pedotransfer functions explain hard-to-quantify variables as a function of easily obtainable parameters such as mean annual precipitation and clay content of the soil (Stoorvogel and Smaling, 1993, Stoorvogel and Smaling 1990).

Table 6: Nutrient balance components and methods of determination

Inputs	Methods of determination	Outputs	Methods of determination

Mineral fertilizer (IN1)	Farm survey	Harvested product (OUT1)	Sampling
Organic input (IN2)	Farm survey	Harvested crop residue (OUT2)	Sampling
Atmospheric deposition (IN3)	Transfer-function	Leaching (OUT3)	Transfer-function
Biological nitrogen fixation (IN4)	Transfer-function	Gaseous losses (OUT4)	Transfer-function
		Soil erosion (OUT5)	Secondary data

Source: (Elias, 2005a)

3.6. Quantification of Nutrients

3.6.1. Quantification Nutrient input flows

IN1 Mineral fertilizer

Primary data were obtained on the amount of NPK nutrients applied to each plot and at both study sites. The amounts of NPS + urea (IN1) and vermicompost (IN2) were quantified across the different treatments. The NPK contents of fertilizers were determined by the chemical composition of each nutrient present in the fertilizer.

- 100 kg NPS (19 N-38 P_2O_5 +7 S) = 19 kg N; 38 kg P_2O_5 *0.46 = 17 kg P
- 100 kg urea = 46 kg N

IN2 = Organic fertilizer input – the NPK content of VC is provided in Table 5 as (total nitrogen (1.35%), available phosphorus (1600 ppm), and exchangeable potassium (6384.3 ppm).

Atmospheric deposition (IN3): was calculated using the square root of mean annual rainfall (mm) (Stoorvogel and Smaling 1990). The mean annual rainfall data was obtained from Entoto and Dire Gedeb metrological stations for Dire and Legedadi sites, respectively.

- **IN3 N=0.14$p^{1/2}$**
- **IN3 P=0.023$p^{1/2}$**
- **IN3 K=0.092$p^{1/2}$**

Where p is the mean annual rainfall (mm y^{-1})

Biological Nitrogen fixation (IN4a): was calculated using a pedotransfer function by linking the nutrient input with the mean annual rainfall (Stoorvogel and Smaling 1990).

- **Biological nitrogen fixation input (N) = 2+ (p− 1350) ∗ 0.005**

3.6.2. Nutrient Outflow Analysis

Quantification of Nutrient outflow

OUT1 and OUT2 – crop yield

Crop seed yield (OUT1) and straw (OUT2) samples were collected from the experimental plots using a quadrant and the N, P and K contents were determined by plant tissue analysis at Holeta plant and soil laboratory research center. Nutrient uptake was calculated by multiplying the grain and straw yield (kg ha^{-1}) with the nutrient (NPK) concentration of grain or straw as follows:

- **Nutrient (N, P or K) uptake by grain or straw (kg/ha) = [Yield of grain or straw (kg ha^{-1} × Nutrient (N, P or K) concentration of grain or straw (%) × 10^{-2}** (Godebo et al., 2021).

OUT3:

According to (Stoorvogel and Smaling, 1993) leaching of N and K (OUT3) was estimated as a function of soil clay and mean annual precipitation of the study site:

- **Leaching output (N) = (Soil N + Fertilizer N) ∗ (2.1 ∗ 10^{-2} ∗ p +3.9), clay < 35%**
- **Leaching output (N) = (Soil N + Fertilizer N) ∗ (1.4 ∗ 10^{-2} ∗ p +0.71) 35% < clay < 55%**
- **Leaching output (N) = (Soil N + Fertilizer N) ∗ (7.1 ∗ 10^{-3} ∗ p +5.4), clay > 55%**
- **Leaching output (K) = (Exchangeable K + Fertilizer K) ∗ (2.9 ∗ 10^{-4} ∗ p +0.41) < 35%**
- **Leaching output (K) = (Exchangeable K + Fertilizer K) ∗ (2.9 ∗ 10^{-4} ∗ p +0.11) clay > 35%**

Leaching output of N and K is in kg $ha^{-1}y^{-1}$, clay is the clay content of the topsoil (%)

The following equations were used to determine leaching of N and K output for Dire site since the clay content of the area was 43.4%.

- **Leaching output (N) = (Soil N + Fertilizer N) $*$ (1.4 $*$ 10^{-2} $*$ *p* +0.71) 35% < clay < 55%**
- **Leaching output (K) = (Exchangeable K + Fertilizer K) $*$ (2.9 $*$ 10−4 $*$ *p* +0.11) clay > 35%**

The clay content of Legedadi farm site was greater than 55% and the following equations were used to determine the leaching of N and K output:

- **Leaching output (N) = (Soil N + Fertilizer N) $*$ (7.1 $*$ 10^{-3} $*$ p +5.4), clay > 55%**
- **Leaching output (K) = (Exchangeable K + Fertilizer K) $*$ (2.9 $*$ 10^{-4} $*$ *p* +0.11) clay > 35%**

The MONQI toolbox estimated gaseous losses as a function of soil and fertilizer contents of N, soil clay and mean annual precipitation (Stoorvogel and Smaling, 1993).

- **Gaseous output (N) = (Soil N + Fertilizer N) $*$ (−9.4+0.13 $*$ clay+0.01*p*)**
  Where soil N: nitrogen content of soil from each plot
  Fertilizer N: N content of NPS + urea and VC

Secondary data from (Awraris, 2017) were used to estimate the erosion rates for both study sites. Erosion output was estimated using a revised universal soil loss equation (RUSLE). The erosion rates were 77.15 t ha^{-1} yr^{-1} and 21.34 t ha^{-1} yr^{-1} at Dire and Legedadi sites, respectively (Awraris, 2017). The amount of soil lost with erosion was multiplied by soil N, P and K and the enrichment factor to quantify N, P and K contents (Roy et al., 2003).

Finally, the MonQI toolbox estimated partial (Partbal X) and full (Fullbal X) nutrient balances.

- **Partbal X = (Inorganic fertilizer input + Organic input) − (Crop product + Straw output)**
- **Fullbal X = ∑Inputs − ∑Outputs**

3.7. Statistical analysis

The collected raw data were recorded in Microsoft Excel. Data normality was assessed before conducting the analysis. The data were used for yield parameters, plant analysis and soil characteristics comparison, with one-way ANOVA. Graphs were made using Origin Pro 9.0 software. Data were presented using line graphs, tables and bar graphs.

Soil data obtained from the laboratory were subjected to analysis using SAS/STAT software, version 9.3 (SAS, 2014). This software was employed to perform descriptive and inferential statistical analysis, including comparisons among treatment means and the evaluation of their effects on surface soil physicochemical properties, and plant analysis using analysis of variance (ANOVA) at a 95% confidence interval ($p< 0.05$). To validate the statistically significant differences arising from the different treatments, the ANOVA results were additionally subjected to Fisher's Least Significant Difference (LSD) test. A paired sample t-test was employed to compare selected parameters of soil and yield between Dire and Legedadi sites. Multivariate Analysis of Variance (MANOVA) was conducted to examine the effect of site, treatments, and their interaction on selected soil properties and yield.

The MonQI toolbox estimated various inflows, outflows, and nutrient balances. The outputs generated by the MonQI were imported into SAS for analysis of variance (ANOVA). One-way ANOVA was used to examine the effect of treatments on nutrient flows and balances.

Chapter four

4. Results

4.1. Soil physicochemical properties of the experimental fields before treatments applied

Table 7 presents the laboratory results of selected soil properties of the study sites. The soils are largely clayey in texture (43-63% clay), low in bulk density (<2g/cm^3), moderately acidic in reaction (pH), very low in electrical conductivity, very low in soil organic carbon, and total nitrogen, but moderately to high in available phosphorus and exchangeable bases. The levels of Cation exchange capacity were exceptionally high (45-56 cmol/kg) suggesting the inherently fertile nature of the soil except for the depletion of nutrients and organic matter.

Table 7: Soil physicochemical properties of the fields (Dire and Legedadi sites) before the field experiment

Physical soil properties	**Dire site**	**Legedadi site**	**Chemical soil properties**	**Dire site**	**Legedadi site**
Sand%	32.2	22.2	pH	5.38	6.38

Silt%	24.4	15.4	EC (dSm^{-1})	0.043	0.032
Clay%	43.4	62.4	SOC (%)	1.57	1.49
Texture	Clay	Clay	SOM (%)	2.19	2.44
BD ($g\ cm^{-3}$)	1.33	1.27	TN (%)	0.24	0.11
			P ($mg\ kg^{-1}$)	5.23	9.86
			K ($cmol^{+}kg^{-1}$)	0.97	1.51
			CEC ($cmol^{+}kg^{-1}$)	44.6	55.6

4.2. Effect of ISFM treatments on crop wheat growth and yield parameters

4.2.1. Effect of ISFM on growth parameters

Plants' height varied significantly ($p< 0.05$) across the various treatments. Application of NPS fertilizer and VC either alone or in combination significantly ($p< 0.05$) affected the plant height of wheat and faba bean compared to the control at both locations. The highest mean plant height for faba bean (93.9 cm and 118.0 cm) was obtained at wheat-faba bean intercropped treatment with 50% of the recommended mineral fertilizer was applied in combination with 50% recommended levels of VC at Dire and Legedadi sites, respectively (Table 8). Similarly, the highest mean plant height for wheat (100 cm at the Dire site and 97.4 cm at the Legedadi site) was obtained at half dose of both VC and NPS added treatment (Table 9).

Table 8: The effect of intercropping and combined fertilizers application on growth and yield parameters of faba bean in 2021 and 2022 cropping seasons (combined over years) at Dire and Legedadi site

T	PH(cm)	SC(no)	PPP(no)	SPP(no)	PH(cm)	SC(no)	PPP(no)	SPP(no)
	Dire				**Legedadi**			
T2	79.7^{c}	19.5^{b}	3.9^{c}	2.1^{c}	90.0^{c}	21.4^{b}	4.6^{c}	2.4^{b}
T6	93.9^{a}	23.4^{a}	6.5^{a}	3.3^{a}	118.0^{a}	24.2^{a}	7.7^{a}	2.9^{a}
T7	92.0^{a}	21.7^{ab}	6.1^{a}	2.6^{b}	111.0^{b}	22.8^{ab}	7.4^{a}	2.6^{b}
T8	89.7^{b}	21.2^{b}	5.3^{b}	2.5^{b}	96.0^{bc}	22.5^{ab}	5.9^{b}	2.5^{b}
Mean	88.8	21.5	5.5	2.6	103.8	22.7	6.9	2.6
SE	1.29	0.72	0.28	0.09	1.01	1.02	1.45	0.09
P value	0.01	0.06	0.004	0.002	0.027	0.137	0.001	0.008
F value	47.2	4.32	33.5	45.5	6.3	5.5	15.2	55.4
Sign.	*	ns	**	**	*	Ns	***	**

Means followed by the same letters within a column are not significantly different at 5% probability level

∗, ∗∗, and ∗∗∗ designate significance at p< 0.05, 0.01, and 0.001, respectively, ns not significant at p< 0.05; SE standard Error, T Treatment, PH plant height, SC Stand count, PPP Pods per plant, SPP Seed per pod

The mean spike length of wheat was higher by 77.7% and 74.6% with full dose NPS fertilizers compared to the control at Dire and Legedadi sites, respectively. Number of seeds per spike (SPS) was also significantly (p<0.05) varied across the treatments. The maximum number of SPS 59.8 at Dire and 55.23 at Legedadi was obtained at full dose mineral fertilizers added treatment (Table 9). The number of SPS is statistically similar between full dose inorganic fertilizers and combined half dose NPS and half dose VC fertilizers treatments while there was variation among wheat-faba bean intercropped treatments at both sites.

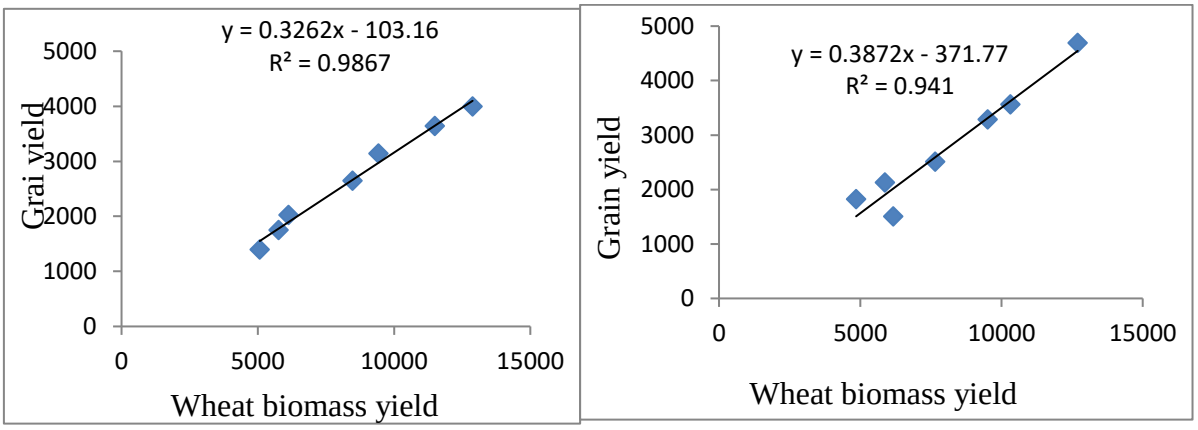
Table 9: The effect of intercropping and combined fertilizers application on growth parameters of wheat combined over two cropping seasons (2021-2022) at Dire and Legedadi sites

T	PH	SL	SPS	TN	PH	SL	SPS	TN
T1	57.1e	4.4d	32.7	2.9	64.1d	4.5c	30.1c	3.3d
T3	93.7ab	7.3ab	55.2	6.1	96.2a	9.0a	59.8a	9.6a
T4	90.8b	5.6cd	45.4	5.1	81.7c	4.9c	47.4b	5.2c
T5	97.4a	7.2ab	54.2	5.3	100.0a	8.7a	57.6a	8.3b
T6	93.4ab	7.7a	48.8	5.1	97.8a	8.1ab	50.9b	8.3b
T7	74.3c	6.4bc	43.4	3.5	86.7b	7.1b	35.3c	6.0c
T8	67.1d	5.3cd	37.0	3.2	77.9c	5.5c	33.4c	4.0d
Mean	81.9	6.3	45.2	4.4	86.3	6.9	44.9	6.4
SE	3.06	0.21	1.26	0.4	7.3	0.35	2.7	0.38
p value	0.0001	0.0005	0.0001	0.003	0.0001	0.0001	0.0001	0.0001
F value	65.67	9.8	30.8	6.80	68.9	29.22	50.05	49.01
Sig.	***	***	***	**	***	***	***	***

Means followed by the same letters within a column are not significantly different at 5% probability level ∗∗, and ∗∗∗ designate significance at p<0.01, and 0.001, respectively, SE standard Error, T Treatment, PH plant height, SL Spike Length, SPS Seed per spike, TN Tiller number

4.2.2. Effect of ISFM on wheat yield parameters

The analysis of the variance of data combined over years revealed that the application of NPS and VC fertilizers had significantly ($p< 0.05$) affected the grain and biomass yield of wheat at both sites. The highest mean wheat grain yield (4000 kg ha^{-1} at Dire and 4151.7 kg ha^{-1} at Legedadi and straw yields (8827.7 kg ha^{-1} at Dire and 8548.3 kg ha^{-1} at Legedadi) were obtained from the application of a full dose of NPS fertilizer (Table 10). The next highest mean grain and straw yield was obtained when 50% of the recommended mineral fertilizer was applied in combination with 50% recommended levels of VC. Figure 13 shows a linear increase in both grain and biomass yield with increasing levels of fertilizer.



Dire site Legedadi site

Figure 13: Interrelationships of biomass yield and total grain yields (kg ha^{-1}) of wheat at Dire and Legedadi experimental sites.

Table 10: Intercropping and application of combined fertilizers effect on yield components of wheat in 2021 and 2022 cropping seasons (combined over years) at Dire and Legedadi sites

	Dire site				Legedadi site			
T	TB kg ha^{-1}	GY kg ha^{-1}	SY kg ha^{-1}	GMV (USD ha^{-1})	TB kg ha^{-1}	GY kg ha^{-1}	SY kg ha^{-1}	GMV (USD ha^{-1})
T1	5073^{g}	1400.3^{g}	3672.7^{e}	1174.1^{g}	5104^{g}	1420.0^{g}	3684.0^{f}	1260.2^{g}
T3	12883^{a}	4000.3^{a}	8827.7^{a}	3354.1^{d}	12700^{a}	4151.7^{a}	8548.3^{a}	3481.0^{d}
T4	9433^{c}	3140.5^{c}	6292.5^{b}	2633.0^{f}	9510^{c}	3285.3^{c}	6224.7^{c}	2754.6^{f}
T5	11500^{b}	3827.3^{b}	7672.7^{b}	3207.3^{e}	11317^{b}	3927.3^{b}	7389.7^{b}	3291.1^{e}
T6	8483^{d}	2647.0^{d}	5836.0^{c}	6150.9^{a}	7658^{d}	2510.0^{d}	5148.0^{d}	6553.9^{a}
T7	6133^{e}	2023.7^{e}	4109.3^{d}	4575.5^{b}	6171^{e}	2128.3^{e}	4042.7^{e}	4467.6^{b}

T8	6767^{f}	1754.0^{f}	5012.0^{d}	4340.1^{c}	5754^{f}	1821.6^{f}	3932.4^{ef}	4305.5^{c}
Mean	8610.3	2684.7	5917.6	3633.6	8316.3	2749.2	5567.1	3730.6
SE	326.0	437.6	185.8	262.3	215.6	75.6	272.6	56.8
p value	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
F value	93.04	377.7	83.9	586.45	368.9	390.9	83.3	566.5
Sig.	***	***	***	***	***	***	***	***

Means followed by the same letters within a column are not significantly different at 5% probability level ***= significant at p< 0.05; T Treatment, TB Total biomass, TY Total yield, SY Straw yield, GMV Gross monetary value, USD= 53.67 Ethiopian birr.

Wheat-faba bean intercropped with the addition of half the recommended rate of both NPS and VC fertilizers gave the highest total intercrop yield 2647 kg ha^{-1} and 2510 kg ha^{-1} of wheat than the remaining intercropped treatments at Dire and Legedadi sites, respectively.

The average yield of this treatment was 89.1% higher at the Dire site and 76.8% higher at the Legedadi site compared to the control. Increasing the recommended VC rate from 50% to 100% resulted in a grain yield increase of 79% at the Dire site and 80.3% at the Legedadi site.

The highest mean faba bean yields (3280.4 kg ha^{-1} at Dire and 3400.7 kg ha^{-1} at Legedadi) were obtained at wheat-faba bean intercrops when 50% of recommended mineral fertilizer applied in combination with 50% recommended levels of VC (Figure 14).

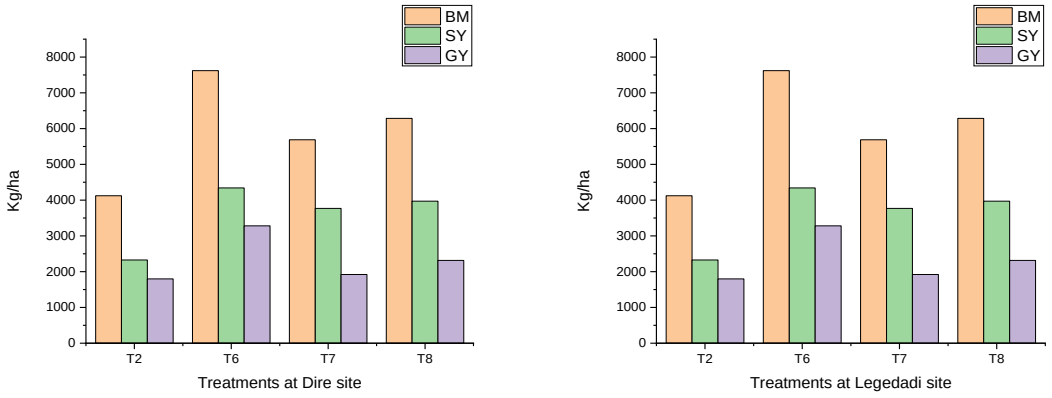
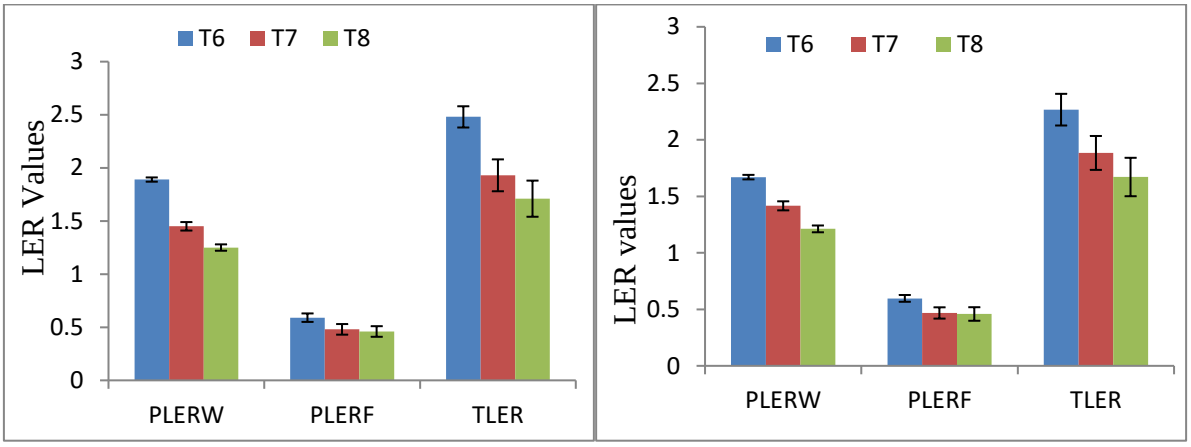


Figure 14: Intercropping and application of combined fertilizers effect on yield components of faba bean in 2021 and 2022 cropping seasons (combined over years) at Dire and Legedadi sites.

BM Total biomass, GY Grain yield, SY Straw yield

4.3. Competition indices

Wheat faba bean intercrop combined with 50% NPS and 50% VC fertilizers had the highest wheat LER 1.89 and 1.76 at Dire and Legedadi sites, respectively. The lowest LER of wheat 1.28 at Dire and 1.26 at Legedadi were found at wheat-faba bean intercrops with 50% VC rate added treatment (Figure 15). All intercrops had LER value greater than a unit.



Dire site Legedadi site

Figure 15: The effect of intercropping and combined fertilizers application on LER of wheat and faba bean at Dire and Legedadi sites in 2021 and 2022 (combined over years) cropping seasons. PLERW Partial land equivalent ratio of wheat, PLERF Partial land equivalent ratio of faba bean, TLER Total land equivalent ratio.

According to the analysis result shown on Table 11, for all intercropped treatments wheat was the dominant crop with a higher K value than faba bean. The highest relative crowding coefficient of wheat 2.91 at the Dire site and 2.38 at the Legedadi site was achieved from wheat-faba bean intercrop with 50% NPS and 50% VC. The product of the relative crowding coefficient was greater than one in all intercropped treatments at both sites.

The highest (0.09) and (0.19) aggressivity values were found at wheat-faba bean intercrop with a combined 50% NPS and 50% VC at Dire and Legedadi sites, respectively. On the other hand, the lowest value 0.05 at Dire and 0.13 at Legedadi site of A was obtained at wheat-faba bean intercrop with half dose mineral fertilizer.

Table 11: Relative crowding coefficient (k), aggressivity value (A) and system productivity index (SPI) of wheat and faba bean grown in intercrops in 2021 and 2022 (combined over years) at Dire and Legedadi sites

T	Relative crowding coefficients						Aggressivity				System productivity index	
	Dire			Legedadi			Dire		Legedadi			
	Wheat	FB	K	Wheat	FB	K	Wheat	FB	Wheat	FB	Dire	Legedadi
T6	2.21	1.32	2.91	2.14	1.11	2.38	0.09	-0.09	0.19	-0.19	5672.0	4423.8
T7	3.15	0.84	2.64	3.42	0.68	2.33	0.02	-0.02	0.16	-0.16	4122.5	3751.5
T8	3.88	0.72	2.81	3.80	0.56	2.13	0.05	-0.05	0.13	-0.13	4088.6	3535.1
Mean	3.08	0.96	2.79	3.12	0.78	2.28	0.05	-0.05	0.16	-0.16	4627.7	3903.5

T Treatment, FB Faba

4.5. Nutrient use efficiency of wheat

Agronomic efficiency (AE) and recovery efficiency (RE) of N were significantly ($p< 0.05$) influenced by rates and types of fertilizers applied. Combined NPS and VC fertilizers produced higher AE of N (40.0 Kg/kg and 42 Kg/Kg) at Dire and Legedadi sites, respectively (Figure 16) compared to the mineral fertilizer applied treatment. The lowest AE of N (15.9 Kg/kg and 17.4 Kg/Kg) was observed in the half rate VC fertilizers at both sites. The RE of N in combined fertilizers treatment was 124.8% higher at the Dire site and 126.7% higher at the Legedadi site compared to the half dose mineral fertilizer. The RE of P in full dose VC treatment was 95.8% higher at the Dire site and 97.5% higher at the Legedadi site compared to the full dose mineral fertilizer treatment.

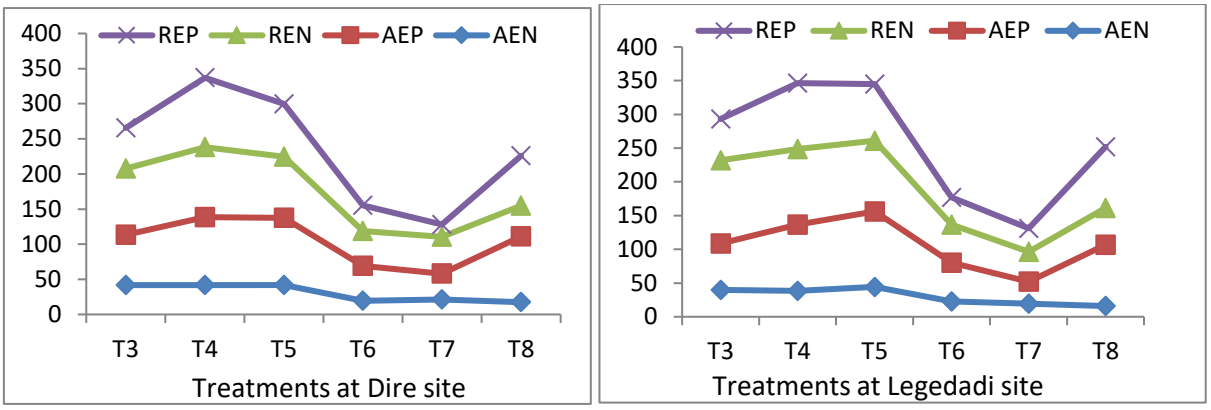


Figure 16: The effect of intercropping and combined fertilizers application on nutrient use efficiency of wheat at Dire and Legedadi sites in 2021 and 2022 (combined over years) cropping seasons

REP Recovery efficiency of phosphorus, REN Recovery efficiency of nitrogen, AEP Agronomic efficiency of phosphorus and AEN Agronomic efficiency of nitrogen

4.6. Nutrient use efficiency of faba bean

The combined application of organic and inorganic fertilizers significantly ($p< 0.05$) affected the N and P contents in the tissue of faba bean. The combined NPS and VC fertilizers resulted in the highest tissue N uptake (118.89 Kg ha^{-1} and 120.34 Kg ha^{-1}), followed by half dose VC added treatment at Dire and Legedadi sites, respectively. The RE of N in combined fertilizers treatment was 129.8% higher at the Dire site and 139.6% higher at the Legedadi site compared to the half dose VC fertilizer (Figure 17).

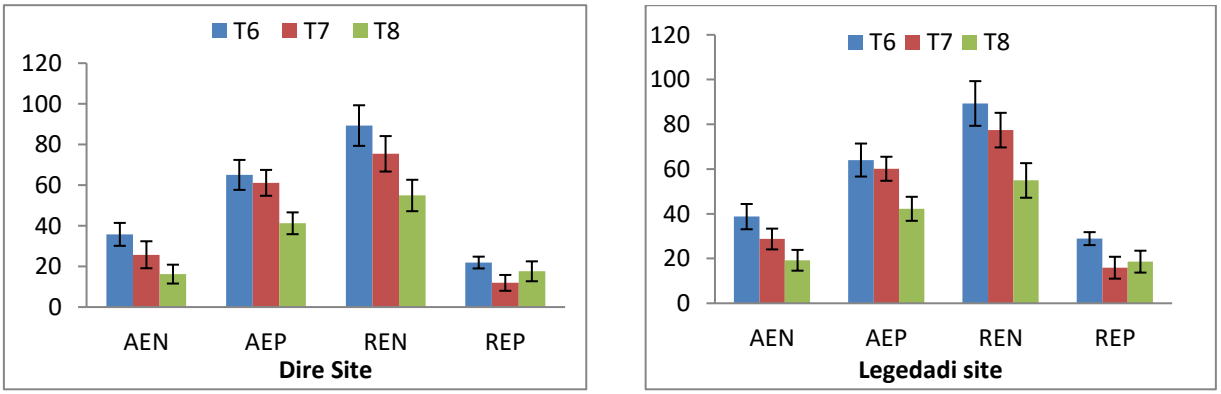


Figure 17: The effect of intercropping and combined fertilizers application on nutrient use efficiency of faba bean at Dire and Legedadi sites in 2021 and 2022 (combined over years)

cropping seasons. REP Recovery efficiency of phosphorus, REN Recovery efficiency of nitrogen, AEP Agronomic efficiency of phosphorus and AEN Agronomic efficiency of nitrogen.

4.7. Partial budget analysis

In the partial budget analysis, the most substantial net benefits, amounting to US$ 5598.1 ha^{-1} at Dire site and US$ 5690.8 ha^{-1} at Legedadi sites, were derived from wheat intercropped plots treated with a combined 50% NPS and 50% VC fertilizers. Conversely, the sole faba bean plots generated the lowest net benefits, with US$ 1036.4 ha^{-1} at Dire and US$ 1260.4 ha^{-1} at Legedadi sites, ranking just above the control plots, which produced US$ 1449.9 ha^{-1} at Dire and US$ 1464.5 ha^{-1} at Legedadi sites (Table 12). The marginal rates of return for the most economically promising treatment, wheat-faba bean intercrop with half dose of both NPS and VC fertilizers, were notably high 4227.2 at Dire and 4890.4 at Legedadi sites.

Table 12: Economic efficiency of wheat-faba bean intercropping in 2021-2022 cropping seasons (combined over years) at Dire and Legedadi site

Treatments	Adj. WY	Adj. SYW	Adj. SYF	Adj. FY	GFB WY	GFB FY	GFB SYW	GFB SYF	TC	NB	MRR
Dire site											
T1	1400.3	3672.7	0.0	0.0	1036.2	0.0	552.6	0.0	138.9	1449.9	1066.8
T2	0.0	0.0	2326.5	1796.9	0.0	1012.7	0.0	133.1	109.4	1036.4	857.5
T3	4000.3	8882.7	0.0	0.0	2960.2	0.0	1234.1	0.0	507.8	3686.4	1299.0
T4	3140.3	6292.5	0.0	0.0	2323.8	0.0	944.0	0.0	220.4	3047.4	1043.6
T5	3827.3	7672.7	0.0	0.0	2832.2	0.0	1013.4	0.0	364.1	3481.5	1207.7
T6	2647.0	5836	4340.2	3280.4	1958.8	2858.8	875.4	394.1	489.1	5598.1	4227.2
T7	2023.7	4109.3	3769.2	1819.5	1497.5	1673.9	616.5	310.8	448.3	3650.4	1166.9
T8	1754.0	5012	3971.3	2314.1	1298.0	2129.0	601.9	346.9	304.6	4071.1	1451.0

Legedadi site											
T1	1420	3684.0	0.0	0.0	1050.8	0.0	552.6	0.0	138.9	1464.5	1009.4
T2	0.0	0.0	3618.5	1890.8	0.0	1196.7	0.0	173.1	109.4	1260.4	915.7
T3	4151.7	8548.3	0.0	0.0	3072.3	0.0	1282.2	0.0	507.8	3846.7	1334.2
T4	3285.3	6224.7	0.0	0.0	2431.1	0.0	933.7	0.0	220.4	3144.4	1254.4
T5	3927.3	6389.3	0.0	0.0	2906.2	0.0	958.4	0.0	364.1	3500.5	1318.3
T6	2510	5148	4366.2	3400.7	1857.4	3119.5	772.2	430.8	489.1	5690.8	4890.4
T7	2128.3	4042.7	3971.3	2014.7	1574.9	1853.5	606.4	358.9	448.3	3945.4	1761.8
T8	1821.7	3932.3	3271.3	2014.7	1348.1	1853.5	589.8	358.9	304.6	3845.6	1761.8

Adj. Adjusted, WY Wheat yield, FY Faba bean yield, SWY Straw wheat yield, SFY Straw faba bean yield, GB Gross field benefit, TC Total cost, NB Net benefit, MRR Marginal rate of return

4.8. Comparison of wheat yield at Dire and Legedadi sites

Table 13, compares the wheat yield, biomass and straw yield at Dire and Legedadi sites. The t-test results revealed significant differences between the Dire and Legedadi sites in terms of total biomass ($p = 0.005$), grain yield ($p = 0.04$), and straw yield ($p = 0.03$).

Table 13: Mean comparison of wheat yield between Dire and Legedadi sites (paired sample t-test results).

T	Dire	Legedadi	Dire	Legedadi	Dire	Legedadi
	TB (kg ha^{-1})		SY (kg ha^{-1})		GY (kg ha^{-1})	
T1	5073	5104	3684	3684	1400.3	1420
T3	12883	12700	8227	8548.3	4000.3	4151.7
T4	9433	9510	6293	6224.7	3140.3	3285.3
T5	11500	10317	6756	6389.3	3827.3	3927.3
T6	8483	7658	5836.3	5148	2647	2510
T7	6133	6171	4109.7	4042.7	2023.7	2128.3
T8	5767	5754	4012.7	3932.3	1754	1821.7
T	4.39		-2.48		2.37	
P	0.005**		0.03*		0.04*	

∗, and ∗∗ designate significance at p< 0.05, and 0.01, respectively; T Treatment, TB Total biomass, SY Straw yield, GY Grain yield

4.9. Multivariate Test for the effect of site and treatment on selected soil properties and wheat yield

The MANOVA result (Table 14) revealed significant differences between the study sites as indicated by Wilks' Lambda (Λ=0.0491\Lambda=0.0491 Λ=0.0491, F(7,8)=15.7185, F(7,8)= 15.7185, F(7,8)=15.7185, p=0.0004, p = 0.0004, p=0.0004). These statistics suggest that there is a significant multivariate effect of the site on the soil and crop variables. Variations in the measured variables across different treatment are significant, as indicated by Wilks' Lambda: Λ=0.0000\Lambda=0.0000Λ=0.0000, F (56, 3.7725) = 9.3067, F (56, 3.7725) = 9.3067, F(56,3.7725)=9.3067, p<0.0001, p < 0.0001, p<0.0001).

The interaction between the study site and treatment showed a significant impact on the soil properties and wheat yield. The effect of treatment on these variables is different depending on the site that may be related to the specific location Wilks' Lambda: Λ=0.0000\Lambda=0.0000, Λ=0.0000, F (56,3.7725)=5.6884, F(56,3.7725)= 5.6884, F(56,3.7725)=5.6884, p<0.0001, p < 0.0001, p<0.0001

Table 14: Multivariate Test for the effect of site and treatment on selected soil properties and wheat yield at Dire and Legedadi sites

Effect	Test Statistic	Value	Num DF	Den DF	F Value	Pr > F
Site	Wilks' Lambda	0.0491	2	8	15.7185	0.0004
	Pillai's Trace	0.9509	2	8	15.7185	0.0004
	Hotelling-Lawley	19.393	2	8	15.7185	0.0004
	Roy's Greatest Root	19.393	2	8	15.7185	0.0004
Treatment (T)	Wilks' Lambda	0	56	3.7725	9.3067	< 0.0001
	Pillai's Trace	431.6354	56	18	3.7725	0.0022
	Hotelling-Lawley	231.3796	56	3.3196	1.4206	0.2594
	Roy's Greatest Root	179.0118	56	1.9776	5.8254	0.0643
Site * Treatment	Wilks' Lambda	0	56	3.7725	5.6884	< 0.0001
	Pillai's Trace	139.4192	56	18	3.7725	0.007

Hotelling-Lawley	99.7257	56	3.3196	3.2095	0.042
Roy's Greatest Root	72.6873	56	1.9776	4.0057	0.0863

4.11. Effects of ISFM practices on soil physical properties

4.11.1 Bulk density

There was a significant variation in soil bulk density (BD) among the treatments. Soil BD means value ranged from 1.24 g cm^{-3} to 1.33 g cm^{-3} and 1.16 g cm^{-3} to 1.25 g cm^{-3} at Dire and Legedadi sites, respectively (Table 15). The highest BD values, recorded from the control, were 1.33 g cm^{-3} at the Dire site and 1.25 g cm^{-3} at the Legedadi site. The lowest BD values were observed in the 100% VC treatment, with 1.24 g cm^{-3} at the Dire site and 1.16 g cm^{-3} at the Legedadi site. These were followed by the combined 50% NPS and 50% VC fertilizers in wheat-faba bean intercropped treatments at both sites.

Generally, VC added treatments showed significantly ($p< 0.05$) lower BD values compared to the control at both sites. The BD value decreased by 7.3% and 4.7% in the 100% VC and 100% NPS treatments at the Dire site, and by 7.8% and 3.3% at the Legedadi site, respectively compared to the control. However, there was no significant difference in BD values between the VC-added treatments at both sites.

Table 15: Intercropping and application of combined fertilizers effect on soil physical properties in 2021-2022 cropping seasons (combined over years) at Dire and Legedadi site**s**

	Dire Site					**Legedadi Site**				
T	Sand (%)	Silt (%)	Clay (%)	Textural class	BD (g/cm^3)	Sand (%)	Silt (%)	Clay (%)	Textural class	BD (g/cm^3)
T1	30.00	28.00	42.0	C	1.33	23.33	12.67	64	C	1.25
T2	30.00	28.00	42.0	C	1.33	23.23	12.77	64	C	1.24
T3	31.00	27.00	42.0	C	1.27	23.00	13.00	64	C	1.22
T4	30.00	26.30	43.7	C	1.24	24.00	11.00	65	C	1.16
T5	29.67	28.33	42.0	C	1.25	22.33	11.67	66	C	1.17
T6	30.33	28.67	41.0	C	1.25	21.00	14.00	65	C	1.17
T7	31.00	28.00	41.0	C	1.29	23.33	13.67	63	C	1.22

T8	29.00	30.00	41.0	C	1.28	24.34	13.66	62	C	1.21
Mean	30.13	28.04	41.84	C	1.28	23.07	12.81	64.13	C	1.21
SE	1.69	1.33	3.42		0.094	0.93	1.06	0.84		0.004
p-value	0.18	0.58	0.38		0.04	0.33	0.35	0.09		0.03
F-value	3.68	2.64	3.00		5.13	49.27	5.16	4.3		0.84
Sign.	ns	ns	Ns		*	ns	ns	ns		*

∗ indicates significant difference at $p < 0.05$, ns not significant at $p < 0.05$; SE standard Error, C clay, T Treatment

4.11.2. Water holding capacity

There were significant ($p< 0.05$) differences in water holding capacity at PWP and FC among treatments at both sites (Figure 18). The mean soil field capacities (FC) at Dire and Legedadi sites were 43.01±1.32 and 44.45±0.49, respectively. The highest (45.9%) water holding capacity at FC was recorded at the full-dose VC rate, while the lowest (40.1%) was observed in the control at the Dire site. Likewise, the Legedadi site exhibited the highest water holding capacity at the FC value of 46.95, in a 100% VC treatment, while the lowest value of 42.25 was observed in the control.

The wheat-faba bean intercropped plot demonstrated a significant difference ($p< 0.05$) in water holding capacity compared to the control. Full dose VC and combined 50% NPS and 50% VC treatments had 14.1% and 5.45% higher FC values than the control at the Dire site. The treatment with a 100% VC rate resulted in the highest AWC value, followed by the wheat-faba bean intercropped treatment with combined half rate both NPS and VC fertilizers at both sites.

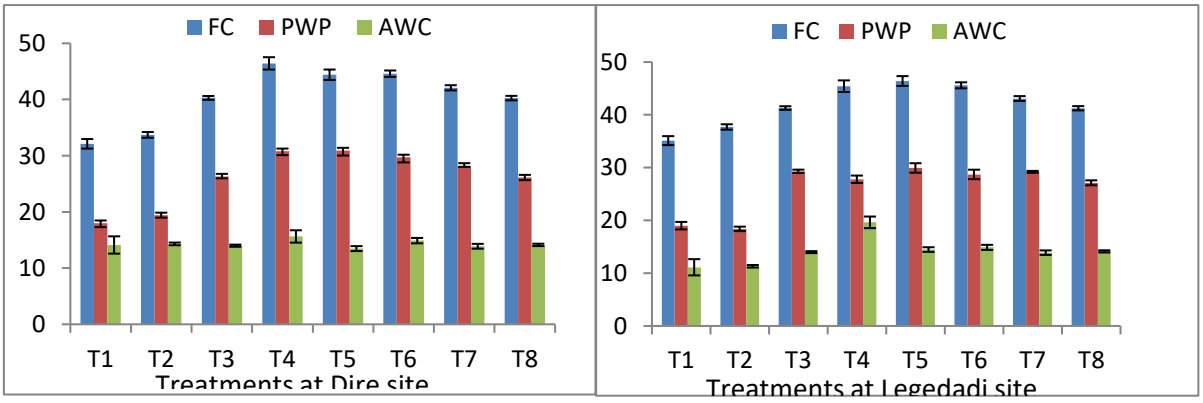


Figure 18: The effect of intercropping and combined fertilizers application on permanent wilting point (PWP), Field capacity (FC) and Available water capacity (AWC) at Dire and Legedadi sites

4.12. Effects of ISFM practices on soil chemical properties

4.12.1. Soil pH and electrical conductivity

Table 16, presents the effects of combined application of fertilizers and intercropping on soil chemical properties. The analysis of variance revealed significant ($p< 0.05$) differences in soil pH among the treatments at both sites. The addition of VC, either alone or combined with mineral fertilizers, significantly ($p< 0.05$) increased soil pH compared to sole mineral fertilizer and the control. Soil pH-H_2O of Dire ranged from (5.18-5.76) with a mean value of 5.45±0.05. Similarly, the soil pH of the Legedadi site ranged from (6.14-6.68) with a mean value of 6.42±0.02. A change in soil pH was observed in all treatments compared to the pre-planting soil.

The highest pH values, 5.76 at the Dire site and 6.68 at the Legedadi site, were recorded in the treatment with 100% VC application. The pH values in the 100% VC were 11.2% higher than in the 100% mineral fertilizer at the Dire site, and 7.7% higher at the Legedadi site. In both locations, the VC-treated wheat-faba bean intercropped treatments exhibited significantly higher pH values compared to the mineral fertilizer and the control.

The **electrical conductivity (EC)** ranged from 0.041- 0.141 ds/m with a mean value of 0.081± 0.008 ds/m at Dire site and 0.026-0.052 ds/m with a mean value of 0.039±0.001 at the Legedadi site (Table 15). The data showed that treatments with combined NPS and VC fertilizers had the highest EC values, while the control recorded the lowest, at both sites.

Table 16: Intercropping and application of combined fertilizers effect on soil chemical properties at Dire and Legedadi sites

	Dire Site				Legedadi Site			
	pH H_2O	EC (mS cm^{-1})	Kexc ($Cmol^+kg^{-1}$)	CEC ($Cmol^+kg^{-1}$)	pH H_2O	EC (mS cm^{-1})	Kexc ($Cmol^+kg^{-1}$)	CEC ($Cmol^+kg^{-1}$)
T1	5.38^{d}	0.041^{e}	0.927^{d}	44.33^{e}	6.38^{d}	0.029^{e}	1.182^{d}	52.85^{e}
T2	5.38^{d}	0.043^{e}	0.888^{e}	46.46^{e}	6.38^{d}	0.026^{e}	1.175^{e}	53.66^{e}
T3	5.18^{f}	0.089^{c}	0.974^{bc}	52.33^{c}	6.14^{f}	0.041^{c}	1.277^{b}	58.60^{bc}
T4	5.76^{a}	0.092^{b}	1.047^{b}	60.63^{a}	6.68^{a}	0.043^{bc}	1.287^{b}	64.79^{a}

T5	5.58^{b}	0.141^{a}	1.103^{a}	58.76^{b}	6.56^{b}	0.052^{a}	1.293^{a}	63.79^{b}
T6	5.58^{b}	0.139^{a}	1.127^{a}	59.61^{b}	6.56^{b}	0.049^{b}	1.306^{a}	63.66^{b}
T7	5.23^{e}	0.048^{d}	0.970^{bc}	49.34^{d}	6.21^{e}	0.038^{cd}	1.233^{c}	57.06^{d}
T8	5.49^{c}	0.051^{d}	0.958^{cd}	48.67^{d}	6.44^{c}	0.036^{d}	1.231^{c}	56.76^{d}
Mean	5.45	0.081	0.999	52.52	6.42	0.039	1.248	58.90
SE	0.053	0.008	0.018	0.986	0.021	0.001	0.392	0.704
p-value	0.002	0.0001	0.0001	0.038	0.033	0.009	0.0001	0.0001
F-value	12.36	18.01	36.40	0.81	3.14	17.83	43.32	34.82
Sign.	**	***	***	*	*	**	***	***

∗, ∗∗, and ∗∗∗ designate significance at p< 0.05, 0.01, and 0.001, respectively; T Treatments, SE Standard error

4.12.2. Soil organic carbon, total nitrogen, and available phosphorus

The soil organic carbon (SOC) also showed significant (p< 0.05) variation among the different treatments. The SOC contents varied between 1.55% and 2.59%, with a mean value of 2.22±0.06 at the Dire site. Likewise, at the Legedadi site, the SOC levels ranged from 1.48% to 2.39% with a mean value of 2.09±0.03. The maximum SOC value of 2.59% at Dire and 2.39% at Legedadi sites were recorded in a 100% VC rate treatment, whereas the lowest value was recorded in the control (Figure 20). The combined application of mineral and VC fertilizers resulted in SOC values that were 64.1% and 59.7% higher than the control at the Dire and Legedadi sites, respectively. Similarly, applying 100% VC resulted in a significant increase in SOC levels, with a 66% increase at the Dire site and a 61.5% increase at the Legedadi site.

4.12.3. Total nitrogen

The analysis of variance results showed that total nitrogen (TN) values were significantly (p< 0.05) varied among the treatments at both sites (Figure 20). The TN value ranged from 0.227% to 0.361% at the Dire site and from 0.11% to 0.297% at the Legedadi site. The TN content was higher than the pre-planting soil analysis results, except for the control treatment. The highest TN values of 0.361% at the Dire site and 0.298% at the Legedadi site were obtained with the 100% VC rate. These values were higher than the control by 59.0% at the Dire site and 63.2% at the Legedadi site. Similarly, the combined fertilizers and wheat-faba bean intercropped treatment had TN values that were 35.5% higher at the Dire site and 40.1% higher at the Legedadi site compared to the control.

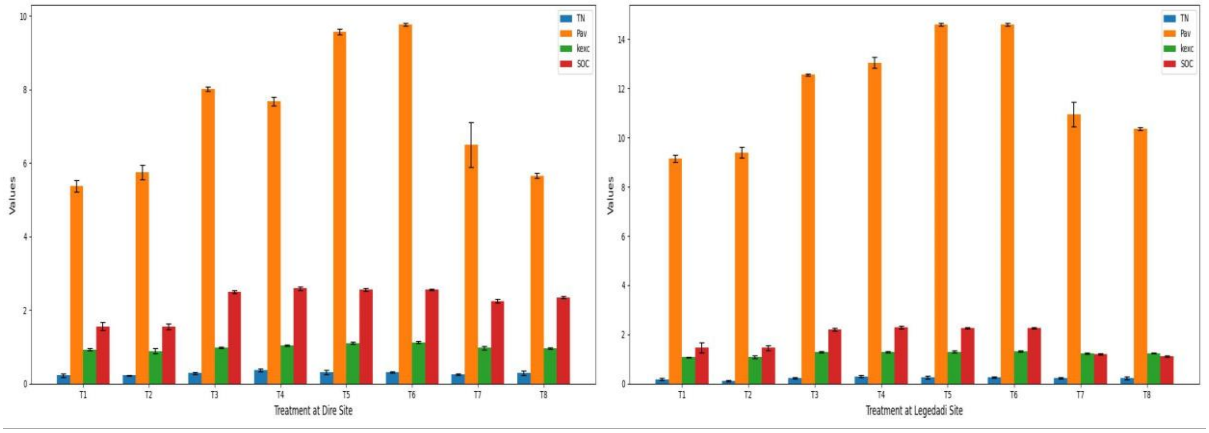


Figure 19: The effect of intercropping and combined fertilizers application on TN, Kexc, and SOC at Dire and Legedadi sites, TN Total Nitrogen, Pav Available phosphorus, SOC soil organic carbon.

4.12.4. Available phosphorus

The mean differences of Pav among the treatments were statistically significant ($P< 0.05$) at both sites. The mean Pav contents of the soil at Dire and Legedadi sites were 7.29±2.02 ppm and 11.83±0.75 ppm, respectively. The highest Pav mean value was observed in combined fertilizers treatment (9.76 ppm and 14.60 ppm) at Dire and Legedadi sites, respectively. The lowest Pav values 5.38 ppm at Dire and 9.15 ppm at Legedadi sites were recorded in the control. The wheat-faba bean intercropped treatment with combined fertilizers had Pav values that were 63% higher at the Dire and 61.1% higher at the Legedadi site compared to the control.

4.12.5. Exchangeable potassium

The analysis of variance revealed significant variation ($p< 0.05$) in exchangeable potassium (Kexc) among the treatments at both sites. Results indicated that the combined fertilizers significantly ($p< 0.05$) increased soil Kexc compared to the sole mineral fertilizers and the control. The Kexc ranged from 0.89 to 1.13 $cmol^{+}\ kg^{-1}$ at the Dire site and from 1.18 to 1.31 $cmol^{+}\ kg^{-1}$ at the Legedadi site after applying a combination of VC and NPS fertilizers (Figure 20). The highest values of Kexc (1.13 $cmol^{+}kg^{-1}$ and 1.31 $cmol^{+}kg^{-1}$) were recorded in combined NPS and VC fertilizers and wheat-faba bean intercropped treatment, whereas the lowest values (0.89 $cmol^{+}kg^{-1}$ and 1.18 $cmol^{+}kg^{-1}$) were recorded in the control at Dire and Legedadi sites,

respectively. The combined NPS and VC fertilizers resulted in a notable increase in Kexc levels, with a 21.57% increase over the control at the Dire site and a 21.48% increase at the Legedadi site.

4.12.6. Exchangeable bases

The combined fertilizers significantly increased Ca^{2+} levels by 20.84% at the Dire site and 26.17% at the Legedadi site compared to the control. Similarly, the sole application of 100% VC increased Ca^{2+} by 18.14% and 17.26%, at Dire and Legedadi sites, respectively. The combined VC and NPS fertilizers increased Na^{+} by 12.21% at the Dire site and 13.18% at the Legedadi site compared to the control (Figure 21).

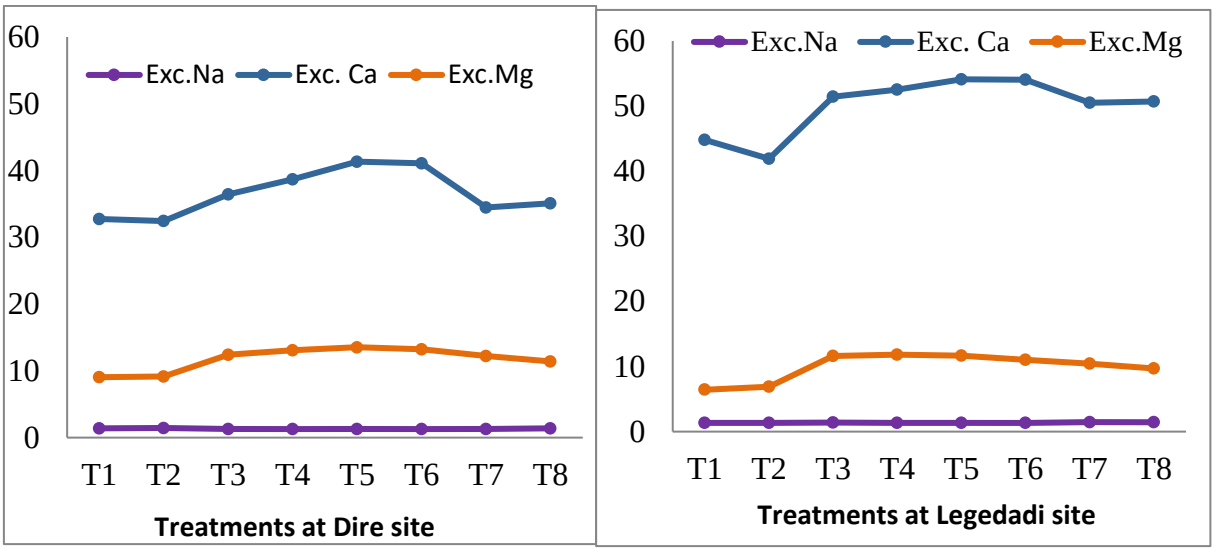


Figure 20: The effect of intercropping and combined fertilizers exchangeable bases at Dire and Legedadi sites

4.12.7. Cation exchange capacity (CEC)

The results indicated a significant ($p< 0.05$) variation in soil CEC among treatments at both sites. CEC ranges from 44.33 to 60.63 $cmo^{+}Kg^{-1}$ at Dire and 52.85 to 64.79 $cmo^{+}Kg^{-1}$ at Legedadi site following the different rates and types of fertilizers applied (Table 16). The full dose VC treatment increased CEC by 36.77% at the Dire site and 22.59% at the Legedadi site compared to the control. Increasing amounts of VC resulted in a significant increase in CEC. The full dose of VC application exhibited the highest CEC values with 60.63 $cmo^{+}Kg^{-1}$ at the Dire site and 64.79 $cmo^{+}Kg^{-1}$ at the Legedadi site. In contrast, the lowest CEC values were

recorded in the control with values of 44.33 $cmol^{+}Kg^{-1}$ at the Dire site and 52.85 $cmol^{+}Kg^{-1}$ at the Legedadi site.

4.13. Soil carbon and carbon sequestration

Table 17, presents the effects of intercropping and combined fertilizer**s** application on soil carbon stock and sequestration at both sites. The full dose VC applied plot resulted in the highest soil carbon stock, with 50.1 t ha^{-1} at the Dire site and 44.4 t ha^{-1} at the Legedadi site. Soil carbon stock increased from 32.2 t ha^{-1} to 50.1 t ha^{-1}, and carbon sequestration rose from 118.3 t ha^{-1} to 183.9 t ha^{-1} at the Dire site. Similarly, at the Legedadi site, soil carbon stock increased from 28.6 t ha^{-1} to 44.4 t ha^{-1}, while carbon sequestration increased from 105.1 t ha^{-1} to 162.8 t ha^{-1}.

The combined application of organic and inorganic fertilizers resulted the second highest soil carbon stock, with values of 49.9 t ha^{-1} at the Dire site and 43.1 t ha^{-1} at the Legedadi site. Similarly, this treatment contributed to notable carbon sequestration value of 183.2 t ha^{-1} and 158.3 t ha^{-1} at Dire and Legedadi sites, respectively. The lowest soil carbon stock value (32.23 t ha^{-1} and 28.63 t ha^{-1}) was recorded in the control plots at Dire and Legedadi sites, respectively. The soil carbon stock and sequestration values in T5 were statistically similar with T6.

The highest soil N stock was observed with the 100% VC treatment, followed by the combined mineral and VC fertilizers at both sites. The soil N stock significantly increased from 4.71 t ha^{-1} to 6.99 t ha^{-1} at the Dire site and from 2.53 t ha^{-1} to 5.53 t ha^{-1} at the Legedadi site with full-rate VC application.

Table 17: Mean effect of intercropping and combined fertilizers application on soil carbon stock and sequestration

T	**Dire Site**			**Legedadi Site**		
	N stock (t ha^{-1})	C stock (t ha^{-1})	C sequestration (t ha^{-1})	N stock (t ha^{-1})	C stock (t ha^{-1})	C sequestration (t ha^{-1})
T1	4.73f	32.37^{f}	118.79^{f}	2.59f	28.86^{f}	105.92^{f}
T2	4.71f	32.23^{f}	118.28^{f}	2.53f	28.63^{f}	105.07^{f}
T3	5.23d	49.33^{c}	181.05^{c}	4.46d	43.38^{c}	156.19^{c}
T4	6.99a	50.10^{a}	183.87^{a}	5.53a	44.37^{a}	162.83^{a}
T5	6.12b	49.92^{b}	183.21^{b}	4.65b	43.13^{b}	158.29^{b}
T6	5.96b	49.73^{b}	182.49^{b}	4.67b	42.95^{b}	157.62^{b}
T7	5.17e	45.28^{e}	166.17^{e}	4.26e	41.49^{e}	152.27^{e}
T8	5.67c	46.73^{d}	167.48^{d}	4.36c	41.05^{d}	150.66^{d}

Mean	5.57	44.46	163.17	4.08	39.23	143.98
SE	0.002	0.024	0.083	0.0002	0.074	0.045
p-value	0.0001	0.0001	0.001	0.001	0.001	0.001
F-value	5.96	68.57	69.7	4.32	75.67	53.29
Sign.	***	***	***	***	***	***

*** designate significant differences at p< 0.001, T Treatment

4.14. Correlation between soil physical and chemical properties

The degree of correlation between physical and chemical properties was generally low. However, BD showed a negative correlation with OC and TN. Among the chemical properties, CEC exhibited a strong positive correlation with OC, Pav, and Kexc at both sites (Table 19). Additionally, FC positively correlates with TN and SOC.

Table 18: Spearman Rank correlations among soil physicochemical properties at Dire and Legedadi sites

Dire	pH	BD	FC	OC	TN	Pav	K
PH							
BD	0.3438						
FC	0.1627	0.0915					
OC	-0.4256	-0.2324	0.7694				
TN	-0.4656	-0.2246	0.6282	0.9813**			
Pav	-0.4427	0.0725	0.6481	0.8725**	0.8047**		
K	-0.4852	0.1298	0.5011	0.9476**	0.9054**	0.9594**	
CEC	-0.3753	0.1851	0.6259	0.9330**	0.8618**	0.9637**	0.9637**

Legedadi	BD	FC	PH	CEC	K	OC	Pav	TN
BD								
FC	0.2776							
PH	0.2190	0.4907						
CEC	0.1224	0.5246	-0.3368					
K	0.1202	0.6771	-0.4890	0.9297**				
OC	-0.2446	0.8282	-0.0835	0.8206**	0.7893**			
Pav	-0.0956	0.7802	- 0.3144	0.9622**	0.9038**	0.7697**		
TN	-0.4173	0.6181	- 0.5192*	0.6948**	0.7733**	0.8200**	0.6410**	

** designate correlation significance at p< 0.01

4.15. Comparison of selected soil parameters between Dire and Legedadi sites

Table 20, presents a comparison of selected soil chemical properties between the Dire and Legedadi sites. The t-test results indicated significant variations in total nitrogen (p = 0.003), available phosphorus (p = 0.0001), exchangeable potassium (p = 0.0001), and soil organic carbon (p = 0.001) between the two sites.

Table 19: Comparison of selected soil parameters at Dire and Legedadi sites

T	Dire	Legedadi	Dire	Legedadi	Dire	Legedadi	Dire	Legedadi	Dire	Legedadi	Dire	Legedadi
	TN (%)		Kexc ($Cmol^{+}kg^{-1}$)		Pav (ppm)		SOC (%)		CEC($Cmol^{+}kg^{-1}$)		pH H_2O	
T1	0.228	0.182	0.927	1.182	5.378	9.153	1.550	1.46	44.33	52.85	5.38	6.38
T2	0.227	0.110	0.888	1.175	5.747	9.398	1.553	1.55	46.46	53.66	5.38	6.38
T3	0.286	0.236	0.974	1.277	8.011	12.555	2.490	2.19	52.33	58.60	5.18	6.14
T4	0.361	0.298	1.047	1.287	7.684	13.052	2.587	2.39	60.63	64.79	5.76	6.68
T5	0.314	0.256	1.103	1.293	9.567	14.604	2.560	2.26	58.76	63.79	5.58	6.56
T6	0.309	0.255	1.127	1.386	9.767	14.603	2.557	2.25	59.61	63.66	5.58	6.56
T7	0.257	0.224	0.97	1.233	6.501	10.952	1.843	1.898	49.34	57.06	5.23	6.21
T8	0.285	0.230	0.958	1.231	5.657	10.353	2.122	1.999	48.67	56.76	5.49	6.44
t	4.75		-5.94		-5.7		-5.35		-7.14		-5.6	
P	0.003***		0.0001***		0.0001***		0.001***		0.0002***		0.0001***	

*** designates significance at p< 0.001, T Treatment, *df* degree of freedom, TN Total nitrogen, Kexc Exchangeable potassium, Pav Available phosphorus, SOC Soil organic carbon

4.16. NPK balances at Dire and Legedadi sites

There was a significant (p< 0.05) difference in partial and full N balances among the treatments at both sites (Table 21). The nitrogen input from VC and mineral fertilizers varied across the treatments. Crops received nutrient inputs of 65.0 kg N ha^{-1} from the application of NPS + urea and 71.6 kg N ha^{-1} from VC at both sites. Nitrogen fixation was recorded at 3.9 kg N ha^{-1} at the Dire site and 4.01 kg N ha^{-1} at the Legedadi site. There was no significant difference in wet deposition and nitrogen fixation across the treatments at both sites. The analysis of N flows indicated that OUT1, OUT2, OUT3 and OUT5 were significantly (p< 0.05) varied among the treatments at both sites (Table 19). The highest values for OUT1 and OUT2 were recorded in the full-dose NPS + urea fertilizers treatment, with values of 71.6 kg N ha^{-1} and 40.6 kg N ha^{-1} at the Dire site, and 73.9 kg N ha^{-1} and 35.2 kg N ha^{-1} at the Legedadi site. No significant differences were observed in partial and full nitrogen nutrient balance among the half-dose VC or mineral fertilizers treatments at both sites. The lowest /highest N deficit/ partial and full N balances were recorded in the full-dose NPS + urea fertilizers with values of -47.2 kg N ha^{-1} and -75.2 kg N ha^{-1} at the Dire site, and -44.1 kg N ha^{-1} and -58.9 kg N ha^{-1} at the Legedadi site. Higher nutrient losses due to erosion were observed at the Dire site compared to the Legedadi site. The combined fertilizers applied treatments had higher/less N deficit/ partial and full N balances compared to the full-dose mineral fertilizer treatments at both sites. Overall,

both full and partial farm-level nutrient balances of N were negative for all treatments at both sites.

Table 20: Full and partial nitrogen balances at Dire and Legedadi sites**.**

T	IN1 (kg N ha^{-1})	IN2 (Kg N ha^{-1})	IN3 (kg N ha^{-1})	IN4 (Kg N ha^{-1})	OUT1 (Kg N ha^{-1})	OUT2 (Kg N ha^{-1})	OUT3 (Kg N ha^{-1})	OUT4 (kg N ha^{-1})	OUT5 (kg N ha^{-1})	Partial N balance (kg N ha^{-1})	Full N balance (kg N ha^{-1})
Dire Site											
T1	00.0±0.0	00.0±0.0	4.65±0.0	0.77±0.0	18.4±2.5	13.4±1.4	3.6±0.4	1.7±0.02	17.6±0.1	-31.0±11.58	-49.3±16.47
T3	65.0±0.0	00.0±0.0	4.65±0.0	0.77±0.0	71.6±5.8	40.6±1.7	4.6±1.2	6.7±0.06	22.1±0.4	-47.2±9.21	-75.2±18.12
T4	0.0±0.0	71.6±0.0	4.65±0.0	0.77±0.0	62.8±5.3	31.4±1.7	5.1±0.2	7.4±0.05	24.9±0.3	-22.6±2.00	-54.6±16.02
T5	32.5±0.0	35.8±0.0	4.65±0.0	0.77±0.0	68.7±4.6	37.3±1.9	4.9±1.4	7.0±0.12	24.2±0.1	-37.7±10.55	-68.4±11.29
T6	32.5±0.0	35.8±0.1	4.65±0.0	0.77±0.0	43.8±2.4	26.9±2.9	4.8±1.3	7.0±0.15	23.8±0.1	-2.4±10.87	-32.7±15.51
T7	32.5±0.0	00.0±0.0	4.65±0.0	0.77±0.0	32.2±3.3	18.6±0.4	2.3±0.9	3.4±0.08	19.8±0.8	-18.3±9.87	-38.5±21.66
T8	00.0±0.0	35.8±0.1	4.65±0.0	0.77±0.0	33.0±4.5	18.9±0.9	2.5±1.1	3.7±0.13	20.4±0.5	-16.4±8.47	-37.4±13.36
F	5.9	13.6	1.16	-	60.55	24.2	24.41	19.26	38.65	57.18	57.15
P	0.02	0.02	0.43	0.49	0.001	0.01	0.01	0.01	0.01	0.001	0.001
Sig.	*	*	ns	ns	**	*	**	**	**	***	***
Legedadi site											
T1	0.0±0.0	00.0±0.0	4.69±0.0	0.85±0.0	23.7±2.1	13.1±0.4	2.42±0.03	3.9±0.22	3.88±0.02	-36.8±3.68	-41.46±4.38
T3	65±0.0	00.0±0.0	4.69±0.0	0.85±0.0	73.9±1.7	35.2±0.6	8.71±0.03	6.45±0.42	5.03±0.03	-44.1±3.41	-58.77±3.81
T4	0.0±0.0	71.6±0.0	4.69±0.0	0.85±0.0	61.8±1.8	30.4±1.7	9.51±0.14	7.0±0.12	5.83±0.02	-20.6±2.62	-37.98±4.61
T5	32.5±0.0	35.8±0.0	4.69±0.0	0.85±0.0	67.3±2.9	34.9±1.3	9.11±0.04	6.76±0.11	5.46±0.03	-33.9±3.71	-49.7±4.14
T6	32.5±0.0	35.8±0.1	4.69±0.0	0.85±0.0	45.4±1.9	28.4±1.7	9.11±0.04	6.76±0.10	5.44±0.03	-5.5±4.41	-21.28±2.55
T7	32.5±0.0	00.0±0.0	4.69±0.0	0.85±0.0	37.7±1.7	20.3±0.2	4.37±0.07	3.24±0.21	4.78±0.06	-25.5±3.77	-32.35±3.78
T8	0.0±0.0	35.8±0.1	4.69±0.0	0.85±0.0	36.7±1.5	17.2±0.4	4.77±0.27	3.54±0.21	4.9±0.23	-18.1±2.44	-25.78±2.63
F	15.9	13.6	1.16	-	41.4	48.8	18.7	11.37	15.3	35.46	45.13
P	0.01	0.01	0.43	0.38	0.001	0.002	0.01	0.01	0.001	0.001	0.001
Sig.	**	**	ns	ns	**	*	**	**	***	***	***

Table 22, presents full and partial phosphorus balances at Dire and Legedadi sites. Significant differences ($p< 0.05$) were observed in partial and full phosphorus balances among the treatments at both sites. The phosphorus input from the applied fertilizers varied across treatments, with an average of 16.3 kg P ha^{-1} from NPS + urea (IN1) and 8.5 kg P ha^{-1} from VC fertilizers (IN2) at both sites. There were no differences in wet (atmospheric) deposition across the treatments at both sites. The highest OUT 1 and OUT 2 values were recorded in the full dose mineral fertilizers applied treatment with values of 20.7 kg P ha^{-1} and 15.3 kg P ha^{-1} at

the Dire site, and 19.7 kg P ha^{-1} and 15.7 kg P ha^{-1} at the Legedadi site, respectively. The P flows of OUT5 were higher at the Dire site compared to the Legedadi site.

The partial phosphorus value for wheat in the full-dose VC treatment was -19 kg P ha^{-1} at the Dire site and -18.6 kg P ha^{-1} at the Legedadi site. Both the partial and the full phosphorus balances in the full-dose VC treatment were higher compared to the full-dose mineral fertilizer treatment at both sites. Treatments with half doses of NPS + urea or VC exhibited lower phosphorus deficits compared to the control. All treatments exhibited negative partial and full phosphorus balances at both sites.

Table 21: Full and partial phosphorus balances at Dire and Legedadi sites

T	IN1 (Kg P ha^{-1})	IN2 (Kg P ha^{-1})	IN3 (Kg P ha^{-1})	OUT1 (Kg P ha^{-1})	OUT2 (Kg P ha^{-1})	OUT5 (Kg P ha^{-1})	Partial P balance (Kg P ha^{-1})	Full P balance (Kg P ha^{-1})
				Dire Site				
T1	0.0±0.0	0.0±0.0	0.76±0.0	6.7±0.26	4.7±2.16	0.41±0.01	-11.4±0.35	-11.1±0.36
T3	16.6±0.0	0.0±0.0	0.76±0.0	20.7±0.35	15.3±5.42	0.62±0.01	-19.4±1.6	-19.3±3.6
T4	0.0±0.0	8.5±0.0	0.76±0.0	16.9±0.50	10.5±5.11	0.75±0.01	-18.9±1.4	-18.9±3.8
T5	8.15±0.0	4.25±0.0	0.76±0.0	19.3±0.57	12.5±2. 5	0.74±0.03	-19.4±1.83	-19.4±2.83
T6	8.15±0.0	4.25±0.0	0.76±0.0	15.4±0.25	9.4±1.43	0.75±0.04	-12.4±1.8	-12.4±3.18
T7	8.15±0.0	0.0±0.0	0.76±0.0	8.8±0.19	6.4±1.16	0.5±0.01	-7.1±1.21	-6.8±1.61
T8	0.0±0.0	4.25±0.0	0.76±0.0	8.7±0.29	6.0±2.12	0.44±0.01	-10.5±1.84	-10.2±1.34
F	8.8	8.6	5.6	5.4	24.6	11.2	41.9	19.4
P	0.01	0.01	0.24	0.013	0.001	0.01	0.001	0.002
Sig.	**	**	ns	**	***	**	***	**
				Legedadi site				
T1	0.0±0.0	0.0±0.0	0.77±0.0	6.9±2.26	4.2±0.26	0.20±0.002	-11.1±1.36	-10.5±3.69
T3	16.3±0.0	0.0±0.0	0.77±0.0	19.7±3.61	15.7±1.35	0.27±0.002	-18.8±2.16	-18.3±2.16
T4	0.0±0.0	13.8±0.0	0.77±0.0	16.3±2.50	10.8±2.28	0.28±0.03	-18.6±2.78	-18.1±2.78
T5	8.15±0.0	6.89±0.0	0.77±0.0	15.5±2.57	10.5±2.17	0.31±0.025	-13.6±2.83	-13.1±2.83
T6	8.15±0.0	6.89±0.0	0.77±0.0	11.2±2.25	9.9±1.24	0.31±0.001	-8.7±1.18	-8.2±1.18
T7	8.15±0.0	0.0±0.0	0.77±0.0	7.8±1.19	6.6±1.21	0.23±0.003	-6.3±1.21	-5.7±1.21
T8	0.0±0.0	6.89±0.0	0.77±0.0	7.7±1.28	6.9±1.11	0.22±0.003	-10.4±2.34	-9.9±1.34
F	8.8	8.6	6.6	27.8	24.6	6.09	8.8	11.3

P	0.01	0.01	0.12	0.001	0.001	0.01	0.001	0.01
Sig.	**	**	ns	**	***	**	***	**

, and *, indicates significance at $p < 0.01$, and $p < 0.001$, respectively, ns: not significant at $p < 0.05$, T treatment

NPS and urea were the sole inorganic fertilizers used in the study areas, with no direct application of potassium from inorganic sources (IN1). Consequently, vermicompost (IN2) which provided 33.9 kg K ha^{-1} at both sites, was the only source of potassium. There were no differences in wet deposition across treatments at both sites. However, potassium output flows, including OUT1, OUT2, OUT3, and OUT5, varied significantly ($p < 0.05$) among the treatments at both sites (Table 23).

Table 22: Full and partial potassium balances in each plot at both sites

T	IN2 (Kg K ha^{-1})	IN3 (Kg K ha^{-1})	OUT1 (Kg K ha^{-1})	OUT2 (Kg K ha^{-1})	OUT3 (Kg K ha^{-1})	OUT5 (Kg K ha^{-1})	Partial K balance (Kg K ha^{-1})	Full K balance (Kg K ha^{-1})
T1	0.0±0.0	3.06±0.0	4.8±1.27	16.5±0.8	0.41±0.01	0.72±0.02	-21.3±2.93	-19.4±3.93
T3	0.0±0.0	3.06±0.0	16.6±2.60	37.7±1.6	0.42±0.06	0.75±0.01	-54.3±4.15	-52.4±5.25
T4	33.9±0.0	3.06±0.0	16.0±2.46	33.4±0.8	9.0±0.02	0.81±0.03	-15.5±1.95	-22.3±3.95
T5	16.95±0.0	3.06±0.0	17.3±3.74	36.1±2.2	7.8±0.08	0.85±0.02	-36.4±4.37	-42.0±4.37
T6	16.95±0.0	3.06±0.0	12.2±2.43	28.1±0.9	7.8±0.07	0.87±0.08	-23.3±2.33	-28.9±2.33
T7	0.0±0.0	3.06±0.0	8.1±2.45	24.2±1.1	0.42±0.04	0.75±0.04	-32.3±4.4	-30.4±3.6
T8	16.95±0.0	3.06±0.0	6.9±1.41	29.6±0.9	7.7±0.01	0.74±0.0	-19.6±2.27	-24.9±2.27
F	18.2	9.6	49.4	30.68	18.67	17.56	55.27	58.7
P	0.01	0.33	0.02	0.001	0.01	0.03	0.001	0.001
Sig.	**	ns	*	***	*	*	***	***
				Legedadi				
T1	0.0±0.00	3.08±0.0	4.1±0.06	9.4±1.32	0.47±0.07	0.23±0.01	-13.5±1.29	-11.1±1.29
T3	0.0±0.00	3.08±0.0	20.5±0.48	40.6±1.69	0.55±0.01	0.273±0.02	-61.2±2.07	-58.9±2.07
T4	33.9±0.00	3.08±0.0	21.2±0.39	36.3±5.83	9.29±0.08	0.274±0.01	-23.6±5.91	-30.1±5.81
T5	16.95±0.00	3.08±0.0	25.1±0.74	38.6±3.01	7.93±0.08	0.275±0.03	-46.8±3.34	-51.9±3.34
T6	16.95±0.00	3.08±0.0	19.0±0.45	31.8±3.59	7.93±0.01	0.278±0.02	-33.8±3.19	-38.9±3.19

T7	0.0±0.00	3.08±0.0	16.1±0.4	14.1±1.33	0.49±0.08	0.241±0.01	-30.2±2.87	-27.8±2.97
T8	16.95±0.00	3.08±0.0	16.3±0.15	18.2±2.61	7.87±0.02	0.243±0.03	-17.5±1.57	-22.6±3.47
F	18.2	0.23	37.6	43.38	16.57	15.23	49.06	51.85
P	0.01	0.43	0.01	0.001	0.02	0.02	0.001	0.001
Sig.	**	ns	**	***	*	*	***	***

*, **, and ***, indicates significance at $p< 0.05$, $p< 0.01$, and $p< 0.001$, respectively, ns: not significant at $p< 0.05$, T Treatment.

The results showed that treatment with a full dose of VC resulted in the lowest potassium deficit, with the highest partial and full potassium balances being -15.5 kg K ha^{-1} and 22.3 kg K ha^{-1} at the Dire site, and -23.6 kg K ha^{-1} and -30.1 kg K ha^{-1} at the Legedadi site. In contrast, the highest potassium deficit was observed in plots receiving a full dose of mineral fertilizers at both sites, with average partial balances of -54.3 kg K ha^{-1} and -61.2 kg K ha^{-1} at Dire and Legedadi sites, respectively. Overall, all plots showed negative partial and full potassium balances at both sites.

4.16.1. Full and partial NPK balances at Dire and Legedadi sites

The partial and full N, P and K balances were significantly ($p< 0.05$) different between the treatments. The full and partial N balances were significantly ($p< 0.05$) higher in 100% VC compared to those receiving combined fertilizers or full dose sole mineral fertilizer at both sites. In the full dose VC treatment, the average total nitrogen input (IN2) was 71.6 kg N ha^{-1}. The corresponding nitrogen exports (OUT1 and OUT2) were 62.8 kg N ha^{-1} and 31.4 kg N ha^{-1} at the Dire site, and 61.8 kg N ha^{-1} and 30.4 kg N ha^{-1} at the Legedadi site. Thus, the partial balance was -22.6 kg N ha^{-1} at the Dire site and -20.6 kg N ha^{-1} at the Legedadi sites. The most significant negative nitrogen full balance was observed in the wheat-faba bean intercropping treatment with combined fertilizers, with values of -164.5 kg N ha^{-1} at the Dire site and -174.5 kg N ha^{-1} at Legedadi site.

All treatments showed a negative partial and full P balance at both sites. The full-dose VC treatment showed the highest phosphorus balances at both sites, compared to those receiving either combined fertilizers or full doses of mineral fertilizers. This treatment achieved a full phosphorus balance of -18.9 kg P ha^{-1} at the Dire site, while at the Legedadi site, the balance was -18.1 kg P ha^{-1}. The highest negative P full balance was recorded on wheat faba bean

intercrop with combined fertilizers applied treatments with values of -31.6 kg P ha^{-1} at Dire site and -22.8 kg P ha^{-1}.

The wheat-faba bean intercropping treatment with combined fertilizers exhibited the highest potassium deficiency, with full K balances of -145.4 kg K ha^{-1} at the Dire site and -154.9 kg K ha^{-1} at the Legedadi site. In contrast, the full dose VC applied treatment exhibited a lower potassium deficiency at both sites.

The partial K balances for the full dose VC treatment were negative, with values of -15.5 kg K ha^{-1} at Dire and -23.6 kg K ha^{-1} at Legedadi site. All treatments across both sites demonstrated negative full and partial K nutrient balances (Figure 22).

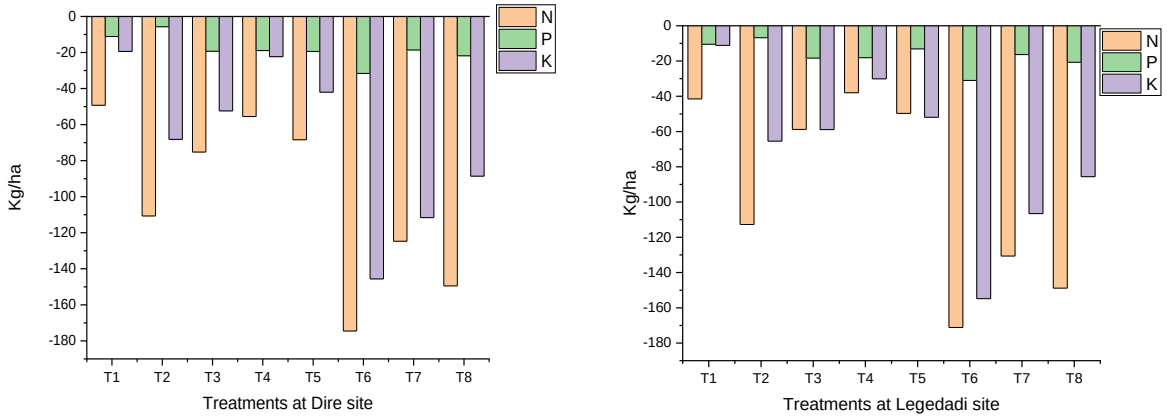
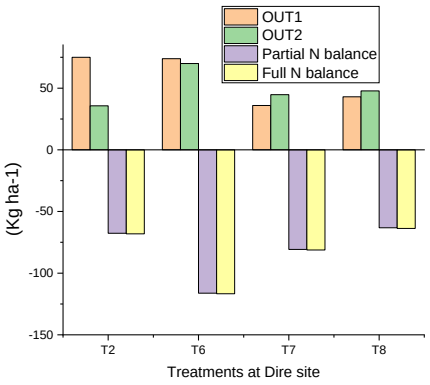


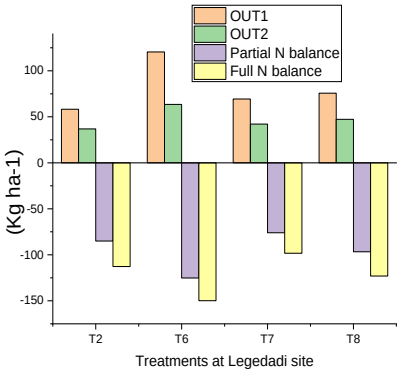
Figure 21: Full N, P and K (kg ha^{-1}) nutrient balances in each plot at Dire and Legedadi sites in 2021and 2022 (combined over years) cropping seasons

4.16.2. NPK balances of Faba bean at Dire and Legedadi sites

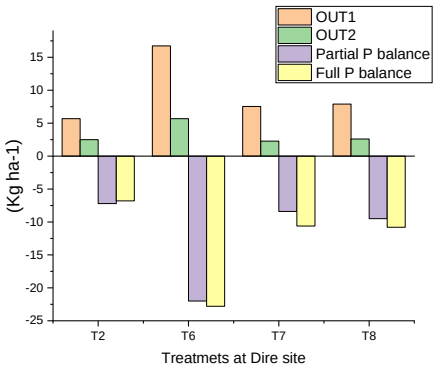
The highest OUT1 and OUT2 of faba bean were recorded in wheat–faba bean intercropped with half dose NPS + urea and VC treatment at both sites. The partial and full NPK nutrient balances were also highest in the intercropped treatments that received a combination of NPS and VC fertilizers (Figure 23).


OUT1
OUT2
Partial N balance
Full N balance
(Kg ha-1)
50
0
-50
-100
-150
T2
T6
T7
T8
Treatments at Dire site

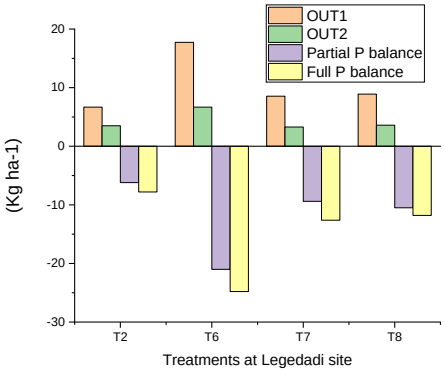
A


OUT1
OUT2
Partial N balance
Full N balance
(Kg ha-1)
100
50
0
-50
-100
-150
T2
T6
T7
T8
Treatments at Legedadi site

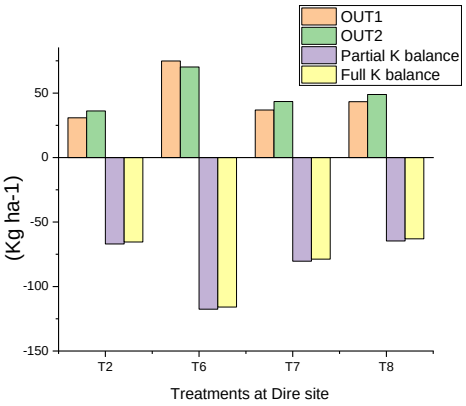
B


OUT1
OUT2
Partial P balance
Full P balance
(Kg ha-1)
15
10
5
0
-5
-10
-15
-20
-25
T2
T6
T7
T8
Treatmets at Dire site

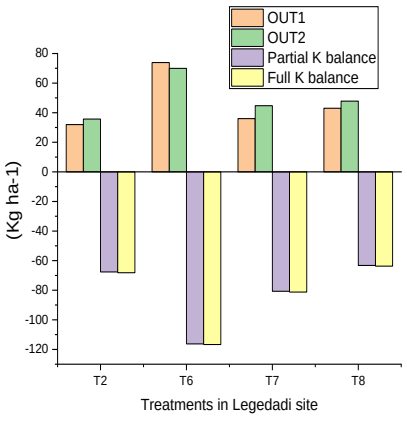
C


OUT1
OUT2
Partial P balance
Full P balance
(Kg ha-1)
20
10
0
-10
-20
-30
T2
T6
T7
T8
Treatments at Legedadi site

D


OUT1
OUT2
Partial K balance
Full K balance
(Kg ha-1)
50
0
-50
-100
-150
T2
T6
T7
T8
Treatments at Dire site

E


OUT1
OUT2
Partial K balance
Full K balance
(Kg ha-1)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
T2
T6
T7
T8
Treatments in Legedadi site

F

Figure 22: A, B, C, D, E, F, Faba bean OUT1, Out2, partial and full nutrient nitrogen (N), phosphorus (P) and potassium (K), (kg ha^{-1}) balances, respectively at Dire and Legedadi site.

Chapter five

5. Discussion

5.1. Effect of treatments on crop growth parameters

Plant productivity and growth rate are correlated with plant height (Sritarapipat et al., 2014). The tallest faba bean was observed in the wheat-faba bean intercrop when a combination of half doses of both VC and NPS fertilizers were applied at both sites. This could be due to the increase in the uptake of available nutrients and the variation in the major nutrient content among the different fertilizer sources (Armin et al., 2016). A similar result was also reported by (Ahmad and Maaroof, 2020, Biswas et al., 2019, Ginwal et al., 2019, Hailu, 2019) who noticed a significant variation in plant height among intercropped plots which may be due to the competition for light, which can lead to increased plant height.

The treatment with combined fertilizers resulted in the highest wheat height compared to other treatments. This improvement may be attributed to the combined effect of the fertilizer application. Combination of organic and inorganic fertilizers enhance water retention, aeration, and root development, allowing plants to access nutrients more efficiently (Ahmad and Aslam, 2018). These findings align with previous studies (Demissie et al., 2017, Habtamu et al., 2015, Mahmud et al., 2016, Woldesenbet and Tana, 2014) that higher plant height was observed in plots treated with combinations of compost and inorganic fertilizers.

The mean plant height of wheat exhibited a decreasing trend across treatments at both study sites, in the order: T5 > T6 > T3 > T7 > T8 > T1. Moreover, simultaneous use of NPS and VC fertilizers also showed a significant ($P< 0.05$) difference in spike length, tiller number and number of seeds $spike^{-1}$. There was a decreasing trend in the mean SPS from T3 >T5 >T6> T4> T7> T8> T1 at both sites. This may be due to root growth and increased nutrient uptake

produced by combined fertilizers application, better growth of nutrient synergy, and the availability of adequate crop nutrients at adequate levels. In this regard, supplying the plants with the appropriate amounts and forms of nutrients enhanced crop growth and growth parameters (Saudy and Mohamed, 2023).

5.2. Wheat and faba bean yield

The highest mean wheat grain and straw yield, next to the sole mineral fertilizer treatment, was obtained when half rate of the recommended mineral fertilizer was applied in combination with half rate of the recommended VC. Wheat responded to vermicompost only when combined with mineral fertilizer. This highlights the significance of combining organic and mineral fertilizers for improved yield. Specifically, this treatment resulted in a grain yield increase of 173.3% at the Dire site and 150.8% at the Legedadi site than the control. The impact of different nutrient sources on grain yield may be attributed to the varying concentrations of NPS in the applied fertilizers. Similarly, (Almaz and Tadesse, 2018, MoA, 2016, Tehulie and Eskezia, 2021, Woldesenbet and Tana, 2014) reported that the use of both organic and inorganic fertilizers improved yields and provided additional soil and environmental benefits, contributing to sustainable production.

However, this did not align with the gross marginal rate of return, which was highest for the wheat-faba bean intercrop with half the recommended rate of both mineral fertilizer and VC. This is mainly due to the flexibility of intercropping to take advantage of varying market prices and demand for different crops. A similar result was reported by (Kermah et al., 2017) that economic returns were greater for intercrops than for sole crops.

There was a linear increase in both grain and biomass yield of wheat with increasing levels of fertilizer suggesting that the diminishing rate of return has not yet been reached. This suggests that, for every additional unit of fertilizer applied, there is a consistent and predictable increase in both grain and biomass production. A similar result was reported by (Godebo et al., 2021) that increasing nitrogen fertilizer rates resulted in a corresponding increase in biomass yield.

The highest wheat yield was obtained with the application of full dose mineral fertilizer. This is likely because nutrients from mineral sources are more readily available to plants (Hammad et al., 2020). This result is in accordance with the reports of (Agegnehu et al., 2008, Hadis et

al., 2018, Mahmud et al., 2016) that, the highest wheat yield was recorded from the application of recommended rate of NPK fertilizer.

The highest total intercrop wheat yields were 2647 kg ha^{-1} at the Dire site and 2510 kg ha^{-1} at the Legedadi site. These wheat yields were achieved with the combined application of half doses of both NPS and VC fertilizers, outperforming other intercropped plots and the control. Therefore, the application of combined VC and mineral fertilizers in intercropping systems can sustain the yield of wheat.

Research by (Girma et al., 2019, Negash and Starr, 2015) indicated intercropping systems result in increased total yield and economic return compared to sole cropping systems. For instance, a three-year study of sorghum/groundnut and sorghum/soybean intercropping in Asosa showed that sorghum/groundnut intercrop had the highest sorghum yield across all growing seasons (Dereje et al., 2016). This result further justifies there is a fertilizer response of intercropping to get better yield. This may be due to intercropping of cereal and leguminous crops, as nitrogen can build up under nodule conditions. Such cooperation is expressed in a higher yield of the mixture than the yield of a single culture (Gao and Wu, 2014). The main advantage of intercropping is its ability to utilize available resources more efficiently and achieve greater productivity compared to each crop grown individually (Mobasser et al., 2014). In addition to yield, intercropping helps to reduce disease incidence (Zhang et al., 2019).

Significant variations in wheat yield, biomass, and straw yield were observed between the Dire and Legedadi sites. This variability is likely due to differences in soil properties at these locations, which significantly impact crop productivity. Significant variations in total nitrogen ($p = 0.003$), available phosphorus ($p = 0.0001$), exchangeable potassium ($p = 0.0001$), and soil organic carbon ($p = 0.001$) were observed between the Dire and Legedadi sites. This soil heterogeneity plays a crucial role in determining crop yields among farmers in Ethiopia (Haileselassie et al., 2011). Furthermore, factors such as elevation, slope, and natural drainage patterns can influence soil moisture levels and erosion, which further influence crop yield outcomes (Ghosh et al., 2014). Farmers and agricultural planners must carefully consider site-specific characteristics when selecting crop planting locations to maximize yield potential.

The study also reveals that both site conditions and treatment methods have significant impacts on crop yield within the study areas. These results underscore the critical roles played by location and the specific interventions (treatments) applied in determining crop productivity. Importantly, the effectiveness of treatments can vary significantly across different sites, highlighting the need for tailored treatment strategies that account for the unique conditions of each location to optimize crop yield. Further research is needed to understand the specific factors at each site that contribute to differences in crop yield.

5.3. Competition indices

In the intercropped plots of wheat and faba bean, the combined VC and mineral fertilizers resulted in the highest wheat LER, with values of 1.89 at the Dire site and 1.76 at the Legedadi site. This indicates that the intercropping system achieved 89% (0.89 ha) and 76% (0.76 ha) higher yields compared to a sole cropping system, meaning that more land area would be required for sole cropping to match the yield of the intercropping (Midya et al., 2005). These results are in line with a study by (Debela, 2022) that intercropping wheat and faba bean showed a yield advantage with LER values of 0.99 for wheat and 0.31 for faba bean, respectively.

The LER values exceeding one, as evidenced in the wheat component of the intercropping systems at both sites, signify the benefit of intercropping in terms of resource utilization for plant growth and higher total production when compared to sole cropping (Mead and Willey, 1980). This implies that intercropping led to greater land use efficiency, where the positive interactions between different plant species outweighed any negative competition between them (Machiani et al., 2018).

Similar results have been reported for various intercropping systems, such as wheat-pea (Pankou et al., 2021), wheat-maize (Gou et al., 2016) and wheat-faba bean (Xiao et al., 2021, Agegnehu et al., 2008), *tef*-lupine (Hunegnaw et al., 2022), maize-soybean (Xu et al., 2020), maize-peanut (Feng et al., 2021) that intercropping led to increased efficiency in land utilization. The partial LER values also demonstrated that wheat had higher land use efficiency than faba bean in all intercropping combinations. The appropriate selection of plants and cropping techniques, as well as the existence of mutualism symbiosis between intercropped plants, can boost land productivity (Hafid et al., 2021).

The relative crowding coefficient (K) indicated that wheat was the dominant crop, exhibiting a higher K value than faba bean, which had a lower K value under the treatment with a half dose of both VC and NPS fertilizers at both sites. The K values of wheat were greater than a unit in all intercrop treatments and at both sites, indicating that wheat was more efficient in utilizing available resources. According to (Willey, 1979a) a crop with relatively lower k and negative (A) values is regarded as being dominated while one with the opposite values is dominant. In this study, faba bean was dominated by wheat. This result corroborates that of (Agegnehu et al., 2008, Mahmud et al., 2016) all k values of wheat were greater than unit indicating wheat dominated faba bean in the mixture. The System Productivity Index (SPI) analysis standardizes the yield of the secondary crop (faba bean) relative to the main crop (wheat). SPI also identified the combinations that utilized the growth resources most effectively and maintained a stable yield performance (Agegnehu et al., 2008). In this study, the highest mean SPI value was recorded in half dose of both NPS and VC-added treatments at both sites. This suggests that intercropping wheat and faba bean with a half dose of both NPS and VC fertilizers is a profitable approach.

5.4. Nutrient use efficiency of wheat

The findings indicated that the combined use of NPS and VC fertilizers resulted in increased nitrogen and phosphorus uptake in both the straw and grain compared to the control at both sites. This resulted in 233.3% and 178.9% higher total N and P uptake respectively, than the control at Dire site. This implies that the combined application of mineral and VC fertilizers had better agronomic value than the control. This finding aligns with the report of (Qaswar et al., 2020) that the simultaneous use of mineral fertilizer and manure increased N, P and K uptake. These findings were also corroborated by the results of (Agegnehu et al., 2016, Hadis et al., 2018, Qaswar et al., 2020, Moe et al., 2017) that grain and straw N uptake showed an increase when a combination of organic and mineral fertilizers were applied, as compared to the use of either one individually. This effect might be attributed to the combined fertilizers improving soil physical characteristics that support root growth and distribution while reducing nitrogen loss, leading to increased nutrient uptake by the crops. Similarly, (Zhihui et al., 2016) reported that manure addition enhanced maize N uptake by 43% from a long-term (28-years) experiment in China.

The combined application of half doses of both NPS and VC resulted in the maximum agronomic efficiency values of 40.0 kg grain per kg N at the Dire site and 42.0 kg grain per kg N at Legedadi site. Higher agronomic efficiency values from the combined application of fertilizers suggest greater improvement in soil health. These findings can be compared to the results of (Gadisa and Wakgari, 2021, Agegnehu et al., 2016b) in Ethiopia, (Dorsey, 2014) in the USA and (Zheng et al., 2017) in North China that agronomic N efficiency was higher in a plot with combined application of organic and nitrogen fertilizers. This indicates that combined fertilizer application is effective in boosting agronomic efficiency.

5.5. Economic analysis

The economic analysis revealed that the wheat and faba bean intercrops with the application of half doses of NPS and VC fertilizers were the most profitable at both sites. The partial budget analysis indicated that the most substantial net benefits (US$ 5598.1 ha^{-1} and 5690.8 ha^{-1}) were achieved from wheat-faba bean intercrop with a combination of NPS and VC fertilizers. Despite the increase in yield attributed to VC, it's important to highlight that the variable costs associated with VC treatments were higher. Consequently, this led to an overall lower economic benefit when compared to the combined use of NPS and VC.

Therefore, at both sites, the treatment combination of half dose of both NPS and VC fertilizers, along with wheat-faba bean intercrop, emerged as the most economically advantageous choice with marginal rates of return (MRR) 4890.4% and 4227.2% at Legedadi and Dire site, respectively. The use of wheat-faba bean intercropping with combined fertilizers is therefore promoted for farmers at Dire, Legedadi, and other locations with similar agroecological conditions to increase crop yields.

4.6. Correlations among wheat yield parameters

Grain yield was positively correlated with plant height ($r = 0.80$; $r=0.88$) and total biomass ($r = 0.99$; $r=0.98$) at Dire and Legedadi sites, respectively. Studies indicated a positive correlation between grain yield and growth-related traits, such as plant height and spike length (Seyoum et al., 2021, Baye et al., 2020). Similarly, (Mecha et al., 2017) reported that there is a significant positive correlation between grain yield and biomass. These correlations provide

valuable insights for improving wheat yield through targeted breeding efforts and optimizing agricultural practices (Ullah et al., 2021).

Seed per spike also positively correlated with yield (r = 0.97; r=0.93), and spike length (r = 0.78; r=0.89) at Dire and Legedadi sites, respectively. A positive correlation between spike length and grain yield indicates that longer spikes tend to be associated with higher yields (Zarei et al., 2013).

5.7. Soil physicochemical properties of the experimental fields before treatments

The bulk density was measured at 1.33 g/cm³ for the Dire site and 1.27 g/cm³ for the Legedadi site, indicating favorable conditions for vigorous root growth in the clay soil (Hazelton & Murphy, 2016). The soil electrical conductivity at both study sites was low (<2 mS/cm), indicating non-saline conditions according to EthioSIS (2014) ratings (Karltun et al., 2013). According to EthioSIS (2014), the soil pH values at the Dire site were strongly acidic, while those at the Legedadi site were moderately acidic.

Based on the ratings (Hazelton and Murphy, 2016) SOC of both study areas' was found low (1.0-1.71). Similarly, total nitrogen was low (0.1-0.15) at the Legedadi site and optimum (0.15-0.3) at Dire site (EthioSIS, 2014). The contents of Pav were low (5-10 mg/kg) at both study sites. According to (Okalebo et al., 2002), low soil test Pav values are defined as being at or below 10 mg/kg, the threshold below which phosphorus effects are expected. The Cation exchange capacity of the soils was high (>40 $Cmol^{+}kg^{-1}$) based on (Hazelton and Murphy, 2016) interpretation.

5.8. Effects of ISFM practices on soil physical properties

The analysis of variance results of soil physical properties revealed that there is no significant difference (p> 0.05) in the proportion of sand, silt, and clay content among the treatments. According to the USDA soil texture classification system, the proportion of the soil at Dire and Legedadi sites were predominantly clay particles (44.88% and 66.08%), respectively. Texture, an essential property of the native soil, does not change with short-term agricultural activities.

The highest sand content was observed in sole wheat with full dose mineral fertilizer at both study sites. A similar finding was reported by (Tesfahunegn and Gebru 2020) at Dura catchment in northern Ethiopia. The highest sand content in the sole crop may be associated with repeated cultivation and inorganic fertilization for a long time. Such practices aggravate the effect of erosion that erodes fine soil particles and leaves coarser particles (Jafari et al., 2022).

5.8.1. Bulk density

The mean bulk density values of 1.28 at Dire and 1.21 g cm^{-3} at Legedadi site, were below the critical value (1.4 g cm^{-3}), which is within the range recommended for plant growth (Hazelton and Murphy, 2016). All VC-treated plots showed a substantial reduction in soil BD. This improvement is attributed to the organic inputs, which enhance soil structure, leading to better water and nutrient retention. This result is in accordance with the findings of (Iqbal et al., 2019, Demir, 2019, Emamu and Wakgari, 2021, Mishra et al., 2017) who reported decreased BD values with VC amendments. Similarly, (Mishra et al., 2017) reported that the application of organic manures to the soil resulted in more pore space and good soil aggregation.

This suggests that the application of VC improved aeration, creating conditions more conducive to nutrient and water retention (Lim et al., 2015). The Spearman rank correlation also confirmed negative correlations between BD and SOC (-0.232, -0.244) at Dire and Legedadi sites, respectively.

5.8.2. Water holding capacity

Vermicompost added treatments demonstrated better water-holding capacity than those with mineral fertilizers and the control at both study sites. The addition of VC significantly enhanced the soil's water holding capacity by 55% compared to the application of mineral fertilizer. Numerous studies (Randall and Macgregor, 2022, Lishan and Alemu, 2024, Emamu and Wakgari, 2021, Abebe and Tana, 2021, Mintesinot, 2020, Demir, 2019) reported that VC application enhanced soil moisture contents and water holding capacity. This is mainly because VC is one of the stabilized, finely divided organic fertilizers with high water holding capacity (Melenya et al., 2015). In addition, applying organic matter helps to maintain a good tilt, improving aeration for seed germination and the growth of plant roots (Edwards and Hailu, 2011). In areas like Dire and Legedadi that are prone to erosion and declining crop productivity,

adding VC to the soil can enhance water-holding capacity and supply essential nutrients to plants.

5.9. Effects of ISFM practices on soil chemical properties

5.9.1. Soil pH and electrical conductivity

According to EthioSIS (2014), soil pH-H_2O at Dire site ranged from (5.18-5.76) with a mean value of 5.45±0.05 rated as strongly acidic to moderately acidic. Similarly, soil pH of Legedadi site ranged from (6.14-6.68) with a mean value of 6.42±0.02 and rated as moderately acidic (Debele, 1982). The wheat-faba bean intercropped treatment had a significantly higher pH value /less acidic/ compared to the control, but it did not differ significantly from the sole wheat treatment with similar fertilizer rates and types. This indicates that the fertilizer had a greater impact on pH value than the intercrop.

The maximum pH value was observed in the treatment with full dose VC addition at both sites. A similar result was reported by (Emamu and Wakgari, 2021, Hossain and Ryu, 2017, Sigaye et al., 2020, Demelash et al., 2014, Angelova et al., 2013, Ozlu and Kumar, 2018) indicating that maximum soil pH was observed in plots treated with organic fertilizers. The increase in soil pH resulting from the application of VC may be attributed to its high concentration of basic cations, which help buffer the soil against a decrease in pH (Assefa and Tadesse, 2019).

In acidic soil areas like Dire and Legedadi, adding VC is essential, as it enhances soil pH and provides a liming effect to modify soil acidity. It also reduces exchangeable acidity and aluminum levels by displacing acidic cations from the exchange sites (Bekele et al., 2018). These benefits help mitigate the negative effects of acidic soil on soil quality and crop productivity. Additionally, incorporating VC promotes soil sustainability and leverages its quality.

In the current study, the lowest pH value was recorded with full dose inorganic fertilizer treatment. This may be due to the acidifying effect of ammonium sourced fertilizer (urea) that oxidized and liberated H^+ ion with NO_3^- leaching/crop uptake and H^+ release of the crop roots to the soil solution (Desta, 2015). NPS and urea fertilizers were solely used in the study areas

for a long time. Repeated applications of N fertilizer may result in soil acidification because of the acidity produced in the nitrification process (Liu et al., 2023).

5.9.2. The electrical conductivity (EC)

The highest EC value was recorded on plots that received a combination of VC and NPS fertilizers measuring 0.141 ds/m at Dire site and 0.052 ds/m at Legedadi sites. This result is in line with (Ozlu and Kumar, 2018, Islam et al., 2017, Geremu et al., 2020, Workineh et al., Asaye et al., 2022) who suggested that the addition of VC to the soil significantly increased EC compared to the application of mineral fertilizer alone in southern Ethiopia. The increased soil EC with the organic amendment is probably due to the release of nutrients (eg. potassium, calcium, magnesium, and sodium) resulting from the decomposition of organic matter in the applied manures (Dhaliwal et al., 2023).

5.9.3. Soil organic carbon

Soil organic carbon is the key element that determines soil quality, fertility, and agricultural profitability (Wawrzyńska and Sirko, 2014). According to (Debele, 1982), (Hazelton and Murphy, 2016), and (Karltun et al., 2013), mean SOC values (2.22) at Dire site and (2.09) at Legedadi site fall into the medium range. Similar to pH, SOC is more affected by the type of fertilizers used than by the cropping system or intercrop.

The application of full dose VC increased the content of SOC by 66.0% and 61.5% than the control at Dire and Legedadi sites, respectively. A similar result was also reported by (Ogundijo et al., 2014) that the application of 5 t ha^{-1} poultry manure significantly increased SOC over the sole application of 120 kg ha^{-1} NPK and the control by 31.2% and 21.2%, respectively. Numerous studies have also reported the application of VC as a practice to increase SOC content (Valdez-Perez et al., 2011, Bai et al., 2013, Desta, 2015, Emamu and Wakgari, 2021). Similarly, studies by (Desta, 2015, Tilahun et al., 2013) in Ethiopia, (Mukta et al., 2015) in Bangladesh (Hammad et al., 2020) in Pakistan (Ding et al., 2012) in China and (Subehia et al., 2013) in the western Himalayas proved that addition of organic fertilizer improved SOC.

The highest possible sustainable agricultural yield and environmental safety are achieved by using organic fertilizer, which also improves soil quality (Lal 2013). Soil organic carbon plays

an essential role in providing plant nutrients, enhancing Cation exchange capacity, supporting soil biological activity, enhance soil aggregation and water retention (Ogundijo et al., 2015). Based on the current results, it is recommended to incorporate VC to boost SOC content, particularly at Dire and Legedadi farmlands with low SOC and limited soil nutrients.

5.9.4. Total nitrogen

Nitrogen is among the nutrients needed in large amounts by all plants. It is also one of the primary limiting nutrients in Ethiopian soils, contributing significantly to high yield gaps (Wolde-Meskel et al., 2018). In the current study, the TN was in the range of 0.23-0.36% at Dire site and 0.11-0.30% at Legedadi site. According to the EthioSIS rating, the TN of the study areas is optimum, with average mean values of 0.28 mg kg^{-1} and 0.22 mg kg^{-1} at the Dire and Legedadi sites, respectively.

The highest TN content (0.36% and 0.30%) recorded at Dire and Legedadi sites was recorded in the treatment with a full dose of VC. This finding is in line with (Emamu and Wakgari, 2021, Zupanc and Justin, 2010, Bekele et al., 2018) which confirm that TN is enhanced through the application of organic matter in the form of VC. Similarly, (Efthimiadou et al., 2010, FAOSTAT, 2017) stated that soil TN increases when bio-fertilizers are solely applied due to the addition of organic matter. As the amount of SOC increases through the application of VC, it also increases TN. This can be evidenced by the significant and positive correlation (r=0.82** and r= 0.981**) between TN and SOC at Dire and Legedadi site, respectively.

The intercropped treatments had significantly higher TN values than the control. Similarly, (Yildirim et al., 2020) reported that intercropping is an effective method to increase fertilizer use efficiency and soil nitrogen. In the other hand, addition of half rate combined VC and NPS fertilizers also enhances TN of soil. There are similar findings reported by (Emamu and Wakgari, 2021, Sigaye et al., 2020, Sumarni et al., 2012, Gebremichael et al., 2017), indicating that combined application of organic and inorganic fertilizers are considered a good option to improve nutrient recovery, enhance soil nutrient, and increase plant growth and yield. Additionally, the combined application of organic and inorganic nutrient sources improved synergism and synchronization between nutrient release and plant recovery (Chen et al., 2001).

Incorporating vermicompost either alone or in combination with mineral fertilizer into soil management practices leads to healthier soil and more sustainable agricultural practices.

5.9.5. Available phosphorus

Phosphorous is called as the key to life as it exerts varied functions in plant metabolism (Dobocha and Bekele, 2021). Soils with Pav < 10, 11-31, 32-56, >56 ppm are described as low, medium, high, and very high, respectively (Tekalign et al., 1991). Hence, the mean result showed that Pav values of the study areas were found low at Dire and medium at Legedadi site. There was a significant Pav content difference between the intercropped plot and the control. The combined application of the VC and mineral fertilizers significantly ($p< 0.05$) increased Pav by 52.82% and 58.79% over the control at Dire and Legedadi sites, respectively. This might be due to the release of phosphorus from VC and NPS fertilizers supply to the soil as well as the decrease of phosphorus fixation, and the enhanced phosphate mineralization from compost (Sharma et al., 2013). Similarly, (Tilahun et al., 2013) reported that the combined application of 15 t ha^{-1} FYM and 100 kg P_2O_5 ha^{-1} increased the available phosphorous from 11.9 ppm to 38.1 ppm.

As the amount of SOC increases Pav also increases, which can be evidenced by the positive and significant correlation (r=0.873** and r= 0.769) between phosphorus and organic carbon at Dire and Legedadi sites, respectively. The result is in agreement with (Kisinyo et al., 2014, Emamu and Wakgari, 2021, Opala et al., 2015, Bayu, 2020, Bedada et al., 2014) reported that the application of compost combined with mineral fertilizers increased the content of available phosphorus.

5.9.6. Effects of ISFM practices on Exchangeable bases

5.9.6.1. Potassium

The exchangeable potassium (Kexc) ranged from 0.89-1.13 $cmol^{+}kg^{-1}$, and 1.18-1.31 $cmol^{+}kg^{-1}$ after applying VC and mineral fertilizers. These values at both sites were high according to ratings by (FAO, 2006). The highest values of Kexc (1.13 $cmol^{+}kg^{-1}$ and 1.31 $cmol^{+}kg^{-1}$) were recorded from combined fertilizers added treatment. In agreement with this, (Ibrahim et al., 2015, Adeyeye et al., 2017) reported that the highest availability of Kexc was found from

compost addition. Therefore, the increment in Kexc over the control might be due to high potassium content and potassium released from VC to soil (Emamu and Wakgari, 2021).

5.9.6.2. Calcium and sodium

Full dose VC rate application increased Ca^{2+} by 18.14% and 17.26% at Dire and Legedadi sites, respectively over the control treatment. The result was in agreement with (Schulz and Glaser, 2012) that calcium content was 10-21 times higher in biochar + compost added samples. This may be due to nutrients such as nitrates, phosphates and exchangeable calcium are in available forms in vermicompost (Olle, 2019). It was also observed that the combined application of VC and mineral fertilizer increased Na^+ more than other treatment combinations. Specifically, the combined organic and inorganic fertilizers application increased Na^+ by 11.47% and 12.53% at Dire and Legedadi sites over the control. A similar result was reported by (Bekele et al., 2018, Alamayo et al., 2022) who indicated that exchangeable soil bases increased when the biofertilizer was applied alone or in combination with the lime and P fertilizer. Therefore, the increase in soil Na^+ could be due to added Na from VC (Bekele et al., 2018).

5.9.6.3. Cation exchange capacity (CEC)

Cation exchange capacity (CEC) is a fundamental soil property used to predict plant nutrient availability and retention in the soil (Rahal and Alhumairi, 2019). In the current study, CEC values range from 44.33 to 60.63 $cmol_+/kg$ at the Dire site and from 52.85 to 64.79 $cmol_+/kg$ at the Legedadi site. Based on (Hazelton and Murphy, 2016) interpretation, these values fall in the very high range (>40 $Cmol^+kg^{-1}$). The highest values of Kexc were recorded from combined fertilizers added treatment. The increment in CEC over the control might be directly related to the increasing of soil organic matter as a result of the application of VC. This can further be confirmed by significant and positive correlation (r=0.933** and 0.929**) between CEC, and SOC at Dire and Legedadi sites, respectively. Similarly, (Adeyeye et al., 2017, Hammad et al., 2020, Woldesenbet and Haileyesus, 2016, Chimdessa and Sori, 2020) reported that the highest availability of CEC was found from compost addition.

CEC is strongly affected by the nature and amount of mineral and organic colloids in the soil. According to (Sharma et al., 1990), the application of organic fertilizer may have increased the

soil's porosity and pulverization to promote better root growth and development, leading to an increase in the root Cation exchange capacity.

5.10. Soil carbon stock and carbon sequestration

The highest soil C stock was observed in the treatment with a full dose of VC. This could be attributed to higher application rates of organic inputs than other treatments at both sites. In addition, the application of organic inputs enhances biomass which in turn increases C stock. In contrast, the lowest soil C stock was recorded in the control. This is because there is no direct carbon accumulation in the soil, due to small biomass and the absence of both organic and inorganic inputs.

The soil carbon stock increased from 32.2 t ha^{-1} to 50.1 t ha^{-1} at the Dire site and from 28.6 t ha^{-1} to 44.4 t ha^{-1} at the Legedadi site due to the application of full VC rate. Similarly, the findings of (Gross and Glaser, 2021) showed that the application of manure increased SOC stocks by 35.4% (10.7 Mg ha^{-1}). Different studies also confirmed that the application of VC plays an important role in the maintenance of SOC levels, soil quality, and productivity (Ngo et al., 2014, Saha et al., 2012, Sarma et al., 2017). This implies that the more stocks of C, the lesser CO_2 emitted into the atmosphere (Melenya et al., 2015, Abebe and Tana, 2021). Thus, VC can potentially reduce greenhouse gas emissions (De la Vega, 2016).

In the current study, it is also confirmed that the combined application of VC and NPS fertilizers and wheat-faba bean intercropped plots showed a significant ($p< 0.05$) effect on soil carbon stock and sequestration compared to the control at both sites. This is supported by other research findings that stated VC + NPK resulted in the highest amount of CO_2 (10.24 t ha^{-1}) being sequestered as the active pool of carbon leads to decades of increased carbon sequestration, water retention, and soil fertility (Alemayehu, 2018).

Similarly, (Bayu, 2020) observed that combining VC and NPS fertilizers is vital to mitigate climate change through increased carbon sequestration and N use efficiency that may lead to trade-offs with GHG emissions such as N_2O. Therefore, combining organic inputs with mineral fertilizer seems promising to sequester carbon in agricultural soils (Hijbeek et al., 2019). Suppose agricultural soils are properly managed and effective policies are in place. In that case,

they have the potential to sequester large amounts of carbon from the atmosphere and store it in the soil in addition to mitigating CH_4 and CO_2 emissions (Gaskell et al., 2007).

5.11. Comparison of selected soil parameters at Dire and Legedadi sites

The results showed significant variations of soil chemical properties between Dire and Legedadi sites for the TN (p=0.003), Pav (p=0.0001), Kexc (0.0001), and SOC (p=0.001). The yield difference between the two sites might be influenced by differences in their soil physicochemical properties. These properties play a crucial role in determining soil health and crop productivity. Key physicochemical properties that could impact yield variation include SOC, TN, Pav and pH. According to (Haile et al., 2024) report, the yield difference between areas can be attributed to variations in soil organic carbon, soil pH, and exchangeable acidity. These factors play significant roles in determining soil fertility and consequently, crop productivity.

Agricultural productivity is heavily influenced by soil properties, which can vary widely over different areas. This variation is driven by a mix of intrinsic and extrinsic factors, including human activities such as soil management practices and the inherent characteristics of the soil in different areas (Abdu et al., 2023). Analyzing soil properties at both sites can help identify specific factors contributing to yield differences.

Addressing any deficiencies or imbalances through appropriate soil management practices can enhance crop yields and reduce variability across sites.

5.12. MonQI validity and reliability

The nutrient balance data were analyzed using the MonQI toolbox; the data were checked for consistency, completeness, and correctness. The results of this study are similar to several other studies in Ethiopia (Mesfin et al., 2021, Van Beek et al., 2016, Gebresamuel et al., 2021, Kiros et al., 2014, Lewoyehu et al., 2020). These findings suggest that the results of this study are consistent with previous research, indicating that the MonQI toolbox is valid and suitable for use in the study areas.

The model estimates nutrient flows and balances at the farm level, though it carries some uncertainty. The use of transfer functions has drawbacks, including an unknown level of uncertainty in the quantified flows. Moreover, the actual losses due to leaching may be overestimated, as some of the N that leaches below the 30 cm soil layer can still be accessible for plant growth (Mesfin et al., 2021).

5.13. NPK balances at Dire and Legedadi sites

The highest N OUT1 and OUT2 were observed at full dose mineral fertilizer added plots, which is mainly, due to mineral fertilizers providing readily available forms of nitrogen that the plants can absorb and utilize efficiently and inorganic fertilizers are absorbed by the plants relatively fast (Sharma and Chetani, 2017). A similar result was reported by (Singh and Sharma, 2016) stated that nitrogen content in grain was increased with the application of 100% NPK.

Similarly, combined fertilizers applied treatment had higher N uptake in the grain and straw than the remaining treatments following, the sole application of mineral fertilizers. A similar result was reported by (Arsalan et al., 2016) who stated that the application of combined fertilizers markedly influenced the nutrient concentration in the grains yield over control in mung bean.

The highest nitrogen nutrient balance deficit was observed in the wheat-faba bean intercrop with the combined application of mineral and VC fertilizers. This is primarily attributed to the higher nutrient outputs (OUT1 and OUT2) from wheat and faba bean uptake. Similarly, the sole application of mineral fertilizers resulted in a higher nitrogen deficit compared to the sole application of VC. This is primarily due to increased nutrient uptake by the crops and soil erosion. In addition, continuous use of inorganic fertilizers alone causes soil nutrient degradation (Debele, 2021, Yadav et al., 2019). Combined fertilizers applied treatment had less N deficit than the sole mineral fertilizer applied treatment. This may be due to the addition of VC.

All treatments had negative partial and full N balances at both sites. The main tracks for these negative balances were higher uptake of the nutrient by the crops, residue removal, leaching and erosion. In addition, the negative full N balance at both sites indicated that macronutrient

inputs to farms did not replace the nutrients removed through crop harvest and straw which cannot sustain crop productivity. Research findings of (Tsegaye, 2019) reported that nutrient loss is mainly caused by erosion in Ethiopia. For example, the erosion rates were 77.15 t ha^{-1} yr^{-1} and 21.34 t ha^{-1} yr^{-1} at Dire and Legedadi sites, respectively (Awraris, 2017). Therefore, Addition of VC can be a mechanism to reduce the effect of erosion in areas that are vulnerable to erosion like the current study sites. The application of organic fertilizers is a potential practice to prevent soil erosion by improving the physicochemical properties of the soil, such as enhancing macro-aggregates, SOC content, and exchangeable cations (Cui et al., 2023).

This study is in line with the studies carried out in smallholder farming systems in Ethiopia that showed negative N balances (Mesfin et al., 2021, Gebresamuel et al., 2021, Aticho et al., 2011, Van Beek et al., 2016). This indicated that there is N depletion at both study sites farmland and different farmlands in Ethiopia. In addition, the negative N nutrient balance leads to nutrient depletion with serious consequences for future food security (Van Beek et al., 2016). To minimize nitrogen loss and negative nutrient balances, it is important to reduce nitrogen loss through leaching and erosion. In addition, accurate fertilizer requirements for the crop must be predicted. The fertilizer requirement depends on both the crop's needs and the nitrogen supply from the soil. Since the soil's nitrogen supply can vary between years and locations based on soil and weather conditions, it is crucial to consider these parameters (Ratjen and Kage, 2018).

Similarly, both partial and full P nutrient balances were negative for all treatments at both sites. The main reason for these negative balances is the nutrient loss during grain and crop harvesting (Kiros et al., 2014). The negative phosphorus nutrient balances indicate that the application of inorganic and organic fertilizers was insufficient to offset the nutrient losses caused by the removal of crops and crop residues.

The higher full P balance was noted in treatments where combined fertilizers were applied than sole mineral fertilizer. Similarly, (Tilahun et al., 2013, Mamuye et al., 2021) also confirmed higher phosphorus balance when mineral fertilizers and manure were applied in combination. Similarly, (Bashagaluke et al., 2018) reported that VC and NPK fertilizers application reduced least cumulative loss for P nutrient. This indicates that the application of combined fertilizer as

a soil management practice offers a robust approach to decreasing nutrient loss. This helps ensure crop productivity and maintain soil quality. To meet the increased food demand, soil nutrient depletion needs to be counterbalanced by soil fertility management practices (Van Beek et al., 2016).

Similar to nitrogen and phosphorus, the potassium balance was negative for all treatments at both sites. Full dose VC added treatment recorded the highest full K balance and less k deficient than other treatments at both study sites. The survey result (EthioSIS, 2016) indicated a deficiency of K in different farmlands of Ethiopia. VC fertilizer application has the potential to sustain crop yields and improve soil productivity. The sole application of mineral fertilizer either in half or full doses indicates that these systems continue to reduce nutrient stocks (Panhwar et al., 2019).

The highest potassium deficiency was recorded in the wheat-faba bean intercrop with combined fertilizers applied treatment, primarily due to the higher nutrient uptake by both wheat and faba bean plants. It also implies that nutrient application at half rate with intercropping is inadequate. Similarly (Onwonga et al., 2015) reported that all cropping activities had negative nutrient balances (N, P, and K), and nutrient depletion rates were highest when the land was used for pasture, fodder, and cereal crops. It is therefore vital to ensure appropriate fertilizer application and cropping system to advance nutrient management increase crop productivity and ensure food security.

Soil fertility management practices and recycling of organic materials such as crop residue, manure, and compost a potential ways out, but require farmers' awareness, and alternatives for animal feed and energy because farmers remove crop residue from farms for animal feed and fuel (Mebrate et al., 2022). Moreover, as significant amounts of nutrients are lost to the environment in the form of erosion, leaching and gaseous loss, there is a need to improve nutrient use efficiencies and encourage farmers to use combined fertilizers at the right time using the right method. The application of expensive inorganic fertilizer needs to be supplemented with cultural practices that are affordable, feasible, and compatible with local farming systems such as compost and vermicompost. These sustainable soil fertility management practices provide multiple opportunities for farmers, as they have the potential to improve food security while simultaneously reducing environmental pollution (Aleminew and Alemayehu, 2020).

Chapter six

6. Conclusions and Recommendations

6.1. Conclusion

The application of vermicompost, NPS fertilizers and intercropping practices impacted growth, yield, and yield-related parameters at both the Dire and Legedadi sites. The highest mean wheat grain and straw yield, following the sole mineral fertilizer treatment, was achieved when half of the recommended both mineral fertilizer and vermicompost were applied. Combined use of VC and NPS fertilizers also improved crop nutrient uptake and recovery efficiency. The highest net benefit was recorded at the wheat faba bean intercrop with combined fertilizers application at both sites.

Significant variations in wheat yield, biomass, and straw yield were observed between the Dire and Legedadi sites. This variability is likely due to differences in soil properties at these locations, which significantly impacted crop productivity. Addressing any deficiencies or imbalances through appropriate soil management practices can help improve crop yields and reduce variability between sites. It is imperative for farmers and agricultural planners to carefully consider site-specific characteristics when selecting to maximize yield potential. This indicates that understanding the specific fertilizer needs of each site is crucial to ensure the appropriate type and amount of fertilizer applied.

The results revealed that applying vermicompost in combination with NPS fertilizer significantly improved pH, total nitrogen, available phosphorus, exchangeable bases (Ca^{2+}, Na^{+} and Kexc), and Cation exchange capacity. Generally, the combined application of organic and inorganic fertilizers improved soil properties more than the sole use of mineral fertilizer. In addition, combined applications of VC with mineral fertilizer significantly increased soil carbon stock and carbon sequestration than the sole application of mineral fertilizer. The application of a full dose of VC resulted in the highest soil carbon stock at both sites.

Combined fertilizer application had better NPK balances than the sole application of NPS fertilizer. The intercropped treatments had a higher NPK deficit than the combined fertilizers

applied treatment due to higher crop and straw nutrient uptake by the intercropped crops of wheat and faba bean. The fertilizer input for intercropped crops needs to be higher than that for sole crops due to the increased nutrient uptake by the combined crops. Additional research is necessary to determine the optimal fertilizer requirements for intercropped systems. For sole crops combined application of VC and mineral fertilizers is a better approach to maintain soil nutrient balance, but NPK input under the fertilizers should be considered to maintain the required amount of nutrients in the soil.

Further research is needed to understand the specific factors at each site that contribute to differences in crop yield. From the current findings, it can be concluded that there is no single integrated soil fertility management approach that satisfies all agronomic benefits. Therefore, it is important to combine different approaches to achieve the best outcomes.

6.2. Recommendations

Based on the findings, the following recommendations are forwarded:

- Combined application of VC with NPS fertilizer is a recommended practice to increase yield, agronomic and nutrient use efficiency.
- It is recommended to adopt wheat-faba bean intercropping with a half rate of NPS + urea and a half rate of vermicompost, as this combination resulted in the highest net benefits.
- Combined application of VC with NPS fertilizer enhances most physicochemical properties of soil at Dire and Legedadi sites.
- The combined application of VC and NPS fertilizers helps farmers reduce the use of inorganic fertilizer requirements by half.
- It is important to understand the specific fertilizer requirements of each site to ensure the appropriate type and amount of fertilizer applied.
- In intercropped systems, additional fertilizer is needed to compensate for the higher nutrient uptake by the combined crops.
- Combined application of NPS and VC fertilizers is a better approach to maintain soil NPK balance, but NPK input under fertilizers should be increased to maintain the required amount of nutrients in the soil.

- ❖ Further study across seasons and places is required to verify the effects of the selected ISFM practices on crop productivity, soil physicochemical properties, soil carbon stock and soil nutrient balance.

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Appendix

A1: Description of faba bean and wheat varieties used in the experiment

Variety	Danda'a	Gabelcho
Date of release	2010	2006
Days to maturity	110-145	103-167
Suitable altitude (m.a.sl)	2000-2600	1900-3000
Suitable rainfall	>600	700-1000
Seed rate (kg ha-1)	150-175	350
Yield on station (kg ha-1)	3500-5500	2500-4400
Yield on station (kg ha-1)	2500-5000	2000-3000
1000 Seed weight(g)	40	797
Adaptation area	Mid to highland areas	Mid to highland areas
Production states	Under production	Under production

A2: Critical levels used for classifying soil fertility analysis results in Ethiopia

Soil parameter	**Status**	**Critical level adopted by EthioSIS**
Soil pH (water)	Strongly acidic	<5.5
	Moderately acidic	5.6–6.5
	Neutral	6.6–7.3
	Moderately alkaline	7.3–8.4
	Strongly alkaline	>8.4
Phosphorus (mg/kg)	Very low	0–15
	Low	15–30
	Optimum	30–80
	High	80–150
	Very high	>150
	Very low	<90
Potassium (mg/kg)	Very low	<90
	Low	90–190
	Optimum	190–600
	High	600–900
	Very high	>900

Total nitrogen (%)	Very low	<0.1
	Low	0.1–0.15
	Optimum	0.15–0.3
	High	0.3–0.5
	Very high	>0.5
OM (%)	Very low	<2.0
	Low	2.0–3.0
	Optimum	3.0–7.0
	High	7.0–8.0
	Very high	>8.0
EC (mS cm^{-1})	Salt free	<2
	Very slightly saline	2–4
	Slightly saline	4–8
	Moderately saline	8–16
	Strongly saline	>16