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Soil nutrient management practices towards climate-smart agriculture: mitigation, adaptation and sustainable yield intensification in a Nitisol in Southwestern Ethiopia

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Articles included

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List of Abbreviations

ADLI	Agricultural-Led Industrialization
ANUE	Agronomic Nitrogen Use Efficiency
ATA	Agricultural Transformation Agency
CA	Conservation Agriculture
CDM	Clean Development Mechanism
CEC	Cation Exchange Capacity
CIF	Climate Investment Funds
CO_2 eq	Carbon Dioxide Equivalent
CRGE	Climate Resilient Green Economy
CSA	Central Statistical Agency
CSA	Climate-Smart Agriculture
DAP	Diammonium Phosphate
DH	Dehydrogenase
ECD	Electron Capture Detector
FAO	Food and Agriculture Organization of the United Nations
FDRE	Federal Democratic Republic of Ethiopia
FLR	Forest Landscape Restoration

GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse Gas
GWP	Global Warming Potential
IFA	International Fertilizer Industry Association
INM	Integrated Nutrient Management
IPCC	Intergovernmental Panel on Climate Change
ISFM	Integrated Soil Fertility Management
NPS	Nitrogen Phosphorus Sulfer
NUE	Nitrogen Use Efficiency
OCBE	Oromia Cooperative Bank of Ethiopia
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SDPRP	Sustainable Development and Poverty Reduction Program
SNNPR	Southern Nations, Nationalities, and Peoples' Region
TPF	Triphenyl-formazan
TTC	Triphenyl-tetrazolium-chloride
UNEP	United Nations Environment Programme
WFPS	Water-filled pore space

Chapter 1: General introduction

General introduction

Justification of the research and background information

Global agriculture faces multiple challenges in producing enough food and fiber to feed an ever-increasing human population (Agegnehu and Tilahun, 2017; Bryan et al., 2011). Agricultural production must increase by 60% to balance food demand for the estimated world population of 9.2 billion by 2050 (FAO, 2013, 2014). The adoption of sustainable soil management techniques and the availability of healthy soils are the main requirements for achieving food and nutrition security (Beek et al., 2013). Ongoing climate change is also another challenge to increase food supply sustainably, as climate influences biotic and abiotic factors relevant to crop production and productivity (Baxter et al., 2011; IPCC, 2014; Tesfai, 2016; Bista et al., 2018; Dinesh et al., 2018; Jiang et al., 2019).

Furthermore, the majority of agricultural operations produce greenhouse gases (GHGs), which are directly linked to climate change due to the excessive use of nitrogen fertilizers, animal manure, and the decomposition of organic matter (Brevik, 2013; Graham et al., 2017). The average amounts of GHG emitted from agricultural soils are estimated to account for 14 % of total global GHG emissions accelerating climate change (African Union, 2013; Baxter et al., 2011; IPCC, 2014; Jiang et al., 2019). Good agricultural practice is a viable option for reducing the impact of GHG on climate change (Bharali et al., 2018; Graham et al., 2017). For instance, an effective policy that includes integrated soil management can reduce environmental pollution and GHG emissions contributed by excessive fertilization (De Rosa et al., 2018; Hu et al., 2020). Thus, soils act as a source or sink of GHGs that have attracted the attention of policymakers to critically review the option of soil carbon sequestration and improve fertilizer management for adapting and mitigating the anthropogenic greenhouse effect (Jiang et al., 2019; Lal, 2014).

Ethiopia's economic development policies and strategies recognize the link between environmental concerns and economic development (EFDRE, 2013). Ethiopia has accepted and endorsed the 2030 Agenda for Sustainable Development Goals (SDGs) as an integral part of its national development (Hoeltl et al., 2020). Because historically, the country has been prone to extreme weather events that have contributed to food and nutrition insecurity for decades (Mengistie & Kidane, 2016; Worku, M. A., 2020).

High rainfall variability leads to droughts and floods almost every year, with severe consequences for the country's economy and the livelihoods of millions of people (Worku, M. A., 2020). The social and economic costs resulting from climate variability and extreme weather events are significant and are expected to be further exacerbated by climate change. Without adaptation and mitigation measures, climate change may reduce Ethiopia's GDP by 2.5% per year by 2050 (EFDRE, 2013). In light of the climate change issue, the Ethiopian government has developed a Climate Resilient Green Economy (CRGE) strategy with different objectives. One of the objectives is to mitigate GHG emissions without harming sustainable food production (Gelaw & Ababa, 2018).

Based on the global average value, Ethiopia contributes negligible amount of GHG (0.3%) as global warming potential from all agricultural activities (Kim et al., 2016; Raji & Dörsch, 2020; Worku, 2020). The amount of mineral fertilizer (37 to 40 kg ha^{-1}) applied in the crop field does not have a significant effect on GHG emissions compared to application rates in other developed countries (169 kg N ha^{-1}) (Lassaletta et al., 2014). However, Ethiopia aimed to increase mineral fertilizer use to 247 kg ha^{-1} by 2030 (Worku, 2020). Furthermore, N_2O emissions from mineral fertilizer applications are expected to increase by about 58% in 2030 relative to current total soil-based emissions, i.e., from 4.3 Mt CO2eq. in 2010 to 35 Mt CO_2eq. in 2030 (Worku, 2020). As a result, increasing the N-fertilizer application rate is expected to increase N_2O emission twice in the near future. The application of high doses of mineral fertilizers also has many adverse effects on the ecosystem and soil health. For example, continuous use of a large amount of nitrate/ammonium/urea-based fertilizers could acidify soils, making the soil unfavorable for living organisms and reducing the availability of nutrients for plant growth and development (Reda & Hailu, 2017). Most of the microorganisms that transform plant nutrients into available forms depend on soil pH (i.e., low pH reduces the activity of microorganisms). In addition, N fertilizers such as urea are converted to anhydrous ammonia and CO_2 by bacteria (Millar et al., 2004). Anhydrous ammonia is toxic and kills soil organisms (Singh et al., 2013). On the other hand, most N fertilizers tend to accelerate the decomposition of organic matter by reducing the C/N ratio, which leads to a rapid mineralization of soil organic matter (SOM) (Menšík et al., 2018). When decomposition of organic matter is high, there is a high production of CO_2 gas and what increases GHGs in the atmosphere. Besides CO_2; N_2O and methane (CH_4) are the most important GHGs from agricultural soils. N_2O has a global warming potential (GWP) of 298 times higher than an equal mass of CO_2 (Kim & Giltrap, 2017; Signor et al., 2013).

Climate-smart agriculture (CSA) has been considered as a strategy to reduce the impact of climate change on crop production (Tadesse et al., 2021; Tessema et al., 2013). Low productivity and climate change impacts require CSA practices in order to improve food security by sustainably increasing crop productivity, improving the resilience or adaptive capacity of agricultural systems, and offsetting GHG emissions (Aweke, 2017; Tesfai, 2016; Tessema et al., 2013). To meet the food demand of the growing population, Ethiopia needs to increase agricultural production and productivity by adopting CSA. Some CSA practices have been practiced in Ethiopia to ensure food security under the changing climate (Aweke, 2017; Tadesse et al., 2021). The practice has been traditionally practiced in different regions. However, the adoption status by smallholder farmers is low due to various challenges (Aweke, 2017). To increase the uptake rate by the smallholder farming system, challenges are not clearly identified and opportunities are not recommended. Among the various CSA practices, the present study emphasized on soil nutrient management and its contribution to CSA practices as it is a primary driving factor determining sustainable food production in Ethiopia.

In the context of CSA, fertilizer application in cropping systems should reduce GHG emissions, strengthen the potential of soils to resist the impact of climate change and sustainably increase crop yields from the same unit area (Bayu, 2020; Tadesse et al., 2021). For example, some fertilizer applications will increase productivity and, at the same time, increase GHG emissions and affect the soil ecosystem. Since this application technique does not meet the definition of CSA, it cannot be considered a CSA practice in any agro ecological zone. Studies agree that the combination of organic and mineral fertilizers can provide better results for CSA than organic/mineral fertilizers alone, although less is understood about its mechanism and how it contributes (Sileshi, 2019; Tesfai et al., 2016; Timsina, 2018). Taking into account the type and amount of fertilizer, as well as the timing and application technique, can improve crop productivity while reducing nutrient imbalances and nutrient losses from agricultural fields and mitigating GHG emissions (Komatsuzaki and Ohta, 2007; Raji and Dörsch, 2020; Sinclair and Rufty, 2012; Timsina, 2018). The combination of organic and mineral fertilizers can balance the amount of N, which decreases N_2O emissions and N leaching losses (Hu et al., 2020; Raji & Dörsch, 2020; Suvendu & Tapan, 2013). To effectively mitigate N_2O emissions, N rates of mineral fertilizers should be adjusted and compensated with slow-release fertilizers (i.e., compost). N_2O emissions are assumed to be reduced by increasing N use efficiency (NUE, percentage of applied N absorbed by the crop). N management to increase NUE has been recognized as an effective way to mitigate N_2O emissions from agricultural soil.

The application of sole organic fertilizer (compost, manure, crop residues, green manure, and biochar) have been recommended as a viable option for sustainable crop production (Hammed et al., 2019; Liu et al., 2015; Partey et al., 2018). However, other research have noted the disadvantages of using sole organic fertilizer in terms of GHG emissions (particularly, NH_3 and CO_2), limited organic resources, and the low content for mineral N nutrition (Chen, 2006; Ma et al., 2021; Mdlambuzi et al., 2021). Ammonia (NH_3) emission is common in the agricultural field, associated with ammonia-based fertilizers and animal manure application (Ma et al., 2021). To better understand how organic fertilizers affect CO_2 emissions, crop yield, and soil quality in particular soil types, research must be conducted.

The extent of GHG emissions varies depending on the different factors: (i) the quantity and quality of the incorporated biomass, (ii) soil temperature, (iii) moisture content, (iv) pH, (v) soil type, and (vi) cropping system (Millar et al., 2004; Oertel et al., 2016). These factors directly affect the activities of soil microorganisms (i.e. microbial enzyme activity) in the soil, which contributes to the emissions of GHGs (Bhattacharyya et al., 2013; Lazcano et al., 2021; Salehi et al., 2017). For instance, the incorporation of materials with a low C/N ratio in the tropical climate during the rainy season may significantly enhances the emission of N_2O and CO_2, as opposed to the high C/N ratio in dry soil, since the condition increases microbial activities such as mineralization and denitrification (Lazcano et al., 2021; Michel Rabenarivo et al., 2014; Muhammad et al., 2011). In addition, soil type is a very important factor for GHG emission, because the microbial activities vary depending on soil physicochemical properties (Bao et al., 2014; Nyamadzawo et al., 2017). For example, Sakata et al., (2015) found significantly different values of N_2O and CO_2 emissions in oil palm plantations for three soil types. GHG differences could be explained by variations in the physicochemical and biological characteristics of the three soils. GHG emission from specific soil is very important to set the appropriate fertilizer management options. Soil type consideration in the fertilizer management plan is crucial during fertilizer selection and application. The emission of GHG is also affected by soil moisture, through affecting microbial activity. Studies reported that, N_2O emission thoroughly increases from 60% water-filled pore spaces (WFPS) and the highest N_2O emission is exhibited around 75% WFPS (SMITH, 2001; Khalil & Baggs, 2005). Not only N_2O, but also CO_2 emission is affected by soil moisture. Studies revealed that CO_2 emissions from soil can increase linearly with the soil water content until saturation point (i.e. for most soils the saturation point for CO_2 emission is >70%), after which the emissions decrease again (Ding et al., 2007; Mazza et al., 2018; Säurich, A et al., 2019; Thangarajan, R et al., 2013).

The current soil nutrient management in Ethiopia

Ethiopia's soil deterioration and decreased soil productivity are caused by the country's rapid population increase and the clearance of natural vegetation for more farmland (Alemu, 2015; Chiemela et al., 2018). Rugged topography, deforestation, low input agricultural practices also accelerate soil degradation particularly in the northern and central highlands of Ethiopia (Gebremedhin & Swinton, 2003). In addition to soil degradation, the majority of smallholder farmers have been dealing with issues caused by insufficient nutrient applications to compensate for lost nutrients. Furthermore, the government has been given more emphasis to mineral fertilizer application with limited nutrients (NPS) than other organic sources and micronutrients (Reda & Hailu, 2017; CSA, 2021). For example, diammonium phosphate (DAP) and urea were the major fertilizers used by farmers in Ethiopia until few years back, whereby other nutrients, particularly K and micronutrients become limiting to produce high yielding cereals (Kebede & Yamoah, 2009; Tamene et al., 2017). Mineral fertilizers, mainly urea and DAP now replaced by NPS, are the only ones that farmers consider when thinking about fertilizer application (Reda & Hailu, 2017). This attributed to a lack of awareness, and less attention has been given by policymakers and top-management bodies (Ministry of Agriculture) to organic fertilizers and micronutrients (Reda & Hailu, 2017). However, studies reported that the majority of micronutrients and K are severely deficient in the most of Ethiopia's cereal soils (Abera & Kassa, 2017; Ashenafi et al., 2016; Brhane et al., 2017; Demiss et al., 2015). As a result, farmers should apply these nutrients either as mineral fertilizer or as organic fertilizer to compensate the deficiencies to produce optimum yield with high quality. Alternatively, the use of compost and other organic materials can increase the soil fertility and resilience; however, the use of organic fertilizer is not widely experienced in Ethiopia and has occasionally been declined due to the farmers demand for fuel, animal feeding, and lack of awareness. (Reda & Hailu, 2017; Tessema et al., 2013). Compost needs to be applied relatively in large quantity due to low nutrient concentrations and cannot fulfill crop demands for available N (Lim et al., 2016). In organic fertilizer the major plant nutrients may not exist in sufficient quantity.

Fertilizer management practice is also influence grain mineral concentrations; however, limited information is available on its effect (Chivenge et al., 2011; Mutuku et al., 2020; Zhihui et al., 2016). Increasing the mineral concentrations in the grain through agronomic practice (i.e., proper fertilizer management) is essential for rural residents who consume maize as a staple food. In sub-Saharan Africa including Ethiopia food and nutrition security; especially in regions in which diets are dominated by cereals are greater challenges (Abate et al., 2015; Fraval et al., 2019; Gashu et al., 2021). The region is vulnerable to malnutrition due to micronutrient deficiencies in their daily diets (Fraval et al., 2019). To alleviate the problem Gashu et al., (2021) suggested food fortification and biofortification to increase the micronutrient concentrations in crops. Even though a sustainable agronomy solution has not yet been suggested, increasing the application of micronutrients to maize cultivation can raise the concentrations of minerals in the grain. Therefore, research should be conducted to suggest the appropriate fertilizer ratio for smallholder agricultural systems that increases grain mineral concentrations.

As a result, the study was initiated to contribute to the knowledge regarding the influence of combined application of compost and inorganic fertilizer on three pillars of CSA practices. Additionally, the amount of GHGs emitted from fertilizer application is not well investigated in different agro-ecosystems and in specific soil types in Ethiopia. The current study aimed to answer the question; what kind of organic and mineral fertilizer combination could fulfill the CSA pillars, and increases the mineral concentrations of maize grain. This enables the selection and adoption of the appropriate fertilizer types and rates and implementing them to support the crop production system that contributes to the sustainable development goals. In addition, it is crucial to consider how sustainable production, soil quality, and GHG emissions can be balanced when developing effective fertilizer strategies.

Objectives and hypothesis of the study

The general objective of the study was to evaluate the contribution of soil nutrient management towards climate-smart agriculture that contributes to increase maize yield, soil health and reduce GHGs. The specific objectives were: To review the current status of CSA and to identify potential CSA practices, challenges and the available opportunities to enhance CSA practice in Ethiopia; to evaluate the effect of combined application of compost and mineral fertilizer on maize (*Zea mays* L.) yield, GHGs emissions, microbial enzyme activity, grain mineral concentrations, nutrient use efficiency of maize and soil chemical properties. The study hypothesized that at least one of the combined applications ratio could fulfill the three pillars and simultaneously increase grain mineral concentrations and nutrient use efficiency of maize.

Significance of the study

The present study could provide critical information on the status of climate-smart agriculture, barriers to increasing its adoption, and insights on how to exploit its potential in Ethiopia. In addition, the research result provides evidence of the benefits of combined fertilizer use (compost plus minerals), in terms of GHG emission reduction, sustainable maize production, improved soil quality, increased maize grain minerals and nutrient use efficiency in a Nitisol. This is a novel contribution in the field of balancing GHG emissions and sustainable crop production without damaging the soil ecosystem for future generations. Previously, there was a knowledge gap on the need to implement effective mitigation measures in the country due to the absence of basic research reports in the area of GHG emissions from the crop production system. As a result, the current study provides critical information for future research in the field, as well as a baseline for future research and policymakers regarding GHG emissions in a Nitisol.

Conceptual framework of the study

The purpose of the conceptual framework is to illustrate how the present study achieved its aim through different techniques.

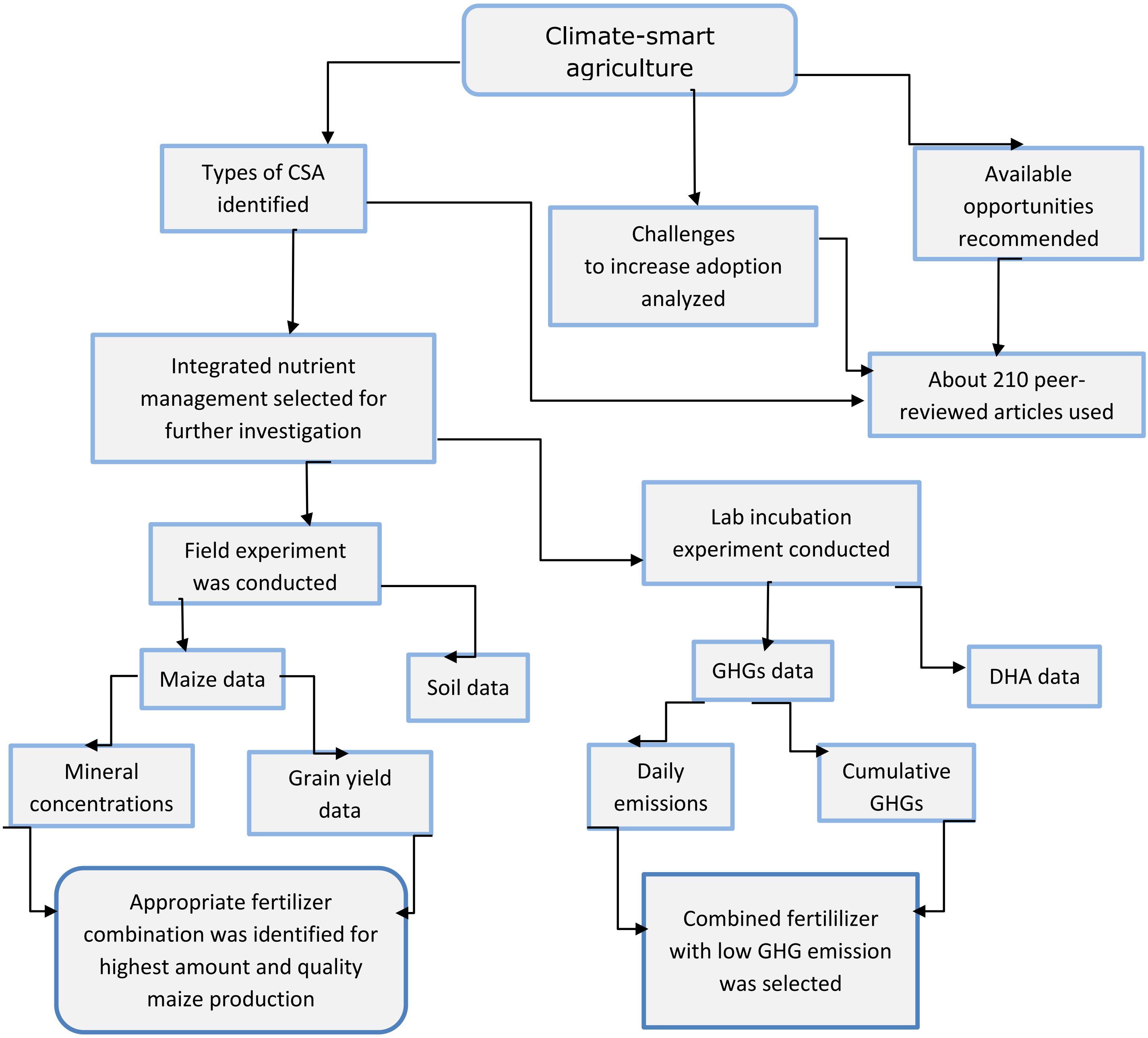

Figure 1. Conceptual framework of the study.

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Chapter 2: Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture: A review

Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture: A review

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Abstract

Agriculture is the backbone of the Ethiopian economy, and the agricultural sector is dominated by smallholder farming systems. The farming systems are facing constraints such as small land size, lack of resources, and increasing degradation of soil quality that hamper sustainable crop production and food security. The effects of climate change (e.g., frequent occurrence of extreme weather events) exacerbate these problems. Applying appropriate technologies like climate-smart agriculture (CSA) can help to resolve the constraints of smallholder farming systems. This paper provides a comprehensive overview regarding opportunities and challenges of traditional and newly developed CSA practices in Ethiopia, such as integrated soil fertility management, water harvesting, and agroforestry. These practices are commonly related to drought resilience, stability of crop yields, carbon sequestration, greenhouse gas mitigation, and higher household income. However, the adoption of the practices by smallholder farmers is often limited, mainly due to shortage of cropland, land tenure issues, lack of adequate knowledge about CSA, slow return on investments, and insufficient policy and implementation schemes. It is suggested that additional measures be developed and

made available to help CSA practices become more prevalent in smallholder farming systems. The measures should include the utilization of degraded and marginal lands, improvement of the SOM management, provision of capacity-building opportunities and financial support, as well as the development of specific policies for smallholder farming.

Keywords: Food security; soil fertility; agroforestry; organic matter; greenhouse gas; agronomy; water harvesting

2.1. Introduction

Agriculture is the backbone of the Ethiopian economy and it contributes about 50% of the country's gross domestic product (GDP) and more than 80% of its exports [1,2]. Furthermore, it is one of the main employment sectors with about 80% of the country's population depending on the agricultural sector for their livelihoods [3]. The agricultural sector of Ethiopia is dominated by smallholder farming [4]. Smallholder farms are defined as being smaller than 2 ha and are mainly managed with family labor [5]. In Ethiopia, about 95% of main crops (e.g., cereals, pulses, oilseeds, vegetables, root crops, fruits, and cash crops) are produced by smallholder farms [4]. However, these farms are facing various constraints that hamper crop productivity. Major constraints include poor soil fertility, severe land degradation, high dependence on rainfall, low availability and poor quality of seeds and fertilizers, economic constraints like low income and lack of financial support, as well as insufficient policies and guidelines [3,6,7]. Weather phenomena related to climate change like severe drought and heavy rainfall also affect the agricultural sector. Smallholder farmers with limited resources have particular difficulties overcoming these obstacles [4,8]. These problems are exacerbated by the rapid population growth and environmental degradation. Consequently, appropriate management practices are urgently needed to resolve the constraints and to increase crop production without altering its potential for future generations [9].

Climate-smart agriculture (CSA) is an agricultural approach that aims to increase agricultural productivity under the new realities of climate change. This includes increasing soil fertility and carbon sequestration, reducing greenhouse gas (GHG) emissions, enhancing resilience to climate change, and a stronger use of natural ecosystem services [10–14]. Managing CSA includes various practices such as mulching, the application of organic materials, intercropping, conservation tillage, crop rotation, integrated nutrient management, water harvesting, and agroforestry [15–17].

Globally, CSA has been recognized as a suitable solution to overcome the challenges of food security and climate change impacts on agriculture especially in vulnerable areas [17]. Thus, the adoption of CSA practices could help smallholder farming in Ethiopia to enhance food security and appropriately manage climate change impacts [18–21]. However, despite these potential benefits CSA is only practiced in some areas of Ethiopia and has not been sufficiently adopted by smallholder farmers [14,22]. This is partly attributed to available labor, knowledge, and level of education [4,23,24], but a shortage of funds as well as policy constraints are further important aspects [6]. Although Ethiopia's agriculture has enjoyed increasing governmental support over the years [25], especially land tenure policy and financial and price support schemes are described as being insufficient or ineffective. This results in an underutilization of techniques for soil and water conservation and hinders the adoption of CSA in Ethiopia [21,25,26]. While many CSA practices are relatively low- cost, they may not be affordable for farmers, who suffer from price distortions, limited land, and low productivity [21,27]. CSA practices can also result in an increased workload. This was for instance shown for conservation tillage, which is often related to a higher occurrence of weeds and may increase the work burden on women, who are usually responsible for manual weeding [28].Therefore, relevant stakeholders must clearly know the impacts of CSA practices and must also assess their costs and benefits under the respective conditions in order to make decisions on promoting one practice versus another [29].

Holistic approaches are needed as a basis for appropriate future strategies to-wards sustainable agriculture and rural welfare, as recently suggested for sub-Saharan Africa by Stewart et al. [30] and more specifically for Ethiopia by Amare et al. [31]. Various studies have shown, that CSA approaches exist which have the potential to enhance resilience to climate change and to achieve more sustainability for smallholder farming in Ethiopia [4,23,32]. However, the studies often narrowly focus on individual CSA practices under specific circumstances. An integrative and systematic analysis considering environmental and socioeconomic conditions as well as agricultural policies on potentials and challenges of adopting CSA in Ethiopian smallholder faming systems has not yet been undertaken. The consideration of interlinking influencing factors in our review resulted in four main objectives: I) to summarize the current situation in smallholder farming in Ethiopia, II) to explore potential CSA practices for a sustainable improvement of agro ecosystems, III) to identify relevant obstacles that hinder the application of CSA practices in smallholder farming systems, and IV) to suggest opportunities and solutions to sustainably develop smallholder farming systems and to empower smallholder farmers to adopt CSA practices.

To provide relevant information on I) conditions in smallholder farming, II) sustainable and climate-smart agriculture, and III) agricultural policy and socio-economic issues and to achieve the aims of this review a comprehensive analysis of articles in the Web of Science and Google Scholar was done using the following terms: “climate-smart agriculture”, or “smallholder farming”, or “integrated nutrient management”, or “soil fertility”, or “sustainable agriculture”, or “agroforestry”, or “conservation agriculture”, or “agricultural policy”, or “socio-economic effects” and/or “Ethiopia”. These terms are commonly used in agricultural research with a focus on climate change adaptations and mitigation and they cover the main research outputs about the current status of CSA in Ethiopia. Moreover, the terms include the concepts of CSA pillars (adaptations, productivity, and mitigations). For our study we mainly focused on developments during the last two decades, when measures to mitigate the impacts of climate change became more relevant.

2.2. Current status of smallholder farming in Ethiopia

2.2.1. Agricultural productivity

In Ethiopia, about 60% of farmers cultivate less than 0.90 ha in very fragmented landscapes [5,20,33]. However, smallholder farming is responsible for a large proportion of Ethiopian food production. It cultivates more than 90% of the total cropland and provides more than 90% of agricultural output [4,34,35]. Smallholder farmers commonly cultivate cereals such as teff (*Eragrostis tef* [Zucc.]Trotter), maize (*Zea mays* L), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*) [36,37] (Figure 1). Crop yields in the smallholder farms are very low compared to their potential capacity [36,38] and are also substantially lower (less than 50%) than the yields obtained in experimental farms and research stations (Figure 2). The gap is especially remarkable for maize, with an average yield of 2.6 t ha^{-1} compared with the potential yield of 7.8 t ha^{-1} obtained in on-farm trials [36,37,39]. The low crop yields affects food security, with a large amount of grain needing to be imported [40,41]. For instance, 30 to 50% of domestically consumed wheat was imported in the past due to a lack of production inside the country [40,41].

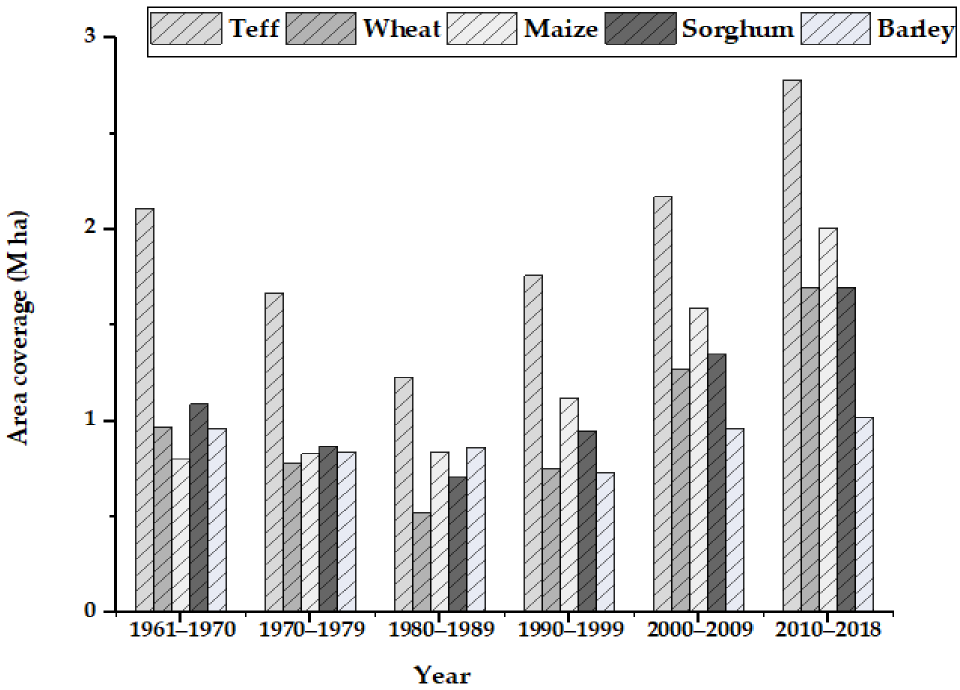

Figure 1. Variation of area coverage of major cereal crops (teff, wheat, maize, sorghum, and barley) in Ethiopia from 1961 to 2018. Source: Taffesse et al., CSA [27,28]

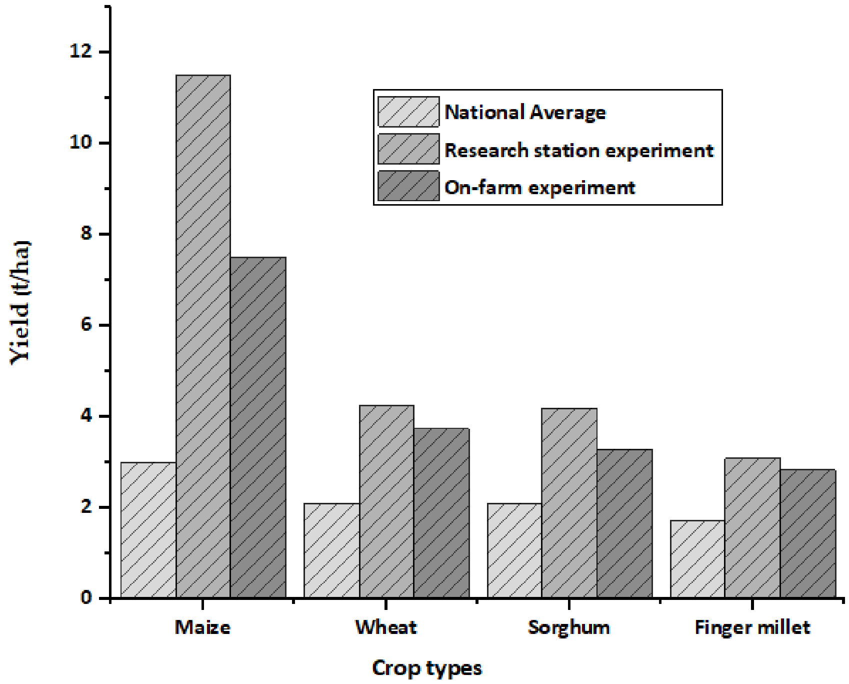

Figure 2. Average of crop yields (t ha^{-1}) (1995–2018) compared to the yields from research stations and on-farm experiments in Ethiopia. Source: Taffesse et al., CSA, Marloes et al. [27–29]

Ethiopia has a large livestock resource with about 60 million head of cattle and about 61 million sheep and goats [42]. The animals belong to various production systems ranging from pastoral to mixed crop–livestock systems with different levels of intensification [24,42]. About 75% of livestock is concentrated in the highlands of Ethiopia. The animals play a critical role in the mixed smallholder farming systems (i.e., livestock and crop production within the same farm unit) as they diversify income sources for smallholder farmers, provide manure as a source of fertilizer, increase the availability of animal traction, and can act as buffer against adverse weather patterns for cropping. [43–45]. It has also been shown that livestock ownership can increase the probability of adopting sustainable farming methods in Ethiopian highlands [21].

However, in the face of decreasing grazing lands and high prices for animal feed animal husbandry competes with crop farming for limited resources [43,46–48]. Despite the limited space for the cultivation of fodder crops, the feeding of crop residues is also problematic, as this material is urgently needed to maintain the fertility of soils [46]. High livestock densities may reduce the quality of soils and overgrazing often exposes agricultural lands to erosion and structure deterioration [49–52]. Understanding the trade-offs between number of livestock, total farm size, and sustainable land production is therefore very important [43].

In Ethiopia about 40% of agricultural land is already affected by land degradation resulting in decreased agricultural productivity [53]. Especially the densely populated highlands of Ethiopia have been experiencing losses in soil fertility for the last three decades [44,50,54]. This is not only related to high livestock densities, but also to improper land management (i.e., tilling steep slopes), an intensive use of water, and the discharge of agrochemicals [53,55].

2.2.2. Agricultural land size

The amount of land dedicated to agriculture has been steadily increasing since 1980 [56]. From 2000 to 2008 croplands were expanded by about 4 million ha, and 80% of this expansion occurred through the conversion of forest land, woodland, and shrub land [57]. Deforestation for the expansion of agricultural land in Ethiopia increased CO_2 emissions from 5.1 Mt in 2005 to 6.5 Mt in 2010 [58]. Although the expansion of cropland has slowed down in recent years, the amount of agricultural land still increases by about 1.5% every year [56]. In spite of the expansion of cropland, due to the quickly growing population in the rural parts of Ethiopia the size of cropland per capita has been decreasing drastically [35,59] (Figure 3). Consequently, most Ethiopian farmers are still smallholder farmers. Farm size is usually negatively correlated with population density. For example, the average farm size of less populated areas like Oromia (average farm size: 1.15 ha) and Amhara (1.09 ha) is larger than that of the densely populated Southern Nations, Nationalities, and Peoples' Region (SNNPR) (0.49 ha) [36]. It has been predicted that smallholder farming systems will continue to dominate the agriculture sector and that average farm sizes will continue to decline, since the further expansion of cropland will become more difficult, while the population will continue to increase [20,60,61].

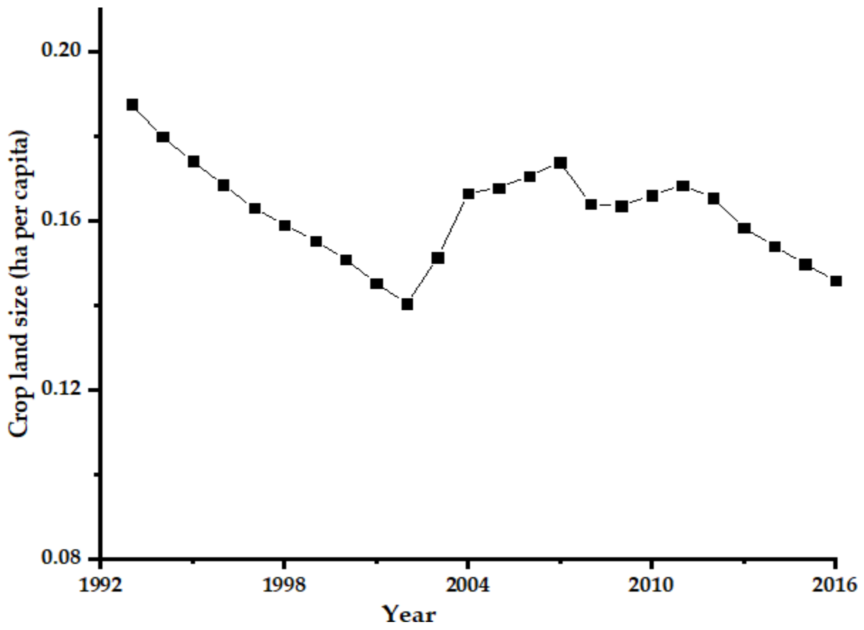

Figure 3. Development of cropland area (ha per capita) in Ethiopia from 1993 to 2016. Source: MoARD, Taffesse et al., CSA [27,28,36].

2.2.3. Fertilizer application and organic matter management

For smallholder farmers, the use of fertilizers is often unaffordable resulting in negative nutrient balances in croplands. Inorganic fertilizer consumption nonetheless increased between 1961 and 2016 (Figure 4). For more than four decades until 2016, urea and diammonium phosphate (DAP) were the only commercial fertilizers used in Ethiopian agriculture [39,62]. Nowadays DAP is being gradually substituted by a combination fertilizer based on nitrogen (N), phosphorus (P), and sulfur (S) in order to meet the S demand of Ethiopian soils [62,63]. The current application rate of inorganic fertilizer is around 40 kg ha^{-1}[62], which is much lower than in many other countries [64]. A further problem is the substantial imbalance between the nutrients applied which results in lower nutrient efficiency [65]. For instance, in the Central Highlands, N and potassium (K) fluxes were negative in teff-based systems (-28 kg N ha^{-1} a^{-1} and -34 kg K ha^{-1} yr^{-1}) and in enset-based systems (*Ensete ventricosum* (Welw.) Cheesman) (-6 kg N ha^{-1} a^{-1} and -14 kg K ha^{-1} a^{-1}), while P balances were almost neutral or slightly positive [66].

Despite many positive effects on soil quality the application of organic fertilizers is limited in smallholder farms, since the majority of available organic matter is used as fuel, animal feed, and construction material [16,67,68]. Ethiopia has a large number of livestock and animal manure should be widely available [45,69]. But because of its use as a rural energy source, the bulkiness of the material, and lack of transport, manure is only spread on a small part of the agricultural area, mainly restricted to home gardens [24,70]. Additionally, out of 22.4 Mt of crop residues annually available in Ethiopia, about 10.3 Mt is used as fuel [47]. With the removal of crop residues from fields the nutrient balances turn further negative [71]. The use of cover crops is also very limited because of the low availability of fields not used for food crops [16,68]. It has been shown that the application of organic fertilization to fields increases when the prices for chemical fertilizers increase [72]. But as long as organic materials are lacking, organic matter management will remain of little importance [73].

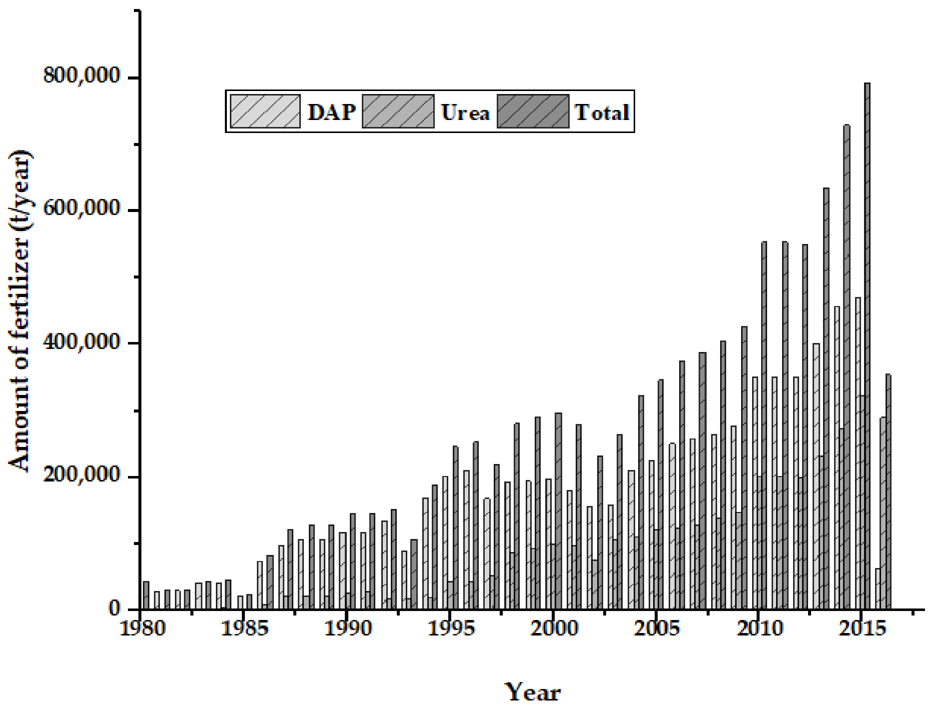

Figure 4. Development of annual urea and diammonium phosphate (DAP) fertilizer consumption (t yr^{-1}) in Ethiopia from 1980 to 2016. Source: CSA, Abraha et al. [30,47].

2.2.4. Water availability

About 80% of Ethiopian farms rely on rainfall [7]. Irregular rainfall patterns have often resulted in low agricultural productivity and food insecurity. The increasing occurrence of extreme weather events (e.g. severe droughts and heavy rainfalls) is a further threat to smallholder farms [74,75]. Intensive rainfall often results in surface runoff combined with losses of the fertile soil from the upper soil layer. Lack of rain over long periods combined with high temperatures causes serious deficits in soil moisture [76]. Due to the low distribution of irrigation facilities, water is often not available for many smallholder farms, causing frequent crop failures [41,76,77]. For instance, smallholder farms in Hararghe faced great production losses of sorghum in 2013 due to a lack of rainfall in the growing season [78]. It has been estimated that variability of rainfall may cause an average reduction in crop yields for teff, wheat, and maize of 2.4%, 6.2%, and 10.8%, respectively, by 2050 at the national level [79]. If no adaptation measures are taken, the effects of climate change and the resulting unfavorable distribution of rainfall may reduce Ethiopia's GDP by as much as 2.5% per year by 2050 and seriously affect the livelihoods of smallholder farmers [80].

2.3. Potential climate-smart agriculture practices for smallholder farming systems in Ethiopia

In order to increase the productivity of small-scale agriculture in a sustainable way appropriate agronomic management practices and suitable technology are needed [8,15,30,44,54,81,82]. This should be linked with the mitigation of climate change impacts and other relevant environmental problems (e.g., soil degradation, soil erosion, water shortages, salinization) [4,83–87]. In Ethiopia, several CSA practices are applied in smallholder farming systems (Table 1) and their current status and future potential are discussed in this section.

Table 1. Summary of potential climate-smart agriculture (CSA) practices for smallholder farming systems in Ethiopia.

CSA practices	Main components	Why it is CSA
Conservation agriculture*	Reduced tillage Crop residue management Crop rotation/intercropping with cereals and legumes Diversifying cropping systems	Sequesters soil carbon and reduces greenhouse gas (GHG) emissions Improves soil fertility Enhances resilience to dry and hot spells
Integrated nutrient management*	Compost and manure management, including green manuring Efficient fertilizer application techniques (time, place, method) Combined use of mineral fertilizers locally available organic matter and soil amendments	Sequesters soil carbon Increases soil resilience to drought Improves soil fertility Reduces nutrient leaching Reduces GHG emissions Increases agricultural productivity
Agroforestry (AF)	Tree-based conservation agriculture Traditionally practiced AF Improved types of AF	Sequesters soil and biomass carbon Supports resilience to drought Increases agricultural productivity
Water harvesting and irrigation	Rainwater and runoff harvesting Small-scale irrigation Traditional irrigation systems	Increases water availability Enhances resilience to dry and hot spells Increases agricultural productivity

* as part of Integrated soil fertility management

2.3.1. Integrated soil fertility management

Integrated soil fertility management (ISFM), which includes and combines soil conservation practices and integrated fertilizer management, is an important measure to increase crop production and mitigate impact of climate change [18,88]. In recent years special attention has been placed on ensuring that ISFM technologies are adaptable to farmers' local conditions and are also tailored to different cropping systems and socioeconomic profiles [89–91]. On-station and on-farm studies conducted in Ethiopia in different agro-ecological zones have shown that ISFM had positive effects on yields of teff, wheat, and maize [92]. A further relevant effect for Ethiopian agriculture is increased soil water retention capacity through ISFM practices [93].

2.3.1.1. Conservation agriculture practices

Conservation agriculture (CA) is a farming system that reduces soil degradation and prevents losses of cropland while regenerating degraded lands [3,94,95]. It encompasses three main principles: I) minimizing soil disturbance through direct seeding, minimal or no-tillage, and the avoidance of excessive compaction by machinery, animals, or humans; II) maintaining permanent soil cover through suitable crop rotations and the use of cover crops and mulch; and III) diversifying cropping systems [9,16,68,96]. Conservation agriculture can provide various benefits to Ethiopian smallholder farming systems (Table 2).

Table 2. Summary of major findings of conservation agriculture studies in Ethiopia.

The role of conservation agriculture	Implication for climate-smart agriculture	References
Soil organic carbon increased by about 0.5% at a depth 0–30 cm by minimum tillage compared to conventional tillage in Akaki district.	Carbon sequestration	[9,97]
Soil organic carbon increased from 2.2% to 2.6% at surface horizon by conservation tillage in the Tigray region.	Carbon sequestration	[98]
Soil organic carbon increased by 33% due to conservation tillage compared to conventional tillage in Amhara.	Carbon sequestration	[99]
Bean grain yield increased by 32% and soil organic matter by 0.4% due to minimum tillage at Melkassa research center.	Increased productivity Carbon sequestration	[76]
Mulch increased grain yield of wheat by 28% in comparison to the control in the Tigray region.	Increased productivity	[100]
Intercropped maize with crotalaria and lablab decreased emissions of GHG.	Lower emissions of GHG	[101]
An increase of the crop diversity index by 10% reduced probability of poverty by 17.5%.	Increased productivity and resilience	[102]
Hagarghe highlands with high diversity of cultivated crops had a higher dietary diversity status (73.9%) than in non-diversified areas (15.2%).	Increased productivity and food security	[103]

Minimal or no tillage can enhance soil organic carbon, which is very important for soil fertility and soil structure [9,17]. In Amhara, reduced tillage increased soil organic carbon by 33% compared to conventional tillage [76,99]. Reduced tillage can also increase the stability of aggregates, water holding capacity, and soil moisture and therefore protect the soil from erosion compaction [95,98,104–107]. These effects on soil can also contribute to increasing crop yields without increasing GHG emissions [73]. Finally, conservation tillage practices can save labor and costs, which is important for resource-poor smallholder farmers and especially for female farmers [16,96,108,109].

Soil cover by covercrops or mulch can help to prevent losses of soil and nutrients and has additional advantages regarding the conservation of soil moisture. For instance, covering soils by straw mulch reduced soil losses due to surface runoff by almost 100% in the highlands of Bale [87]. In northern Ethiopia, mulching with crop residues increased soil water in the root zone by more than 13% compared to a control treatment without mulch, which also affected the wheat grain yields positively [100].

The diversification of cropping systems is another approach to increase yields while reducing GHG emissions, as recently shown by Raji & Dörsch [110] for intercropped maize with crotalaria (*Crotalaria juncea*) and lablab (*Lablab purpureus*). Diversification of cropping systems also serves as a tool to improve the livelihood of the smallholder farmers [103,111]. In this regard Dessie et al. [101] demonstrated that the diversification of cropping systems in northwestern parts of Ethiopia is a suitable strategy for risk reduction and to increase food security. Survey results from 15 villages in Ethiopia from 1989 to 2009 revealed that an increase of the crop diversity index by 10% reduced the probability of poverty by 17.5% [102].

Conservation agriculture has been practiced in Ethiopia for the last 20 years and its adoption level among smallholder farmers has increased [68,95]. For example, 70,000 smallholders have adopted CA in the Wolaita area to control soil erosion, improve soil fertility, and address climate variability [95]. The Agricultural Transformation Agency (ATA) of Ethiopia supported about 6,000 farmers in seven Woredas (the third-level administrative divisions of Ethiopia) in 2012 and 2013 to increase conservation tillage practices and trained hundreds of experts and development agents [23]. Apart from these promising facts, Ethiopia still has significant problems in implementing conservation farming methods in the whole country.

2.3.1.2. Integrated nutrient management

Integrated nutrient management (INM) is a holistic approach and can be defined as the maintenance and regulation of soil fertility and plant nutrient supply to an optimum level in an integrated manner. It is based on the combination of organic, inorganic and biological nutrient sources in a specific cropping system under consideration of local conditions to achieve and sustain optimum yield without harming soil ecosystem[89,112–114]. Beside the positive effects on the soil nutrient status INM can also enhance SOM and increase the retention and storage of water [17,115]. Thus it can increase the resilience of agricultural systems and contribute to increasing carbon sequestration in soils [71,75,116].

Various benefits of INM have been found in Ethiopia regarding crop yields and soil organic carbon (Table 3). A meta-analysis using studies conducted in sub-Saharan Africa including Ethiopia found that mixed application of manure and inorganic fertilizer resulted in 1.1 to 4.7 times higher maize yields compared to sole application of manure or inorganic fertilizer [117]. In the Benishangul-Gumuz region, the integrated use of inorganic fertilizer and compost increased maize yield (3.25 t ha^{-1}) and the harvest index (1.9%) compared to sole inorganic fertilizer application [118]. In the central highlands of Ethiopia, mixed application of NP fertilizer and organic amendments increased the content of soil organic carbon by about 0.5% in comparison to sole application of NP fertilizer [116].

Table 3. Summary of major findings of integrated nutrient management (INM) studies in Ethiopia.

Effects of integrated nutrient management	Implication for climate-smart agriculture	References
Integrated use of compost and NP (55/10 kg ha^{-1}) resulted in higher maize yield (2.34 t ha^{-1}) than sole application of NP (110/20 kg ha^{-1}).	Increased productivity	[119]
Integrated use of NP (30/10) and compost produced greater maize yield (3.25 t ha^{-1}) than sole application of NP (60/20).	Increased productivity	[118]
Mixed application mineral and organic fertilizers increased content of soil organic carbon by about 0.5% in comparison to sole application of NP fertilizer.	Carbon sequestration	[116]
Mixed application of manure and inorganic fertilizer produced 1.1 to 4.7 times higher maize grain yields than sole application of manure or inorganic fertilizer.	Increased productivity	[117]
Compost application increased the soil organic matter by 3.8% and increased the availability of soil nutrients in the Amhara region.	Carbon sequestration Soil fertility	[120]
Straw after compost application resulted in higher yields of cereal grains in the Amhara region.	Increased productivity	[121,122]

As organic fertilizer, compost plays an important role because of its nutrient contents and its diverse effects on soil fertility and crop productivity. Compost application positively affects soil structure, resulting in higher resistance to erosion, improved water infiltration, and increased water holding potential, which is of great importance in Ethiopia [75]. Effects of compost application on soil chemical properties like pH, cation exchange capacity, and electrical conductivity can result in higher bioavailability of nutrients [120]. The addition of organic matter to soil also positively affects biological soil characteristics and enhances the microbial activity of soils [123,124]. The low technical effort for compost production is very important for countries with a weak economy [120]. Because of these benefits, compost application has been well studied and practiced in Ethiopia. For example, compost application resulted in a better status of soil macro and micro nutrients compared to mineral fertilizer application in Amhara region [120]. It increased maize yields in Tigray ([121,125] and barley yields in Amhara [122] compared to mineral fertilizer applications. In Arsi Negelle, compost application over three years resulted in soil carbon sequestration of about 0.2 t ha^{-1} [126]. Considering the high cost for mineral fertilizer in Ethiopia smallholder farmers are encouraged to use compost [68,73,127].

However, the availability of organic materials for soil application is a mayor issue. Theoretically, the annually available organic materials in Ethiopia were estimated to be 8.5×10^{9} t of poultry manure, 1.8×10^{10} t of farmyard manure, and 1.6×10^{11} t of compost [128]. This amount of organic materials could be a good basis for sustainable agricultural practices [73,127], but the majority of available organic matter is used for other purposes as fuel, food for animals or construction material (see section 2.3).

2.3.2. Water harvesting and small-scale irrigation

Water harvesting is the collecting and storing of rainwater (from rooftops and local catchments) and of seasonal floodwaters (from local streams) as well as the conservation of water through watershed management [129]. The water collection system can be categorized into I) in-situ water conservation practices, which mainly refers to the collection of water in small basins, pits, and bunds/ridges, and II) runoff-based systems, which mainly refers the collection of water from the catchment and roadside ditches [130,131].

In Ethiopia, the rainfall pattern is characterized by a large variation in spatial and temporal distributions: annual rainfall ranges between 2,700 mm in the south- western highlands and less than 200 mm in some parts of the northern and south- eastern lowlands [41,132]. To compensate for the limited precipitation in certain areas, the adoption of water harvesting is very important. In addition, it is a useful mechanism to overcome the recurrent erratic rainfall and dry spell conditions, which often result in crop failures in the smallholder farming systems in Ethiopia. [133].

Various benefits of water harvesting and small-scale irrigation have been found in Ethiopia (Table 4). Farmers increased their household income by 5% through using water harvesting for the production of tomatoes and onions in the Tigray region ([134]. Onion cultivation with water harvesting provided higher annual income compared to rain-fed teff and wheat cultivation in the Amhara region [130,135]. Application of water harvesting increased the yield of teff by about 0.5 t ha^{-1}, wheat by about 0.7 t ha^{-1}, and barley by about 0.6 t ha^{-1} in Tigray compared to rain-fed crops [132,136]. In addition, small-scale irrigation allows the production of more crops per year on a certain area and consequently contributes to sustainable food security in Ethiopia [137]. Research findings by [138] and [139] revealed that there is a significant welfare difference between farmers applying and farmers not applying irrigation.

Ethiopia has great potential for irrigation with 12 river basins, about 122 billion m^3 annual runoff volume, and 2.6 billion m^3 groundwater [130,132]. Although small-scale irrigation schemes have been promoted in sub-Saharan Africa to ensure food security, only about 5% (640,000 ha) of the agricultural land in Ethiopia is irrigated, which includes 128,000 ha from rainwater harvesting, 383,000 ha from small-scale irrigation, and 129,000 ha from medium and large-scale irrigation [114, 115]. Studies on irrigation schemes have shown that much of the perceived water scarcity level is rather attributed to poor water management practices, weak local institutions, unfavorable governance regimes, and financial issues than to the physical scarcity of water [137,142,143].

Table 4. Summary of major findings of water harvesting and small-scale irrigation studies in Ethiopia.

The role of water harvesting & small-scale irrigation	Implication for climate-smart agriculture	References
Onion cultivation with water harvesting provided $2,000 higher annual income compared to rain-fed teff and wheat cultivation in the Amhara region.	Increased productivity	[130,135]
Securing adequate water availability for crops through water harvesting in Tigray.	Increased resilience of cropping systems	[136]
In-situ rainwater harvesting provided higher maize yield (25%) than rain-fed crops in northern Tigray.	Increased productivity	[135,144]
Farmers applying small-scale irrigation had a lower incidence of poverty (28%) than the non-irrigation users (67%).	Increased productivity	[137]
Higher yield of teff (0.3–0.6 t ha^{-1}), wheat (0.5–0.8 t ha^{-1}), and barley (0.45–0.75 t ha^{-1}) obtained with small- scale irrigation compared to rain-fed cropping in Tigray.	Increased productivity and resilience	[136]
The annual income of irrigation beneficiaries in the Great Rift Valley of Ethiopia was at about 10200 Birr per household about 34% higher than that of non-users.	Increased productivity and resilience	[139]
In Ambo district about 60% of farmers without irrigation facilities but only about 35% of farmers with irrigation facilities were estimated to be below the poverty line,	Decreased poverty	[138]

2.3.3. Agroforestry

Agroforestry is a farming practice of cultivating trees in combination with crops and/or livestock. It can provide additional food, fuel woods, and various ecosystem advantages such as increased soil fertility and carbon sequestration as well as less soil erosion and land degradation [3,145–147]. Agroforestry allows smallholder farmers to produce various goods and services in an integrated manner to address a broader range of demands [148]. Therefore, it has been widely recognized as a good strategy to cope with food insecurity and climate change in developing countries [146,149].

In Ethiopia, various types of agroforestry have been practiced e.g., home garden, tree-crop intercropping, parkland or scattered trees in croplands, shaded perennial-crop systems. They have contributed to enhanced food security, resilience to climate change, and carbon sequestration (Table 5). For example, agroforestry adopters received about 17% higher yields [150] and about 7% higher incomes [31] than non-adopters in the Amhara region. As trees can obtain moisture from the underground water through their deep root systems they can still grow in times of water shortages [149,150] and produce various fruits, which are sources of supplementary food and income generation for smallholder farmers in Ethiopia [31,145]. Studies conducted in eastern Tigray [151] and the south-eastern Rift Valley escarpment [127] highlighted the increased carbon sequestration by agroforestry while protecting native trees. The increased fertility of agricultural land was the most common reason (about 40%) for farmers to practice agroforestry [27].

Table 5. Summary of major findings of agroforestry studies in Ethiopia.

The role of agroforestry	Implication for climate-smart agriculture	References
The land productivity of agroforestry adopters is 16.6% greater than non-adopters in the Amhara region.	Increased productivity	[150]
Agroforestry with white acacia (*Faiderbia albida*) sequestered 9.7 Mg ha^{-1} of organic carbon compared to rain-fed crop production in the Tigray region.	Carbon sequestration	[151]
Soil organic carbon increased by 52% compared to annual cereal rotation.	Carbon sequestration	[149]
Protection of native trees and increase of annual income by 7% could be achieved by farmland agroforestry in the Amhara region	Resilience to climate change Improved livelihood	[31]
Aboveground and belowground carbon could be accumulated in the south-eastern Rift Valley escarpment while protecting native trees.	Carbon sequestration Resilience to climate change	[152]
Restoration of degraded land in various regions of Ethiopia	Resilience to climate change Improved livelihood	[153–155]
Promotion of ecosystem services in Southern Ethiopia	Resilience to climate change Improved livelihood	[156]

Despite these advantages, the practice of agroforestry is still limited in many parts of Ethiopia due to increases in fuel wood demand, agricultural intensification, and lack of knowledge about the conservation of trees [31,157]. Unsecured or ambiguous land tenure and shortage of labor were identified as further limiting factors [27,158].

2.4. Challenges for adoption of climate-smart agriculture practices in smallholder farming systems

Despite the advantages of CSA there are still various challenges hindering the adoption of CSA in smallholder farming systems. The most commonly identified challenges in Ethiopia are discussed below.

2.4.1. Shrinking cropland and land tenure issues

The size of the land holding is a major challenge for Ethiopian smallholder farmers in the adoption of new technology and practices [159]. Due to growing population pressure and the limited availability of unexploited land the size of cropland per capita has been decreasing (see section 2.2). Farm size plays a critical role in the adoption of new technologies. Farmers with larger farms were found to be more likely to adopt CSA practices since they could use one part of the farm for trying new techniques and the other part for conventional practices [160]. In contrast, farmers with small farms are hesitant to apply CSA practices since they are afraid of the uncertainty of obtaining the claimed benefit [160]. As consequence pressure on land has caused land degradation and reduced agricultural productivity in many parts of Ethiopia [24].

Land tenure is another issue for smallholder farmers. In Ethiopia, the current land management system allows farmers to use and manage the land, but they are often not the owners of the land [161,162]. This discourages farmers from investing [162,163] and accordingly there is a consensus that the more responsibility farmers have for the long-term management of their land the more they are willing to undertake larger investments in land management [148]. This is especially important for the establishment of agroforestry systems because of the long growing periods of trees. Another example is the long-term investment in stone terraces as important soil conservation structures against soil erosion, which is associated with secure land tenure [164].

Declining fertility of soil and unsustainable farming practices are often related to insecurity of farmers about their land tenure and suitable policies are needed to create an environment, which enables individual farmers as well as communities to invest in sustainable long-term land management [19].

2.4.2. Lack of adequate knowledge and information transfer

Lack of adequate knowledge and skills is a major constraint in the adoption of CSA practices in Ethiopia [16,23,68]. Ethiopia has five agro-ecological zones based on climatic factors such as temperature [165] and the amount and distribution of rainfall [166] for which completely different recommendations regarding suitable CSA are needed. Some CSA practices are more important in temperate and humid climates with higher yield levels, e.g., integrated nutrient management. Others, however, are more effective in arid and semi-arid conditions, where soil moisture needs to be conserved, e.g., conservation tillage [83,167]. Furthermore, changing rainfall pattern in combination with warming trends make agriculture more risky in Ethiopia and increase the demand for specific, locally adapted agricultural knowledge and technologies [54,167]. These also require additional resources in agricultural research and extension services in order to provide the data basis for appropriate decisions and recommendations [28,168]. However, new research and technology must not result in neglecting indigenous knowledge, which is also needed to make agriculture sustainable in Ethiopia [168].

Another constrain is the inefficient transfer of knowledge, skills, and technologies from governmental institutions and development agencies to the local farming communities [23,68]. Smallholder farmers are often afraid of adopting new practices before seeing clear evidence of successes and getting clear explanations regarding benefits and risks of the practices [6,7,41]. For instance, it is still a great challenge to adopt methods of water harvesting and small-scale irrigation technologies in Ethiopia. This is partly due to a lack of awareness among the farmers and insufficient information about advantages of small-scale irrigation, like diversification of crops grown, increased household income, employment opportunity and participation in community decisions [129,130,132].

Additionally, exposure to new technology remains highly gendered, with most of the related initiatives targeted at men [169]. Women usually have less access to new technology, information, and training related to climate adaptation and CSA [170].

2.4.3. Slow return of benefit and lack of financial support

One of the major challenges that hinder the adoption of CSA in Ethiopia is its slow return on investment. Many CSA practices, such as agroforestry, take time to provide tangible benefits to the farmers [4], but due to the low status of the economy and lack of finance, most farmers need immediate benefits from a specific technology or practice [16,68]. As a result, the preference for the adoption of CSA is often lower than that of other agricultural practices with fast yield effects [4]. Farmers may also give up suitable technologies after a few years of using them due to a shortage of materials for construction, maintenance and operation, as shown for water harvesting technologies by [171]. Thus, incentives and support during the transition period as well as guarantees in the case of failure are necessary for the extension of CSA practices [16,172].

Access to finances is a critical factor for smallholder farmers [173]. Financial support systems in Ethiopia can be separated into informal and formal institutions. Informal financial support institutions are I) self-support groups for social development (*Idhir/ Meredaja Mahiber*) and II) traditional voluntary cooperatives (*Iqub*). Formal institutions are microfinance schemes, state-owned banks, and private commercial banks [173]. There are however problems concerning financial and institutional support. The informal financial institutions often lend money at high interest rates, so smallholder farmers face challenges paying back the loan on time. The formal finance providers support commercial farmers but often ignore smallholder farmers [4].

2.5. Opportunities for enhancing climate-smart agriculture practices in smallholder farming systems

In order to successfully implement CSA practices coordinated actions by farmers, researchers, the private sector, civil society, and policymakers are needed [11]. In the following, promising opportunities to extend the application of CSA practices in Ethiopia are discussed.

2.5.1. Utilization of degraded and marginal lands

Instead of expanding agricultural lands at the expense of forest, the widely distributed degraded lands and marginal lands (around 26% of the country; [174]) should be restored and utilized. To achieve this will involve two key changes: greater access to organic materials for soil management and alternative energy sources to reduce land clearing and degradation.

Access to and use of organic inputs is one of the most suitable methods to increase the fertility of degraded soils and an important CSA practice [16,30,68,175] (see also section 3.1). However, biomass is commonly used as an energy source in the rural part of Ethiopia [176,177] (see also section 2.3). Therefore, it is important to introduce and adopt appropriate measures to increase energy efficiency and to use alternative energy sources. Various types of improved cook stoves have been developed in Ethiopia (e.g., Mirt, Mirchaye, Lakech, and Rocket stoves) and their fuel efficiency is about 30 to 40% higher than conventional cook stoves (e.g., open fire) [178–180]. This can reduce significantly the use of biomass as an energy source. Furthermore, Ethiopia has great potential to produce renewable energy from sources other than biomass [178]. Potential renewable energy sources in Ethiopia are solar energy (500 MW km^{-2} in the lowlands and 100 MW km^{-2} in the highlands), hydropower (about 45 GW potential), wind energy (about 10 GW potential), and geothermal energy (about 5 GW potential) [58]. Increasing awareness among smallholder farmers to fully exploit the locally available organic materials can also help to provide organic fertilizers to soils. For example, coffee husk is especially common in the highland area of Ethiopia. In Shabedino district in southern Ethiopia, a small coffee-producing village dumps about 7,000 t of dry coffee husk in rivers annually [181]. That gives an idea of how much coffee waste is produced in the whole country. The coffee husk can be used as a mulching material to prevent moisture losses and as a feedstock for producing compost, which can improve soil fertility and crop production [181,182]. Residues from khat or chat (*Catha edulis*) are other locally available and cheap organic sources and can be a basis for compost production. It was found that khat vermicompost had relatively high nutrients (1.6% N, 0.6% P) [183]. Another promising opportunity of using wastes to increase the fertility of soils is to produce biochar from wastes of the meat processing industry [65]. In addition, composting organic waste such as food waste and garden waste, which is disposed of in urban Ethiopia can also be sources of organic fertilizer for agricultural use as long as it does not contain critical levels of harmful substances [183–185].

Salinity and waterlogging are also key issues for Ethiopia's agriculture and often reasons for land degradation [186]. Appropriate water management practices, drainage systems and irrigation methods can mitigate these problems and increase the availability of productive agricultural land [187]. For example, in the Awash Basin, reclaimed saline fields increased sugarcane production by 50% [188]. Challenges in relation to costs and technology in the design, implementation, and operation of drainage and irrigation systems can be overcome by introducing low-cost technologies [186]. For instance, an improved water management and surface drainage method, called "broad bed and furrow", has been introduced in several parts of Ethiopia [189]. The mapping of spatial and temporal dimensions of waterlogging and salinity can help to better describe their impacts on the agricultural productivity and thus to initiate appropriate measures [186].

Degraded land which is not suitable for the pure production of crops should be converted to agroforestry, since agroforestry is one of the most promising CSA practices [190] and has a great potential to improve soil fertility [7,19,146] (see also section 3.3). In particular agroforestry systems that contain leguminous tree species are vital since they provide additional value due to biological nitrogen fixation [191].

On-farm trees and a return to a more diverse agricultural landscape mosaic may provide provisioning and other ecosystem services [52,153,192]. Especially in landscapes dominated by cropland, the benefit of such tree-planting is very high and linked to greater livestock numbers, improved resilience and diversification of income sources, and increased biodiversity [155]. Thus, trees can be seen as a sustainable intensification of agriculture [153]. Eucalyptus is often chosen for tree-planting, as it is a lucrative form of income [32]. However, eucalyptus trees can have a negative impact on the environment (e.g., due to their high water consumption) and more emphasis should be placed on the establishment and management of mixed-species woodlots [154,156].

Interdisciplinary landscape approaches that promote agricultural productivity as well as ecological functions should be applied in order to regenerate agricultural land, contribute to rural livelihood, and conserve biodiversity in landscapes where farmers co-exist with nature [32,148,153,154]. This is also addressed in the Forest Landscape Restoration (FLR) program. With 15 million ha Ethiopia is one of the countries with the most ambitious FLR targets [52]. A main objective of this strategy is to restore degraded and marginal landscapes in order to mitigate impacts of climate change [193,194]. This program will have particular advantages for smallholder farmers as the most vulnerable to landscape degradation and the greatest beneficiaries of restoration [195].

2.5.2. Providing microfinance for the adoption of climate-smart agriculture practices

Access to financial support services strongly influences the decision of smallholder farmers to apply suitable CSA practices [73]. Financial support, however, also requires an increased awareness of the farmers of the financial opportunities [196], and often farmers must be trained regarding their rights of credit use and the obligation to repay in time [7]. There are various international programs that support climate funds in Ethiopia which can be useful for smallholder farmers to shift their farming system to CSA and to overcome barriers such as poor equipment and lack of inputs [14]. They include the Scaling-Up Renewable Energy Program for low-income countries (SREP) of the Climate Investment Funds (CIF), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM) [4,197]. They provide financial support for climate-related projects either to mitigate the impact of climate change or to increase the resilience potential of the agricultural and environmental sectors. In addition, the REDD+ program is a relevant CSA funding option administered directly through United Nations agencies and implemented by the United Nations Environment Programme (UNEP) [14,74,80]. This program makes investments in small and medium- sized enterprises dealing in clean energy solutions in rural areas, thereby increasing climate change mitigation.

Some regional organizations like banks and microfinance institutes also provide financial support for CSA investments of smallholder farmers. For example, Oromia Cooperative Bank of Ethiopia (OCBE) supports local agri-businesses related to sustainable agricultural production in smallholder farming systems [7]. The development of specialized finance schemes throughout the country and a strong framework from federal schemes to local institutions could provide even more effective support of CSA practices in smallholder farming [4,197].

2.5.3. Education, empowerment and capacity-building

Training is an important capacity-building tool to disseminate CSA practices and for agricultural extension workers to pass on their knowledge to the farmers in a targeted manner [3,96]. Besides theoretical information the practical aspects should also be transferred in order to increase the adoption of CSA practices. For example, practical training is often needed regarding suitable soil nutrient management, compost preparation from locally available materials, conservation agriculture, and water harvesting techniques because these practices are very dependent on the respective local circumstances [4,162]. As a result of such targeted teaching, the farmers would have more experience and can easily familiarize themselves with CSA practices [96]. Most farmers prefer to see at firsthand the workability and applicability of new technologies and practices and to compare them with their own farming practices. Knowledge-sharing and joint educational activities allow farmers, extension workers, NGOs, and researchers to learn about success stories and the challenges associated with local CSA practices [23]. Ultimately, farmers should be empowered to develop solutions and make decisions on their own [198].

Women usually have less access to new technologies and training related to climate adaptation and CSA [169,170] (see also section 4.2). Gender mainstreaming can increase women’s potential to access useful information and training on new technologies [3,166]. Education and training on CSA practices can also enhance opportunities and reputation of women in rural areas [23]. For example, a study indicated that women's skills have been increased through training on compost preparation from locally available materials, water harvesting systems, and small-scale irrigation schemes [28]. This training has finally increased the income of women in rural Ethiopia [199]. Empowering women means increasing their power to think and act freely, exercise choice, and to fulfill their potential as full and equal members of society [200]. But gender empowerment cannot only be achieved through training and education. Allowing the participation of women in the process of decision-making and giving them access to inputs and resources is just as important [28,201]. In addition, increasing the engagement of women in political, social, and economic issues can in turn increase the adoption of CSA among smallholder farmers in Ethiopia [28,199].

In addition, theoretical and practical aspects of CSA should be more incorporated in higher education curricula [202]. As education raises the awareness on both problems and solutions of land management it also has a positive impact on investments in CSA practices [85].

2.5.4. Policy support for the implementation of climate-smart agriculture practices

Policy support is fundamental for the spread of CSA practices in the country. In the past decades several policies and strategies have been established for the agriculture sector to reduce poverty, especially for rural smallholder farmers in Ethiopia. These include the Agricultural-Led Industrialization (ADLI), according to which a rapid growth in agricultural production, increased income for rural households (especially for crop producers), and national food self-sufficiency can be obtained [61,203]. ADLI was later complemented by programs such as the Sustainable Development and Poverty Reduction Program (SDPRP) (2000 to 2005), a Plan for Accelerated and Sustained Development to End Poverty (PASDEP) (2005 to 2010), and the Growth and Transformation Program I (2010 to 2015) and II (2015 to 20202) [204]. The development of these programs show that compared to other sub-Saharan African countries, Ethiopia has an admirable record of supporting agriculture [25].

However, it becomes clear that the effects of climate change on agriculture can hamper the progress achieved so far and that practices more relevant for climate change adaptation and mitigation need to be promoted by means of specific policies. While Ethiopia does not have a standalone CSA strategy, significant efforts are made to develop policies and strategies relevant to climate change [3]. One important example is the

Climate Resilient Green Economy (CRGE) strategy which was established in 2011 targeting climate change adaptation and mitigation [166] with the aim of achieving a carbon-neutral middle-income status by 2025 in Ethiopia [3]. The policy incorporated CSA and sustainable land management for improving crop and livestock production, food security, integrated watershed management, and farmer income while reducing GHG emissions (limiting emissions to 150 Mt CO_2-e in 2030) [205,206]. It also explicitly includes the protecting and re-establishing forests [3] and it indicates that agroforestry is one of the initiatives to reduce pressure on forest resources while preventing soil erosion and land degradation [27]. Forest protection and extension is also a responsibility of the forest proclamation [207], which was approved in 2018 and regulates options for forest development, conservation and utilization. The forest proclamation also contains tenure reform and states that communities and associations can have forest ownership rights. This is an important factor to overcome the current impediments regarding forest landscape restoration (FLR), agroforestry and the adoption of other CSA practices [208] (see section 4.1).

These measures indicate that climate change and CSA have been recognized in the process of establishing policies and strategies in Ethiopia. However, considering the challenges described in section 4 several suggestions can be made in order to enhance the implementation of CSA among smallholder farmers. First, a strong awareness among the community members of the need to improve their land use systems for sustainable livelihood and environmental protection must be achieved. In this regard it is also necessary that communities are involved in relevant decision finding processes and that land use rights are clarified [19,208]. No policy or strategy will be especially successful without the involvement of the local community and the integration of the local farmers as a basic stakeholder [96]. For example, the CRGE was established at the national level to implement the projects. Since Ethiopia has five institutional levels (federal, regional, zonal, woreda, and kebele), the CRGE should also consider these structural administrative levels [80]. Second, agricultural development policy and strategy should carefully consider the specific issues related to small-scale farming and should place more emphasis on capacity-building, information dissemination systems, and institutional and financial support [6]. Third, formulating policies and strategies that promote the adoption of CSA should better consider the differing characteristics of climatic conditions and agro-ecology that are found across the country (e.g., different rainfall and temperature patterns) [3,167].

Conclusion

Agriculture in Ethiopia is dominated by smallholder farming systems, which together produce more than 90% of agricultural output and cultivates more than 90% of the entire cropland. In recent decades, agricultural production has made some progress; however, it needs further transformation to increase crop production in smallholder farming systems while adapting to and mitigating climate change. Various CSA practices have been adopted locally and studies have identified their various benefits, including increased drought resilience, household income, carbon sequestration, and GHG mitigation. How-ever, the adoption of CSA is still low in smallholder farms due to a lack of land, resources, adequate knowledge, and financial and policy support. In our study, we comprehensively evaluated currently available CSA practices, which allow us to suggest opportunities and solutions for a sustainable improvement of smallholder farming systems. In this regard, we have particularly emphasized the following measures: (1) Improvement of soil quality and restoration of degraded and marginal land instead of expanding cropland through deforestation; (2) Providing training, education, and capacity-building for farmers and extension workers; and (3) Development of specific financing schemes and policies for smallholder farming systems. Although our study focuses on the situation in Ethiopia, the results may also be relevant for other countries, which aim at increasing agricultural production while mitigating the effects of climate change.

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Chapter 3: Combination of Compost and Mineral Fertilizers as an Option for Enhancing Maize (*Zea mays* L.) Yields and Mitigating Greenhouse Gas Emissions from a Nitisol in Ethiopia

Combination of Compost and Mineral Fertilizers as an Option for Enhancing Maize (*Zea mays* L.) Yields and Mitigating Greenhouse Gas Emissions from a Nitisol in Ethiopia

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Abstract

Combined application of organic and mineral fertilizers has been proposed as a measure for sustainable yield intensification and mitigation of greenhouse gas (GHG) emissions. However, fertilizer effects strongly depend on the soil type and still no precise information is available for Nitisols in Ethiopia. The study evaluated effects of different ratios of biowaste compost and mineral fertilizers (consisting of nitrogen (N), phosphorus (P), and sulphur (S)) on maize (*Zea mays* L. Bako-hybrid) yields in a two- year field trial. Soil samples from each treatment of the field trial were used to estimate emissions of nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), and microbial activity in a 28-day incubation experiment with two moisture levels (40% and 75% water-filled pore space, WFPS). The application of fertilizers corresponded to a N supply of about 100 kg ha^{-1}, whereby the pure application of mineral fertilizers (100 min) was gradually replaced by compost. Maize yields were increased by 12 to 18% (p < 0.05) in the combined treatments of compost and mineral fertilizers compared to the 100 min treatment. The cumulative emissions of N_2O and CO_2 but not CH_4 were affected by the fertilizer treatments and soil moisture levels ($p < 0.05$). At 75% WFPS, the N_2O emissions in the 100 min treatment was with 16.3 g ha^{-1} more than twice as high as the treatment with 100% compost (6.4 g ha^{-1}) and also considerably higher than in the 50% compost treatment (9.4 g ha^{-1}). The results suggest that a compost application accounting for 40 to 70% of the N supply in the fertilizer combinations can be suitable to increase maize yields as well as to mitigate GHG emissions from Nitisols in Southwestern Ethiopia.

Keywords: organic fertilizer; soil fertility; global warming potential; microbial activity; crop yields

3.1. Introduction

In the context of climate-smart agriculture (CSA), soil management should balance the three CSA pillars of mitigation, adaptation, and productivity [1]. Considering type and amount of fertilizer as well as application time and technique can improve the productivity while reducing nutrient imbalances and nutrient losses from agricultural fields [2,3]. Applying organic fertilizers was shown to have positive yield effects in a broad range of cropping systems [4–8] and also has environmental benefits, as evaluated in a life cycle assessment study [9]. With regard to soil fertility, among others, organic materials were shown to enhance aggregation and stability of the soil and reduce erosion ([10,11], suppress soil borne diseases [12], store nutrients [13], and improve biological functions [14,15]. Despite the advantages of organic fertilization, various studies agree that the combination of organic and mineral fertilizers can provide even better results concerning CSA than sole organic or mineral fertilizer. For instance, the results of Sileshi [16] from a meta-analysis on studies conducted in sub-Saharan Africa, including Ethiopia, reported higher yields (factor 1.1 to 4.7) of maize when combinations of organic and inorganic fertilizers were applied compared to sole application of manure or inorganic fertilizer.

Although, improper application of organic fertilizers can result in considerable releases of greenhouse gases (GHG) [14,17], combining organic and mineral fertilizers was frequently described as a viable option to reduce nitrogen (N) losses and emissions of GHGs, especially carbon dioxide (CO_2) and nitrous oxide (N_2O) in different cropping systems [3,18–20]. The potential to reduce GHG emissions depends largely on the type of the organic amendments and their effects on soil microbial community structure and functions [14]. Mainly processed amendments, as compost, were found to increase the carbon (C) stocks in soils and to reduce the emissions of N_2O [14,21]. In this context, research findings by Das and Adhya [20] showed that combined application of compost (30 kg N ha^{-1}) plus urea (90 kg N ha^{-1}) lowered the N_2O emissions by about 18% in comparison to sole application of urea (120 kg N ha^{-1}).

Microorganisms are important components of the C and N cycles in soil and they also affect the emission of GHGs through the decomposition of organic matter and nitrification and denitrification processes [8,9,22,23]. As microbial activity is strongly affected by the availability of N and labile C [14], the activity of dehydrogenase (DH), as an indicator of the intracellular activity of living microorganisms [24,25], was usually found to increase after application of organic amendments [26,27]. In contrast, the sole application of mineral N fertilizer can decrease DH activity in the soil by soil acidification or secondary salinization [28,29]. Furthermore, high rates of microbial activity in soil usually occur when soil moisture is near field capacity, which is equivalent to about 60% water-filled pore space (WFPS) [30]. Raising WFPS to 70 or even 90% increases N_2O emissions [19,31].

Reduced emissions of GHGs after combining mineral with organic fertilizers were found for tropical as well as for temperate regions [32]. However, the extent of GHG emissions from soils strongly depends on the climate [33] and soil quality, whereby especially soil type, temperature, and moisture content are decisive [34–36]. For example, Sakata et al. [37] found significantly different values of N_2O and CO_2 emissions in oil palm plantations for three soil types, despite the same N fertilizer management. Consequently, the trade-off between sustainable production, soil quality, and GHG emissions should be taken into account when developing suitable fertilizer strategies.

The southwestern part of Ethiopia is characterized by a mono-modal rainfall pattern with high rainfall intensity during the summer season from June to September

[38,39]. This is the main cropping season with WFPS values of about 90% and average temperatures above 20 °C [38], which favor GHG emissions. On a global perspective, Ethiopia emitted relative low amount of GHG with about 150 Mt CO_2 equivalents in 2015, of which about 61% came from agriculture, mainly livestock [3,40]. Because of the low amount of N applied to cropping fields in Ethiopia during the last decades, N fertilizers were not a main driver of GHG emissions [40]. However, the government of Ethiopia has planned to increase the mineral fertilizer (mainly urea) dose from about 65 kg ha^{-1} in 2010 to about 250 kg ha^{-1} by using a combined N, phosphorus (P), and sulphur fertilizer (S) in 2030 [41]. As a result, based on modeling studies by Worku [40] and FDRE, [37] N_2O emissions from mineral fertilizer are expected to increase from 4.3 Mt CO_2 eq. in 2010 to 35 Mt CO_2 eq. in 2030, which accounts to 58% of the total soil- based emissions. However, these data contain a certain inaccuracy as concrete studies on GHG emissions from crop fields under specific environmental conditions and management practices are widely lacking in Ethiopia.

Combining organic and mineral fertilizers was frequently shown to increase crop yields and to reduce the emissions of GHGs in different cropping systems (see above). However, it was also shown that site conditions have great effects on the efficiency of fertilizer practices and on nutrient losses. Although Nitisol is the major soil type of cereal growing areas in the highlands of Ethiopia [42], so far N fertilizer practices have not been studied with regard to crop yields and GHG emissions. These research gaps encouraged us to investigate different ratios of compost and urea/NPS applied to a Nitisol regarding crop productivity and GHG emissions. In order to take into account the role of microorganisms in this respect, the activity of the DH was analyzed as well.

The concrete objectives of this study were: I) to quantify GHG emissions of compost and urea/NPS fertilizers as N source, II) to identify the most suitable ratio of compost and urea/NPS in order to reduce the emissions of GHGs while having positive effects on maize yield, and III) to evaluate if the ranking of the combinations regarding GHG emissions depends on soil moisture. Considering the state of the art, we hypothesized, that (i) combined N application with compost and urea/NPS to a Nitisol will produce less GHG emissions than the N application with only mineral fertilizers, (ii) the ratio of compost to urea/NPS influences GHG emissions and maize yield, and (iii) the GHG emissions will be higher when the water content in the Nitisol is higher.

3.2. Materials and Methods

3.2.1. Experimental Site and Treatments

The study consisted of two experiments—one field experiment to evaluate the maize yield and one incubation experiment to analyze the emission of GHG after application of organic and mineral N sources. The field experiment was performed at the research station of Jimma University College of Agriculture and Veterinary Medicine (JUCAVM) at an altitude of 1710 m above sea level in Southwestern Ethiopia (Eladale; latitude, 7° 42′ N; longitude 36° 49′ E) (Figure 1). The research site is characterized as humid tropical climate with temperatures between 13 °C and 28 °C (Figure 2). The annual minimum and maximum rainfall in the area is around 1200 and 2400 mm, respectively, whereby for our experiment, considerably higher rainfall occurred in 2020 than in 2019. The soil texture of the experimental field was silty clay loam with a pH of 4.98, organic carbon content of 2.4%, and total N of 0.22% (Table 1). According to the World Reference Base, the soil was classified as Nitisol, which was characterized as red, well-drained soil with a clay content of more than 30% and a blocky structure. In addition, the site was characterized by low P content, and high iron and aluminum content [42,43]. The soil of this site was also used for the incubation experiment.

Figure 1. Map of the study site and photos of the field experiment and research activities at the site (Jimma University Research Center, Ethiopia).

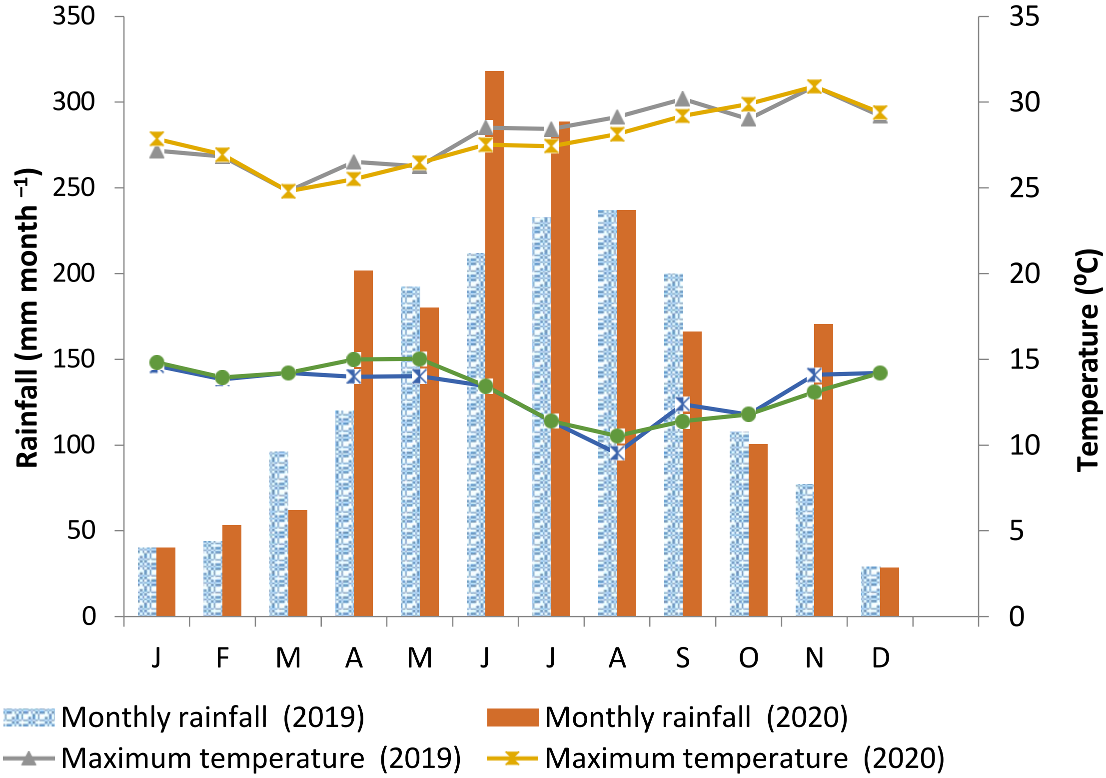

Figure 2. Monthly rainfall and temperature of the study area during the experimental periods 2019 and 2020. Data source: Regional Meteorological Service Agency, Jimma Meteorological Branch Office, Ethiopia.

Table 1. Properties of soil and compost used for the incubation experiment (N = 4, Mean ± standard error).

Parameters	Biowaste Compost	Soil
Org. C (g kg^{-1})	92.9 ± 0.8	24.0 ± 4.0
N (g kg^{-1})	12.0 ± 0.7	2.2 ± 0.1
S (g kg^{-1})	2.2 ± 0.08	0.5 ± 0.02
Ca (g kg^{-1})	25.1 ± 1.5	2.3 ± 0.2
P* (mg kg^{-1})	718.2 ± 7.5	2.1 ± 0.1
K* (g kg^{-1})	1.9 ± 0.02	0.4 ± 0.1
Mg* (g kg^{-1})	1.3 ± 0.04	0.2 ± 0.01
Cu (mg kg^{-1})	39.8 ± 1.6	22.3 ± 1.2
Fe (mg kg^{-1})	44.4 ± 0.2	66.6 ± 1.6
Zn (mg kg^{-1})	188.9 ± 2.3	98.1 ± 3.2
Mn (g kg^{-1})	1.9 ± 0.05	0.4 ± 0.02
pH	7.1 ± 1.0	4.9 ± 0.9
EC (µS cm^{-1})	6.1 ± 0.5	0.3 ± 0.01
CEC (cmole kg^{-1})	118.0 ± 4.8	42.7 ± 5.3
Moisture content (%)	9.7 ± 1.1	8.2 ± 1.0
Texture	-	Silty clay loam
Bulk density (g cm^{-3})	-	1.2 ± 0.2

*P, K, and Mg in the compost are given as total contents and in the soil as bio-available nutrients.

In order to assess the impact of the fertilizers on maize yield, GHG emissions and microbial activity in soil, different ratios of mineral and organic fertilizers were applied to the soil. The fertilizer application based on previous recommendations for N and P supply in the maize cropping systems under similar growing conditions [44,45] and 100 kg N ha^{-1} and 33.3 kg P ha^{-1} were defined as the optimum amount of nutrients to be supplied with mineral fertilizers in this experiment (=100% mineral fertilizer). In the other treatments, the nutrient supply with the mineral fertilizers was gradually replaced by biowaste compost. The maximum amount of compost applied to the field was 7 t ha^{-1} (dry weight, 1.2% N and 0.072% P) (=100% compost). Compost applications in this range were previously reported to be suitable for maize production in this region [46–48]. In total, seven treatments, including control without fertilizers, were established. The nomenclature followed the percentage of mineral fertilizer applied, starting with 100 min (= 100% mineral fertilizers), followed by 80 min, 60 min, 50 min, 30 min, and 100 comp (= 100% compost) (Table 2).

Table 2. Description and nutrient application of the treatments applied in the study**.**

Treatment	Description of treatments	
	Urea/NPS	Compost
Control	0	0
100% min	100% mineral fertilizer [urea (135 kg ha^{-1}) and NPS (200 kg ha^{-1}) fertilizers; 100 kg N ha^{-1}and 33.3 kg Pha^{-1}] (conventional fertilizer management practice)	0
80% min	80% mineral fertilizer [urea (108 kg ha^{-1}) and NPS (160 kg ha^{-1}); 80 kg N ha^{-1} and 26.64 kg P ha^{-1}]	(1.4 t ha^{-1} compost): 130.1 kg C ha^{-1}, 16.8 kg N ha^{-1} & 1.01 kg P ha^{-1}
60% min	60% mineral fertilizer [urea (81 kg ha^{-1}) and NPS (120 kg ha^{-1}); 60 kg N ha^{-1}and 19.98 kg P ha^{-1}]	(2.8 t ha^{-1} compost): 260.1 kg C ha^{-1}, 33.6 kg N ha^{-1} & 2.02 kg P ha^{-1}
50% min	50% mineral fertilizer [urea (67.5 kg ha^{-1}) and NPS (100 kg ha^{-1}); 50 kg N ha ha^{-1} and 16.65 kg P ha^{-1}]	(3.50 t ha^{-1} compost): 325.2 kg C ha^{-1}, 42 kg N ha^{-1} & 2.5 kg P ha^{-1}
30% min	30% mineral [urea (40.5 kg ha^{-1}) and NPS (60 kg ha^{-1}); 30 kg N ha^{-1} and 9.99 kg P ha^{-1}]	(4.90 t ha^{-1} compost): 455.2 kg C ha^{-1}, 58.8 kg N ha^{-1} & 3.53 kg P ha^{-1}
100% comp	0	100% Compost (7 t ha^{-1} compost): (650.3 kg C ha^{-1}; 84 kg N ha^{-1} and 5.04 kg P ha^{-1})

As a mineral fertilizer commercially available, NPS (19% N–38% P-7% S) and urea (46% N) were applied. A compost based on locally available materials such as residues from vegetable plants, animal manure, and wood ash was prepared following the standard procedure of Tulema et al. [49]. The soil and compost were analyzed regarding nutrient concentration and physical characteristics (Table 1). The pH of compost and soil were measured using a pH meter (pMX 3000) in 1:2.5 compost/soil: $CaCl_2$ ratios. The organic C was measured by the Walkley–Black oxidation method and the total N by the micro-Kjeldahl method. The total element concentrations of the compost and soil were measured after microwave digestion (aqua regia) by using inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin Elmer). The available phosphorus (P), potassium (K), and magnesium (Mg) contents were measured in a spectrophotometer (P) or flame photometer (K, Mg) after extraction with calcium lactate ($C_6H_{10}CaO_6$ * 5 H_2O) solution. The cation exchange capacity (CEC) was determined by Chapman [50]. In addition, soil texture was determined using the hydrometer method [51] and bulk density was determined using a core sampler method [52].

3.2.2. Determination of Maize Yield and Agronomic N Use Efficiency

Maize was cultivated for two growing periods in a randomized complete block design with seven treatments (see Section 2.1) and four replications. The Bako hybrid (BH_661) variety was used, because it is the most commonly used by farmers in the study area. In February 2019 and March 2020, twelve plants per row were planted at 0.75 m inter-row and 0.30 m intra-row spacing with a plot size of 4 m by 2.5 m (10 m^2) (Figure 1). No irrigation was applied during the experiment as the maize crops were sown during the main growing season with sufficient rainfall. Weeding and other agronomical practices were applied manually using labor forces. During maturity (July 2019 and August 2020), the two central rows in each subplot were harvested in order to determine the maize grain yield [53].The grain samples were oven-dried for 72 h at 70 °C in order to get dry weight. Beside the yields, agronomic nitrogen use efficiency (ANUE) for each treatment was also calculated, as described by Baligar and Fageria [54].

$$\text{ANUE (kg grain /kg N applied)} = \frac{GYf - GYu}{Nap} \quad \text{(1)}$$

where *GYf* is the grain yield of the N fertilized plot (kg), *GYu* is the grain yield of the unfertilized plot (kg), and *Nap* is the quantity of N applied with compost or mineral fertilizer (kg).

3.2.3. Incubation Experiment and Greenhouse Gas Measurement

Composite sampling of the topsoil (0–5 cm) of the unfertilized plots was performed assuming farmers usually incorporate fertilizers at the surface of the soil. The soil was homogenized, air-dried, sieved (2-mm pore size), and immediately stored at 4 °C until the beginning of the incubation experiment. Larger (>2 mm) surface aggregates and below-ground plant matter were removed beforehand. The laboratory incubation experiment was conducted at the University of Rostock (Germany) with the Nitisol from the field experiment in Ethiopia, applying the same fertilizer treatments as in the field experiment in four replications (Table 2). Two hundred grams of air-dried soil was filled into a 1000 mL jar, the soil aggregates were evenly compacted to a bulk density of 1.2 g cm^{-3} (to mimic the natural soil pore spaces), and pre-incubated at 25% WFPS and 25 °C for 15 days. Pre-incubation of soil samples is suggested before starting GHG measurement to settle and standardize the soil microbial community following the disturbance of sampling and sieving [55]. After the pre-incubation, fertilizers were applied and the moisture contents were adjusted to 40% and 75% WFPS in order to mimic the dry and rainy season. The fertilizer addition was adapted to the soil volume in the jars, whereas 100 kg N ha^{-1} corresponded to 33.3 mg N kg^{-1} soil. The mineral fertilizers and fresh compost were evenly spread and homogenized with the dry soil. The jars were incubated constantly at 25 °C in the dark in a completely randomized order. Loss of water during incubation was compensated by adding H_2O_{demin} on a daily basis.

Gas samples were collected each day from the first day to the 13th day. For the first three days, gas samples were collected three times a day and for the remaining ten days, once a day. This approach considered the higher production of GHG immediately after fertilizer application [56]. Gas samples from the headspace of the sealed jars were collected by 60 mL syringes, transferred to evacuated vials, and the gas concentrations of N_2O, CO_2, and CH_4 were measured with a gas chromatograph (GC-2014, Shimadzu) equipped with an electron capture detector for the N_2O analysis, and a flame ionization detector (FID) for the CO_2 and CH_4 analysis. Jars were opened for 20 min to maintain aeration after every measurement and closed until the next measurement. The loss of moisture was re-adjusted to maintain the chosen moisture content throughout the incubation [35]. Gas fluxes were calculated by assuming a linear increase in gas concentrations inside the incubation bottles over time.

3.2.4. Determination of N_2O, CO_2, and CH_4 Emissions, N_2O Emission Factor, and Global Warming Potential

The GHG fluxes were calculated area-based by considering the surface of jars filled with soil. We measured the height and diameter of the jar, which was filled with soil (bulk density 1.2 g cm^{-3}) and calculated the surface of the jars occupied by the soil. The diameter of the jar was determined by considering the average of the upper and lower surface of the jar. The soil emissions were estimated based on the rate of linear GHGs increase in the container headspace over time from a given amount of soil. Gas fluxes (g ha^{-1} day^{-1}) were calculated by the following equation of Comeau et al. [57] for soil heterotrophic respiration assessment using minimally disturbed soil microcosm cores. The conversion factor of ppm/ppb N_2O, CO_2 and CH_4 to mg N_2O, CO_2 and CH_4 was calculated with Eq. (2):

$$Cf = P \times \frac{Mm(C \text{ or } N) * 1000}{RT} \quad \text{...(2)}$$

where *Cf* = conversion factor of ppm/ppb of N_2O, CO_2 and CH_4 to mg N_2O-N, CO_2-C and CH_4-C; *P* = air pressure (kPa); *Mm* = molar mass of C (12) or N (28); *R* = gas constant (8.314); *T* = incubation air temperature (K). Finally, the N_2O, CO_2, and CH_4 fluxes were computed on an area basis. The N_2O-N, CO_2-C, and CH_4-C per unit of area were calculated using the following equation:

$$Flux = \frac{((\frac{C}{t}) * Cf * Hs)}{(Area)} \times 10^{-6} \quad \text{...(3)}$$

where *Flux* = linear gas efflux in incubation container on soil area basis (g CO_2-C m^{-2} h^{-1}); *Cf* = conversion factor of ppm CO_2 to mg CO_2-C m^{-3}; *t* = incubation time (hours); C = change in gas concentration during the incubation period; *Hs* = headspace volume of the incubation jar (m^3); *10^{-6}* = conversion factor from µg to g; *Area* = area of the microcosm surface (m^2). The cumulative GHG emissions were calculated by summing the daily fluxes [58]. The final results were converted from µg N_2O $h^{-1}m^{-2}$, g CO_2

$h^{-1}m^{-2}$, and µg CH_4 $h^{-1}m^{-2}$ to g N_2O ha^{-1} day^{-1}, kg CO_2 ha^{-1} day^{-1}, and g CH_4 ha^{-1} day^{-1}, respectively, and presented in figures and tables.

The N_2O emission factor (EF) was calculated following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Tier (I) methodology [59], as follows:

$$N_2O\ EF\% = \left(\frac{N_2O\ ENI - N_2O\ EC}{Ninput} \right) \times 100 \quad (4)$$

where *N_2O EF%* = N_2O emission factor; *N_2O ENI* = N_2O emission in treatments with N input; *N_2O EC* = N_2O emission in the control treatments with no N addition; *N input* = the amount of N added to the soil.

The GWP was determined for fertilizer rate and type using the following equation [60]:

$$GWP = N_2O \times 298 + CO_2 + CH_4 \times 25 \quad (5)$$

where *GW*P = global warming potential (kg CO_2 eq. ha^{-1}); N_2O = is the amount of N_2O (kg ha^{-1}); CO_2 = the amount of CO_2 (kg ha^{-1}); CH_4 = the amount of CH_4 (kg ha^{-1}); 298, and 25 = GWP coefficients to convert N_2O and CH_4, respectively, to CO_2 equivalents [61].

3.2.5. Dehydrogenase Enzyme Activity

Dehydrogenase enzyme activity (DHA) was determined following the modified method based on [62]. During this procedure, 0.8% triphenyl-tetrazolium-chloride (TTC) was added to 1 g of soil and incubated for 24 h at 37 °C. As a result of DHA, TTC was reduced to triphenyl-formazan (TPF) by most microorganisms. TPF was extracted with acetone after incubation and measured with the spectral photometer (Specord 40, Analytik Jena, Germany). The activity was expressed as 1 g TPF per g soil released within 24 h (1 g TPF g^{-1} 24 h^{-1}). Soil samples were taken three times during the incubation period and analysed for DHA. The first sample was taken immediately after the incorporation of different fertilizers. The second sample was taken after seven days of incubation.

3.2.6. Statistical Analysis

The normality of residuals was assessed by the Kolmogorov–Smirnov normality test [63], and it was shown that our data was approximately normally distributed. One-way analysis of variance (ANOVA) was used to determine the effect of different fertilizer types on GHG emissions, N_2O EF, GWP, and DHA. The interaction effect of moisture content and fertilizer types was analyzed by a two-way ANOVA. The mean values were determined by using the Tukey multiple-comparison test by using SPSS (22.0 version). Pearson correlation analysis was used to determine the relationship between C inputs and emissions of N_2O, CO_2, CH_4, and N_2O EF.

3.3. Results

3.3.1. Maize Yield and Agronomic Nitrogen Use Efficiency

The maize grain yields were measured in two consecutive years in an on-station experiment (Table 3). The maize yield depended on the experimental year as well as on the fertilizer treatments. Averaged across the fertilizer treatments, the yields were lower in the second year, which is linked to unexpected rainfall and windy weather conditions. Relatively high yields were found for the combined fertilizer treatments. This was especially true for the 60 min treatment with significantly ($p < 0.05$) higher yields (9.9 Mg ha^{-1}) than the control without fertilizers or the single fertilizer applications in both years. For example, averaged across both years, the 60 min treatment had 9.8 Mg ha^{-1}, which was 18% higher than the 8.3 Mg ha^{-1} in the 100 min treatment. The combined treatment with only 80 min was not found to be more effective than the 100 min treatment. No differences were found between the 100comp and 100 min treatments.

Table 3. Maize grain yield and agronomic nitrogen use efficiency (ANUE) in a two-year field experiment (N= 4) (Mean ± standard error).

Treatments	1st year yield (Mg ha^{-1})	2nd year yield (Mg ha^{-1})	Average yield (Mg ha^{-1})	1st year ANUE (kg grain kg^{-1} N)	2nd year ANUE (kg grain kg^{-1} N)	Average ANUE (kg grain kg^{-1} N)
Cont.	8.5 ± 0.3^{a}	7.5 ± 0.2^{a}	8.0 ± 0.1^{a}	-	-	-
100 min	9.0 ± 0.1^{ab}	7.6 ± 0.2^{a}	8.3 ± 0.2^{ab}	4.5 ± 1.2^{a}	0.3 ± 3.8^{a}	2.4 ± 0.8^{a}
80 min	9.0 ± 0.1^{ab}	8.1 ± 0.3^{ab}	8.6 ± 0.3^{abc}	5.6 ± 0.8^{a}	6.3 ± 4.0^{ab}	5.6 ± 0.6^{a}
60 min	10.4 ± 0.7^{c}	9.2 ± 0.7^{c}	9.8 ± 0.1^{d}	18.8 ± 2.6^{c}	17.6 ± 1.9^{bc}	18.2 ± 1.9^{b}
50 min	10.1 ± 0.2^{bc}	8.6 ± 0.2^{bc}	9.2 ± 0.3^{bcd}	16.6 ± 1.8^{bc}	11.2 ± 0.7^{bc}	13.9 ±1.9^{b}
30 min	9.1 ± 0.2^{ab}	9.2 ± 0.3^{c}	9.3 ± 0.3^{cd}	6.6 ± 1.6^{a}	19.2 ± 2.2^{c}	12.7 ± 1.0^{b}
100 comp	9.5 ± 0.4^{b}	7.6 ± 0.2^{a}	8.5 ± 0.3^{abc}	11.0 ± 1.9^{ab}	−0.002 ± 0.5^{a}	5.5 ± 0.5^{a}

Means followed by the different lower-case letters within a column indicate significant differences among the treatments (Tukey HSD test, $p < 0.05$). Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost).

In accordance to the yields, a combined application of compost and mineral fertilizers increased the ANUE of maize, and for the 60 min and 50 min treatment, about three times higher values than in 100 min treatment were measured (18.2 and 13.9 vs. 5.5 kg grain per kg N applied).

3.3.2. Daily Greenhouse Gas Emissions

The emission of GHGs was estimated in an incubation experiment with different soil moistures. Generally, GHG emissions were lower in dry soil (40%WFPS) than in wet soil (75% WFPS). High GHG emissions were measured on the second and third day of incubation. After the sixth day, the emission clearly decreased and remained at a similar level until the end of the experiment.

The N_2O fluxes varied depending on the treatments, although a treatment effect was not found on each day of the experiment (Figure 3, Tables A1 and A2). Relatively high fluxes were observed on the second day for the 60 min (3.17 g N_2O-N ha^{-1} day^{-1}) and the 100 min (2.71 g N_2O-N ha^{-1} days$-^1$) treatments in wet soil. On day three to five, the treatment with 100% mineral fertilizer stood out with about three to five times higher N_2O emissions than the control (0.44 to 0.81 g N_2O-N ha^{-1}day^{-1}) and the 100comp treatment (0.54 to 0.91 kg N_2O-N ha^{-1}day^{-1}) ($p < 0.05$). Under dry conditions at 40% WFPS, the differences between the fertilizer treatments were less pronounced, though significant at several days of measurement with high values found again for the 100 min treatment. Lowest N_2O emissions throughout the measurement time were usually observed in the control and 100comp treatments under both moisture conditions.

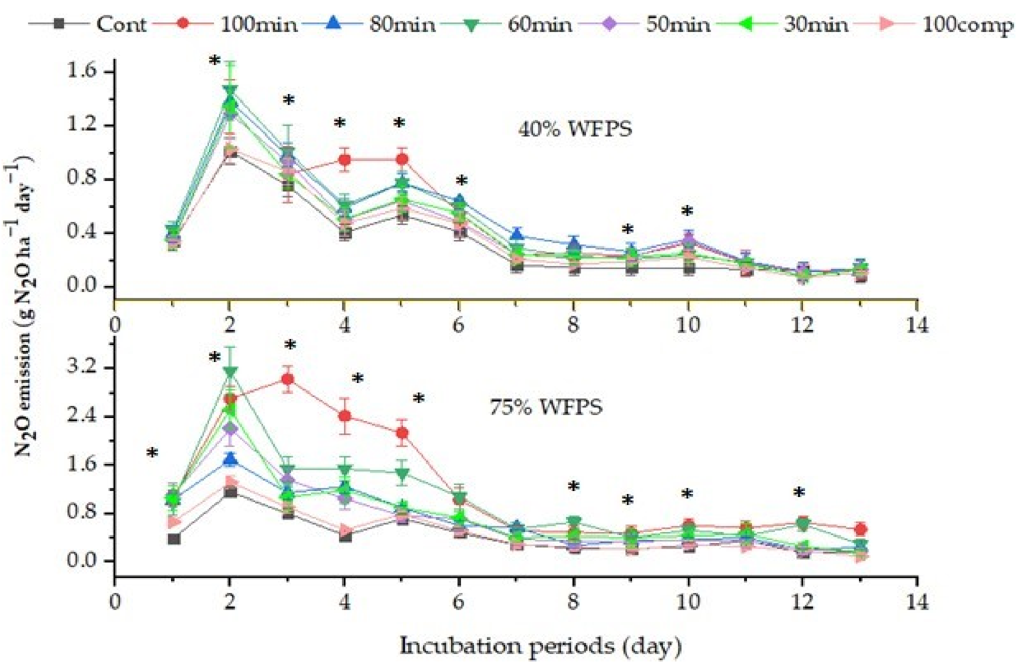

Figure 3. Emissions of nitrous oxide (N_2O-N) from treatments with different fertilizer types and water-filled pore space (WFPS) (40 and 75%). Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost).* indicates significant differences among the treatments (Tukey HSD test, $p< 0.05$). Error bars indicate the standard error of the mean (n = 3).

Similar to N_2O, we usually observed greater daily emissions of CO_2 from amended soil than from the control soil in the first days of measurement (Figure 4, Tables A3 and A4). The peaks were observed on day two and three for both moisture levels. The fertilizer treatments showed different patterns depending on the soil moisture. For 75% WFPS, the 100 min treatment showed high values which were significantly higher than the control and the 100comp treatment ($p < 0.05$) and tendentially higher than all other fertilizer treatments on day two with 2.27 kg CO_2-C $ha^{-1}day^{-1}$ and three with 2.20 kg CO_2-C $ha^{-1}day^{-1}$. Under dry conditions, the 40comp treatment emitted more CO_2 than the control and the 100comp treatment ($p < 0.05$) and tendentially more than all other fertilizer treatments on days two with 1.17 kg CO_2-C $ha^{-1}day^{-1}$ and three with 1.21 kg CO_2–C $ha^{-1}day^{-1}$. With running incubation time, as for the wet conditions, again the 100 min was found to release relatively high amounts of CO_2.

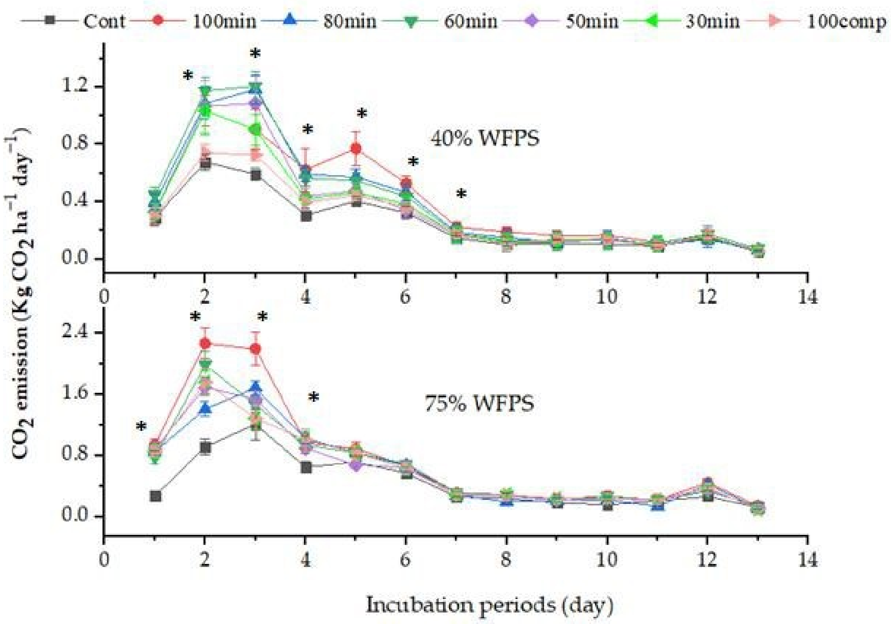

Figure 4. Emissions of carbon dioxide (CO_2-C) from treatments with different fertilizer types and water-filled pore space (WFPS) (40 and 75%). Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost). * indicates significant differences among the treatments (Tukey HSD test, $p < 0.05$). Error bars indicate the standard error of the mean (n = 3).

The CH_4 emissions were highest on days two and three (Figure 5). No differences were found between the treatments.

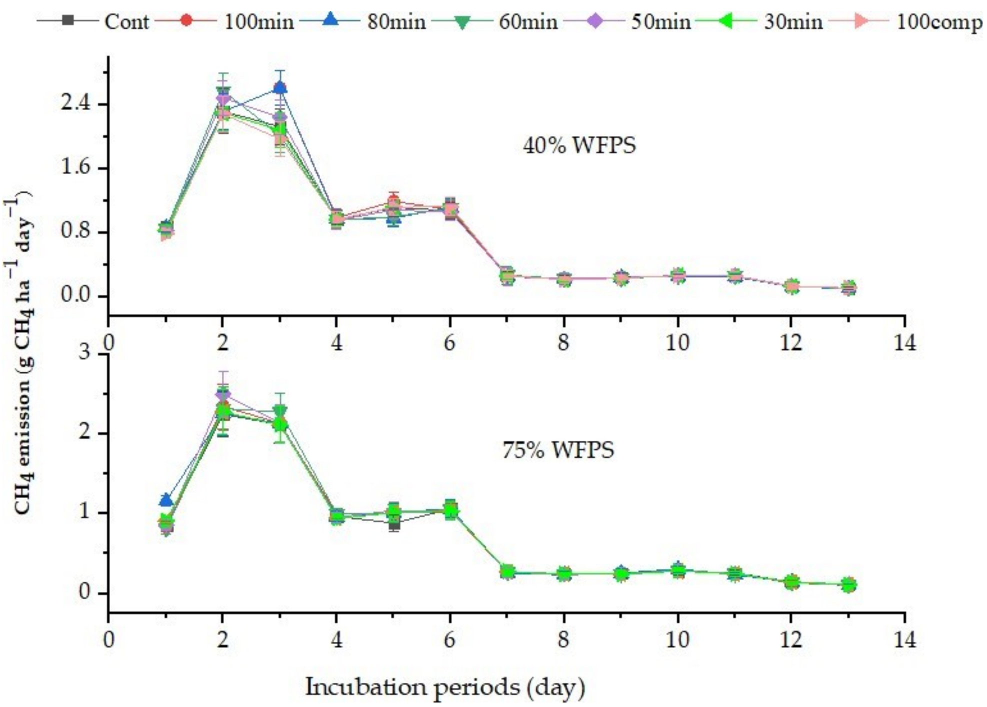

Figure 5. Emissions of methane (CH_4-C) from treatments with different fertilizer types and water filled pore-space (WFPS) (40% and 75%). Cont.: Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost). Error bars indicate the standard error of the mean (n = 3).

3.3.3. Cumulative Greenhouse Gas Emissions, Global Warming Potential, and Nitrous oxide Emission Factor

Over the 28 days of incubations time, the cumulative N_2O and CO_2 but not CH_4 emissions were affected by the fertilizer treatments and moisture levels ($p < 0.05$) (Table 4). In both moisture levels, the application of 100% mineral fertilizers resulted in higher ($p < 0.05$) N_2O emissions than the application of 100% compost under wet (156% more) and dry (31% more) conditions. The different ratios of compost and mineral fertilizers rarely resulted in significant differences of N_2O emissions, but tendentially more

N_2O was emitted when the ratio of mineral fertilizers increased. Similar statements can be made for CO_2, with low emissions in the control and 100comp treatment.

Table 4. Cumulative nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions, global warming potential (GWP), and N_2O emission factor (EF) (Mean ± standard error) in different fertilizer types and 40% and 75% water filled pore space (WFPS) for 28 days of incubation. (N = 3).

Treatment	N_2O (g N_2O-N ha^{-1})		CO_2 (kg CO_2-C ha^{-1})		CH_4 (g CH_4-C ha^{-1})		GWP (kg CO_2 eq. ha^{-1})		N_2O EF (%)	
WFPS	40%	75%	40%	75%	40%	75%	40%	75%	40%	75%
Cont.	4.5 ± 0.1^{Aa}	5.7 ± 0.6^{Aa}	3.4 ± 0.2^{Aa}	5.9 ± 0.3^{Ba}	10.0 ± 0.1^{Aa}	9.6 ± 0.1^{Aa}	4.9 ± 0.1^{Aa}	7.8 ± 0.4^{Ba}	-	-
100 min	6.6 ± 0.3^{Ab}	16.3 ± 2.2^{Bb}	5.3± 0.02^{Abc}	9.9 ± 0.3^{Bc}	9.9 ± 0.04^{Aa}	9.7 ± 0.1^{Aa}	7.5 ± 0.5^{Ac}	15.0 ± 0.9^{Bd}	0.74 ± 0.08^{Ab}	3.85 ± 0.62^{Bc}
80 min	6.7 ± 0.3^{Ab}	9.1 ± 0.5^{Aa}	5.2 ± 0.3^{Abc}	8.2 ± 0.3^{Bbc}	9.8 ± 0.1^{Aa}	10.0 ± 0.3 ^{Aa}	7.4 ± 0.4^{Ac}	11.8 ± 0.4^{Bbc}	0.80 ± 0.09^{Ab}	1.56 ± 0.32^{Bab}
60 min	6.5 ± 0.3^{Ab}	13.3 ± 1.6^{Bab}	5.4 ± 0.3^{Ac}	8.6 ± 0.3^{Bc}	10.5 ± 0.2^{Aa}	9.9 ± 0.1^{Aa}	7.5 ± 0.4^{Ac}	12.8 ± 0.4^{Bcd}	0.75 ± 0.1^{Ab}	2.97 ± 0.53^{Bbc}
50 min	5.9 ± 0. 3^{Aab}	9.4 ± 0.3^{Aa}	4.6 ± 0.2^{Abc}	8.1 ± 0.5^{Bbc}	10.1 ± 0.2^{Aa}	9.9 ± 0.2^{Aa}	6.6 ± 0.3^{Abc}	11.5 ± 0.6^{Bbc}	0.50 ± 0.1^{Aab}	1.47 ± 0.34^{Bab}
30 min	5.8 ± 0.3^{Aab}	9.1 ± 0.2^{Aa}	4.4 ± 0.2^{Ab}	8.2 ± 0.1^{Bbc}	10.2 ± 0.1^{Aa}	9.6 ± 0.1^{Aa}	6.3 ± 0.2^{Abc}	11.2 ± 0.2^{Bbc}	0.47 ± 0.09^{Aab}	1.38 ± 0.23^{Bab}
100 comp	5.1 ± 0.4^{Aa}	6.4 ± 0.2^{Aa}	3.9 ± 0.1^{Aab}	7.1 ± 0.2^{Bab}	10.5 ± 0.5 ^{Aa}	9.7 ± 0.1 ^{Aa}	5.6 ± 0.2^{Aab}	9.2 ± 0.2^{Bab}	0.24 ± 0.1^{Aa}	0.28 ± 0.08^{Aa}

Different upper-case letters indicate significant differences between the moisture levels; different lower case letters indicate significant differences between the fertilizer treatments (Tukey HSD test, $p < 0.05$). Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost).

At both moisture levels (40% and 75%), we observed strong negative correlations between C-input and cumulative N_2O emissions (40%: r = −0.77, $p < 0.001$; 75%: r = −0.52, $p < 0.047$), and also between C-input and CO_2 emissions (40%: r = −0.82, $p < 0.001$; 75%: r = −0.59, $p < 0.02$) (Table 5).

Table 5. Pearson correlation coefficients between carbon (C) inputs and emissions of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) and N_2O emission factor (EF) in 40% and 75% water-filled pore space (WFPS).

		N_2O		CO_2		CH_4		N_2O EF	
C input	WFPS	40%	75%	40%	75%	40%	75%	40%	75%
		−0.77 **	−0.52 *	−0.82 **	−0.59 *	0.36	−0.31	−0.76 **	−0.51

* Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

The N_2O emission factor (N_2O EF) depends mathematically on the N_2O emission and consequently; as for the N_2O emissions, the N_2O EF values were found to be higher ($p < 0.05$) in the 100 min treatment than in the 100comp treatment at both moisture levels (Table 4). At 75% WFPS, the N_2O EF was in the 100 min treatment more than ten times higher as in the 100comp treatment (0.28 vs. 3.85%).

Clear differences between the mineral and the compost treatments were also found for the global warming potential (GWP) (Table 4), which is mathematically based on the emissions of the three GHGs. At 75% WFPS, the GWP in the 100 min treatment was with 15.0 kg CO_2 eq. ha^{-1} higher than all other treatments, except the 60 min treatment. With increasing ratios of mineral fertilizer, there is a trend of increasing GWP values under both soil moisture conditions.

3.3.4. Dehydrogenase Enzyme Activity

The dehydrogenase (DH) activity hardly varied between the two sampling dates on day 1 and day 7 (Table 6). The control without any amendments had with about 65 µg TPF g^{-1} 24 h^{-1} usually lower DH activities than the treatments with fertilizer application. The ratio of organic to mineral fertilizers was not decisive for the activity of the DH. In contrast to the other characteristics, the soil moisture was also not relevant for the activity of the DH ($p < 0.05$).

Table 6. Dehydrogenase activities in different fertilizer types and water-filled pore space (WFPS; 40% and 75%) (N = 3) (Mean ± standard error).

Treatments	Day 1 (µg TPF g^{-1} DM 24 h^{-1})		Day 7 (µg TPF g^{-1} DM 24 h^{-1})	
WFPS	40%	75%	40%	75%
Cont.	67.2 ± 3.7^{Aa}	71.9 ± 3.8^{Aa}	65.5 ± 4.9^{Aa}	61.01 ± 2.2^{Aa}
100 min	85.3 ± 2.1^{Ab}	82.9 ± 1.4^{Ab}	90.2 ± 1.7^{Bd}	64.5 ± 2.6^{Aa}
80 min	87.8 ± 2.6^{Ab}	83.3 ± 2.1^{Ab}	79.2 ± 4.9^{Bb}	61.4 ± 4.4^{Aa}
60 min	86.6 ± 3.1^{Ab}	94.9 ± 3.0^{Ac}	81.0 ± 1.0^{Ab}	79.3 ± 3.5^{Ab}
50 min	88.7 ± 2.5^{Ab}	81.9 ± 0.9^{Ab}	79.7 ± 3.8^{Ab}	67.5 ± 4.0^{Aa}
30 min	89.0 ± 3.6^{Ab}	88.1 ± 5.2^{Ac}	86.7 ± 6.4^{Acd}	62.0 ± 1.7^{Aa}
100comp	82.8 ± 2.6^{Ab}	80.9 ± 3.1^{Ab}	84.8 ± 3.1^{Abc}	81.3 ± 3.8^{Ab}

Different uppercase letters indicate significant differences between the moisture levels; different lowercase letters indicate significant differences between the fertilizer treatments (Tukey HSD test, $p < 0.05$). Cont.: Control (no input); 100 min: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 min: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 min: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 min: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 min: 30% mineral fertilizer + 4.9 t ha^{-1} compost, and 100comp: 100% compost (7 t ha^{-1} compost). DM = dry matter.

3.4. Discussion

3.4.1. Higher Maize Yields and Agronomic Nitrogen Use Efficiency in the Combined Fertilizer Treatments

The results of our study showed that higher yields and ANUE were found in the combined application of compost (compost N: 40–70%) and mineral fertilizers (mineral fertilizer N: 30–60%) compared to other treatments. Positive yield effects of combined applications of organic and mineral fertilizers were also found in other studies under varying growing conditions [29,64–66], and often this was attributed to an improved soil structure [67,68], intensification of biological processes in soil [68], higher water storage capacity [64,65], and higher cation exchange capacity [69] (see also Introduction).

The rainfall pattern in the second year was less suitable for plant productions than in the first year, which resulted in lower yields, even if the differences were not particularly great (8.26 vs. 9.39 Mg ha^{-1}, averaged across all treatments). Even under less-favorable conditions, higher yields and ANUE were found when mineral fertilizers were combined with compost. The results suggest that under extreme weather conditions and stronger yield depressions, which will probably occur more frequently in Ethiopia in the future [70], compost application can contribute to maintaining yields which has been demonstrated for agricultural and horticultural crops [8,9,68].

Another advantage of compost application is the supply of plant nutrients. The mineral fertilizer application in this experiment only consisted of N, P, and S, while composts contain all plant nutrients, albeit in differing concentrations, depending on the original material [65]. And although the site was not described as being deficient in nutrients—apart from the low P content—the application of various nutrients could have supported plant growth. However, despite of all these positive impacts of the compost application described, the treatment with 100% compost application was (at least tendentially) agronomically less suitable than the fertilizer mixtures with 40 to 70% of the N provided by compost. This can be explained by the availability of mineral N. The majority of N in composts is bound in stable organic compounds [71], and assumed 35% of N released in the year of application [48]. This can hamper maize growth, especially in periods of high N demands during the plant development [72]. Our results showed that shares of 40 to 70% N from compost in the fertilizer combinations are most suitable for maize growth under these growing conditions. The C:N ratio in these combinations were 2.7, 3.5, and 5.1, respectively. The addition of only 20% compost with a C:N ratio of 1.2 was obviously not enough to benefit from the organic matter supply.

The experimental field in our study was well managed in previous years, including adequate fertilizer management. The total content of N (about 2.2 g kg^{-1}, which corresponds to about 5000 kg N ha^{-1} in the upper 30 cm of soil) as well as the content of organic C (about 24 g kg^{-1}) in the soil were rather favourable and in the range of other Nitisol sites with proper soil management [73,74]. A fallow was applied at this site one year before our study started. These facts can explain the relatively high maize grain yield with the control treatment without fertilizers. In contrast to the fertilizer mixtures, we observed a non-responsiveness of maize yields to the application of sole mineral fertilizer (100 min) in both experimental years. This is partly related to the fertility of the soil, as also shown in a study by Negassa et al. [75]. However, we believe that the non-responsiveness of maize yields to mineral fertilizers in this study was also attributed to low availability of P. The bio-available soil P content was with 2 mg kg^{-1} very low at the beginning of the study, which can be reasoned with the acidic soil conditions (pH= 4.9) and high iron content, which usually reduce the availability of P [42,48,76]. As organic matter in soil can reduce P fixation, it contributes to a better availability of P for crops [77], which can explain the positive effect of compost in the mixtures. Unfavorable soil or weather conditions were cited in 68% of the surveyed agricultural fields in sub-Saharan Africa as a reason why mineral fertilizer use did not increase maize yield [78]. This indicates that the multiple interacting factors affecting crop yields are difficult to quantify in general, and that a careful evaluation of fertilizer practices for each cropping site is necessary to ensure returns on fertilizer investments.

As described above, the organic material in the compost is stabilized during the composting process. Although it was not tested in our experiment, fresh organic materials such as farmyard manure may have different effects, because of the faster decomposition of organic matter and cycling of nutrients [79]. For areas with same soil type, recent results showed an advantage of compost over farmyard manure [29,65].

Higher yields in the combined treatments were related to higher NUE, which is of great importance in Ethiopian agriculture. The results of the two growing seasons showed that the 30 min, 50 min, and 60 min treatments had with 12.7 to 18.2 kg grain per kg N about three times higher NUE than the other treatments. Thus, the results indicate that combined fertilizer application having 40% to 70% of the total N from compost can be a suitable measure to stabilize maize yields and increase nutrient efficiency in the study area.

3.4.2. Mitigation of GHG Emissions by Compost Application

Fertilizer types and rates had a significant effect on N_2O and CO_2 emissions and GWP from the Nitisol soil in the incubation experiment, although their influences varied in dependence on the soil moisture. The 100 min treatment resulted in higher N_2O and CO_2 emission than the control or 100comp, especially under wet soil conditions (75% WFPS).

High amounts of available N usually intensify the denitrification process and the N_2O emissions [32, 55, 80] (see also introduction). In our study N_2O emissions were reduced when the mineral fertilizers were combined with compost. This can be explained by the replacement of the mineral N by organic N, and consequently by an initial microbial immobilization of N [80,81] and/or slow release of N from the organic part in the ratios. Furthermore, compost application can increase the abundance of denitrifying microorganisms and thus favoring the complete denitrification and production of dinitrogen gas instead of N_2O [14]. The availability of N also plays a role in CO_2 emissions. Due to a reduction of available N, the microbial activity and decomposition of native SOM usually decreases [82].

Besides the availability of N, the interactive effects of N and C supply also influence the emission of GHGs [83]. High microbial activity due to C supply with organic fertilizers can result in an intensification of microbial-induced processes [84]. However, negative correlations were observed between C input and N_2O and CO_2 emissions in our incubation experiment. The increased C:N ratio with increasing portion of compost in the mixtures could be the reason, which resulted finally in a limitation of N for microbial activities despite the higher C stocks. This is also supported by the microbial activity (DHA), which was not increased with increasing rates of compost in comparison to 100 min.

The reduction of CO_2 and N_2O emissions after the application of organic material was also highlighted in other studies with other amendments, such as crop residues [35,80] or manure [85]. Amendments with high C:N ratio like straw (up to 100:1) resulted in low N_2O emission and is also an option to replenish SOM [80] but may hamper the N nutrition of crops [86].

The majority of the gases were emitted during the first days after incubation, which was also shown in other incubation studies, as for Ferralsol [35] and Vertisol [80]. The results indicate the risk of high GHG emissions in a relatively short period after fertilizer application during the main crop growing season in Ethiopia when the soil is relatively wet. For sites with a high availability of N, the addition of organic material with a high C:N ratio like crops residues could be a good means under these conditions to reduce N_2O emissions [35,80].

Generally, for soils rich in C and N, higher CO_2 and N_2O emissions can be expected. The C and N content of our soil (C, 24 g kg^{-1} and N, 2.2 g kg^{-1}; see Table 1) were in the range of other Nitisols in Ethiopia [42] but higher than the majority of other soils in Ethiopia and other East African regions [87]. The results of other incubation experiments can also be interpreted in this context, with very low N_2O emissions from Ferralsol with little or no N input [35] and high N_2O emissions in fertilizer treatments with N application of >200 kg ha in Vertisol [80].

The fertilizer types and rates did not affect CH_4 emissions in either moisture level and no correlations between C or N-input and CH_4 emission were found in our incubation experiment. The emission of CH_4 comes primarily from fields under flooded conditions [24,88] with higher water content than in our experiment. In this context, Brembong et al. [89] described soils with normal WFPS as very effective CH_4 sinks.

Results of management strategies from other studies have to be considered with caution, as GHGs emissions vary depending on the physicochemical properties of soils [32,83]. For instance, a higher clay content of soil is usually related to higher water retention and higher emission of CH_4 and N_2O, which can explain that relatively high GHG emission were often found for Vertilsols due to their tendency to become waterlogged [80]. Nyamadzawo et al. [32] reported comparably low N_2O emissions for

Lixisol (about 0.5 kg ha^{-1}) and Inceptisol of (about 1.5 kg ha^{-1}) for different fertilizer treatments during a cropping season in Zimbabwe, which was attributed to the soil texture with high content of sand and low water retention. Another important soil characteristic regarding GHG emissions is soil pH. A low pH value is not suitable for most microorganisms involved in CH_4 and CO_2 metabolism [90], and from acid soils like Nitisols (the pH of soil in our study was 4.9) potentially lower CH_4 and CO_2 emissions can be expected than from neutral soils.

The effect of moisture was especially important for N_2O emissions in the 100 min treatment, which were much higher under wet (75% WFPS) than under dry soil conditions. In wet conditions, anaerobic bacteria use NO^- as an electron acceptor during microbial oxidation and release N_2O through the process of denitrification [19]. The CO_2 emissions were also generally higher under wet conditions and the effects of the treatment were more pronounced than under dry conditions. The proportion of the pores filled with water and soil aeration affect CO_2 emissions [91,92] and CO_2 emissions from soil can increase linearly with the soil water content until saturation point, after which the emissions decrease again. For most soils, the saturation point for CO_2 emission is >70% [36,93]. In this study, no effects of soil moisture were found on DH activity. Probably the range of moisture was still relatively suitable for microbial activity and with about 70 to 80 µg TPF g^{-1} TS 24 h^{-1} the activity of DH was relatively high (e.g., in comparison to Stagnic Cambisol [84]). Clear inhibitions of microbial activities can be found for very low water contents of air-dried soils [24].

Compost was shown to be a suitable amendment considering GHGs and maize yield in our study. However, like mineral fertilizers, compost is also limited in Ethiopia, especially in the area where organic resources are used for another purpose such as fuel, food for animals, or construction material [65,94,95]. As different ratios of compost and mineral fertilizers in the mixtures were found to be suitable to reduce N_2O and CO_2 emissions and increase maize yield (see Section 4.1), upon the availability of resources, the proportions of these types of fertilizers can be set flexibly in a certain range around 50:50. Beside the evaluation of the fertilizer effect, the ANUE might also be a good indicator to predict GHG emissions [80] and accordingly, the ANUE was found to be highest in the 30 min, 50 min, and 60 min treatments (see Section 4.1).

Conclusions

The results of this study showed that the combined application of compost and mineral fertilizer can be an option for enhancing maize yields and mitigating GHG emissions from Nitisols in Southwestern Ethiopia. Utilization of compost as fertilizer can be especially suitable during the wet season and might be an option to mitigate negative yield effects of extreme weather conditions, which will probably occur more frequently due to climate change in Ethiopia. To verify the results of the GHG emissions from the incubation experiment, further investigations should take place at the field level.

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Chapter 4: Grain mineral concentrations in maize (*Zea mays* L.) and nutrient use efficiency as affected by fertilizer management on a Nitisol in Southwestern Ethiopia

Grain mineral concentrations in maize (*Zea mays* L.) and nutrient use efficiency as affected by fertilizer management on a Nitisol in Southwestern Ethiopia

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Abstract

The combined application of organic and mineral fertilizers is an appropriate agronomic measure and is particularly important for smallholders who have limited access to mineral fertilizers. However, fertilizer recommendations in terms of crop nutritional value and nutrient efficiency strongly vary in dependence of site-specific conditions. In this study seven different ratios of bio-waste compost (comp) and mineral fertilizers (MF), consisting of nitrogen (N), phosphorus (P), and sulphur (S) were tested in a two-year field experiment on a Nitisol soil in order to assess their effects on nutritionally important minerals in maize (*Zea mays,* L. Bako-hybrid) grains as well as the nutrient use efficiency. The application of fertilizers corresponded to a N supply of about 100 kg ha^{-1}, whereby the application of only MF (100 MF) was gradually replaced by compost. Compared to 100 MF the treatments with 40 to 70% of N supply given with compost had higher concentration of most grain minerals. Most pronounced elevations were found for Fe (570 vs. 304 mg kg^{-1}) and Mn (70.1 vs. 36.3 mg kg^{-1}) when 50% of the

N was given with compost in comparison to the 100 MF treatment. The P use efficiency increased particularly when compost was part of the nutrient supply. The results suggest that replacing mineral fertilizer with compost accounting for 40 to 70% of the total N supply would be a suitable option for increasing the nutritional quality of maize grains and to efficiently use fertilizers on this Nitisol.

Keywords: compost; mineral fertilizer; maize; grain mineral concentration; nitrogen use efficiency; phosphorus use efficiency; sulphur use efficiency

4.1. Introduction

Maize (*Zea mays* L.) is a commonly being cultivated (ca. 2.3 million ha) and consumed cereal next to teff (*Eragrostis tef* [*Zucc*] *Trotter*) (ca. 3.5 million ha) in Ethiopia (Abate et al. 2015; Zerssa et al. 2021) and the area cultivated with maize has significantly increased over the last two decades (Abate et al. 2015). However, the average yield of maize grains in Ethiopia is with about 3 Mg ha^{-1} considerably lower than the potential in the country, which is expected to be about 11 Mg ha^{-1} (Ejigu et al. 2021; van Dijk et al. 2020; Zerssa et al. 2021). The low production is mainly attributed to an inappropriate soil nutrient management and low nutrient use efficiency (Ejigu et al. 2021; Selassie 2015).

The sub-optimal production conditions also reduce the grain mineral concentrations (Manzeke et al. 2014; Suganya, Saravanan, and Manivannan 2020). In addition, maize already has relatively low contents of mineral elements compared to other crops, especially calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), and zinc (Zn) (Gashu et al. 2021; Suganya, Saravanan, and Manivannan 2020). For example, maize grains have significantly less mineral contents compared to teff with differences of about 1400 for Mg, 1210 for Ca, 160 for Fe, 71 for Mn, and 4.8 for Cu; all values are in mg kg^{-1} (Nyachoti, Adebayo, and Godebo 2021). Consequently, people who depend on maize-based diets, especially rural people in Ethiopia, are likely to have a relatively low mineral intake, causing malnutrition. For instance, prevalent deficiency for the micronutrients Fe and Zn significantly affected women and children in Ethiopia (Aragaw, Nohr, and Callo-Concha 2021; Harika et al. 2017; Melash, Mengistu, and Aberra 2016). Due to the Fe deficiency anemia occurred in 31% of the children in the Amhara region Ethiopia (Herrador et al. 2014). Calcium and Mg are also very important for proper growth and development children and a deficiency of these minerals may results in a weak development of bones and problems with muscle contraction and the transmission of nerve impulses (Herrador et al. 2014; Maru, Birhanu, and Tessema 2013). The nutritional sources for these macro elements mostly come from livestock-based diet, which, however, is not frequently available for rural people. Therefore, increasing mineral concentrations in main food crops is very crucial (Manzeke et al. 2014).

In Ethiopia, application of mineral fertilizer in croplands started in the 1960s through programs such as the “freedom from hunger” with the focus on N and P (Tamene et al. 2017). Since then, the total amount of mineral fertilizer applied has been gradually increased and is currently about 2 million tons in the country, whereby mainly urea and NPS fertilizers are used (CSA 2021). However, about 40% of Ethiopian smallholder farmers have been applying about 40 kg ha^{-1} of either urea or NPS which is significantly below the rates recommended by the Ethiopian Ministry of Agriculture of about 110 to130 kg ha^{-1} (Abate et al. 2015; Abdulkadir et al. 2017; Rashid et al. 2013). Other nutrients beside N, P, and S are even less available at the market (Abdulkadir et al. 2017; Zerssa et al. 2021a). In Ethiopian cropping systems almost no micronutrients are applied (Ashenafi, Bobe, and Muktar 2016) which affects not only the yield but also reduces the quality of grains (Gashu et al. 2021). Furthermore, the unfavorable ratio of the added nutrients ultimately also leads to poor utilization of the fertilizers given (Abay et al. 2021).

The combined application of locally available organic resources and mineral fertilizers is a promising approach for achieving a more balanced nutrient application, as organic fertilizers ideally contain all essential plant nutrients (Dornal Vijayakumar et al. 2022; Gashu et al. 2021; Gezahegn 2021; Qaswar et al. 2020). Positive effects have been previously demonstrated, for instance, in maize grains with increased concentrations of nitrogen (N), phosphorus (P), and potassium (K) after the application of combined organic and mineral fertilizers compared to compost or mineral fertilizers alone (Ewais, Sahar, Mohamed 2015). Augustine and Kalyanasundaram (2021) also found enhanced Zn and Fe concentrations in maize grains after the combined application of diverse organic and mineral fertilizers. Furthermore, the incorporation of organic amendments is one of the most important agronomic measures to improve of broad range of soil physicochemical and biological properties as shown for different sites. Especially the higher water storage capacity and the microbial nutrient and matter cycles were previously highlighted in relation to organic matter management (Eichler-Löbermann et al. 2021, Maselesele, Ogola, and Murovhi 2021; Qaswar et al. 2020). However, research has shown that combining organic and mineral fertilizers can be even more effective than using only organic fertilizers. For instance, Sileshi et al. (2019) recommend in a combined application of cattle manure (5 to 10 Mg ha^{-1}) and inorganic N fertilizer (ca. 50 kg N ha−1) for maize cropping in sub Saharan Africa. Good effects were found for compost application in an amount of 4 t ha^{-1} together with mineral fertilizers in an amount of 50% of the N supply on yields of maize grown on a Nitisol (Mamuye et al. (2021). Similar ratios of organic to mineral fertilizers were suggested for maize cropping Ejigu et al. (2021) and Yigermal, Kelemu and Fenta (2019). Nevertheless, the optimum combination ratios of organic and mineral fertilizers with regards to nutrient use efficiency and nutritional quality of crops may vary from site to site (Liang et al. 2013; Singh et al. 2014).

Enhancing the nutrient use efficiency (NUE) contributes to reduce nutrient losses, to reduce environmental pollution, and to lower the cost for fertilizer application (Abay et al. 2021; Salim and Raza, 2020; Sileshi et al. 2019). Combined application of different types of fertilizer was found to enhance the NUE and can be an option especially for resource-poor farmers (Agegnehu and Tilahun 2017; Sileshi et al. 2019).

In our previous study (Zerssa et al. 2021b), we investigated the effects of combined applications of compost and mineral fertilizers on maize yield and greenhouse gas emissions in a Nitisol in Southwest Ethiopia and proposed suitable combination ratios. However, as the concentration of minerals in grains is often decoupled from yields (Ryan, Derrick, and Dann 2004), it is uncertain whether these proposed combination ratios are also suitable for enhancing the nutritional quality of maize grains. Thus, in this study we aimed to evaluate fertilizer combinations with regard to grain mineral concentrations. In order to manage the nutrient application in a best possible way, the NUE was also considered with focus on N, P, and S.

4.2. Materials and methods

4.2.1. Field experiment

The field experiment was carried out in the consecutive growing seasons 2018/19 and 2019/20 in summer season, (which is the main growing season in Ethiopia) at the research station of Jimma University College of Agriculture and Veterinary Medicine in Southwestern Ethiopia (latitude, 7° 42` N; longitude 36° 49`E, altitude of 1710 meter above sea level.) (Figure 1). The region is characterized as a humid tropical climate with average minimum and maximum temperatures of 13 and 28 °C and an annual rainfall between 1200 and 2400 mm (Gemeda, Feyssa, and Garedew 2021). According to the World Reference Base the soil is classified as Nitisol, which is the main soil type in this area and often used for cereal production (Abebe, Gebremedin, and Endalkachew 2013; Aticho et al. 2013; Elias 2017). The soil texture is a silty clay loam, with 4.98 pH, 2.4% organic carbon and 0.22% total N (Abebe, Gebremedin, and Endalkachew 2013).

Figure 1. Map of the study area and photos during field experiment (Jimma University Research Center, Ethiopia).

Seven fertilizer treatments, including a control without fertilizers and six different combinations of bio-waste compost and mineral fertilizers, were established in four replications in a randomized complete block design (see further detail in Zerssa et al. 2021b). The amount of applied fertilizers was determined based on the recommendations for N and P supply in the maize cropping systems under similar growing conditions (Wasonga, Sigunga, and Musandu, 2010). The mineral nutrient supply was set at 100 kg N ha^{-1} and 33.3 kg P ha^{-1} [100% mineral fertilizer (100 MF)]. In the other treatments, a biowaste compost with 1.2% N and 0.072% P in the dry matter gradually replaced the nutrient supply with the mineral fertilizers. The maximum amount (dry matter) of compost applied to the field was 7 t ha^{-1} [100% compost (100 Comp)]. The nomenclature of the treatments followed the percentage of mineral fertilizer applied, starting with 100 MF (100% mineral fertilizers), followed by 80 MF, 60 MF, 50 MF, 30 MF, and 100 Comp (Table 1). As a mineral fertilizer commercially available, NPS (19% N–38% P–7% S) and urea (46% N) were applied. Prior to the field experiment, biowaste compost was prepared mixing locally available materials such as vegetable plant leftovers, animal manure, and wood ash following the procedure outlined by Tulema, Aune, and Breland (2007). The properties of the compost are presented in Table 2.

Table 1. Nutrient application with the treatments in the field experiment.

Treatment Name	Composition of treatments	
	Biowaste Compost	Urea and NPS
Control	without	without
100 MF	without	100% mineral fertilizer [urea (135 kg ha^{-1}) and NPS (200 kg ha^{-1}) fertilizers); 100 kg N ha^{-1} and 33.3 kg P ha^{-1}]
80 MF	(1.4 t ha^{-1} compost): 130.1 kg C ha^{-1}, 16.8 kg N ha^{-1} and 1.01 kg P ha^{-1}	80% mineral fertilizer [urea (108 kg ha^{-1}) and NPS (160 kg ha^{-1}); 80 kg N ha^{-1} and 26.64 kg P ha^{-1}]
60 MF	(2.8 t ha^{-1} compost): 260.1 kg C ha^{-1}, 33.6 kg N ha^{-1} and 2.02 kg P ha^{-1}	60% mineral fertilizer [urea (81 kg ha^{-1}) and NPS (120 kg ha^{-1}); 60 kg N ha^{-1} and 19.98 kg P ha^{-1}]
50 MF	(3.50 t ha^{-1} compost): 325.2 kg C ha^{-1}, 42 kg N ha^{-1} and 2.5 kg P ha^{-1}	50% mineral fertilizer [urea (67.5 kg ha^{-1}) and NPS (100 kg ha^{-1}); 50 kg N ha^{-1} and 16.65 kg P ha^{-1}]
30 MF	(4.90 t ha^{-1} compost): 455.2 kg C ha^{-1}, 58.8 kg N ha^{-1} and 3.53 kg P ha^{-1}	30% mineral [urea (40.5 kg ha^{-1}) and NPS (60 kg ha^{-1}); 30 kg N ha^{-1} and 9.99 kg P ha^{-1}]
100 Comp	100% Compost (7 t ha^{-1} compost): (650.3 kg C ha^{-1}; 84 kg N ha^{-1} and 5.04 kg P ha^{-1})	without

MF = Mineral fertilizer, Comp = compost, adopted from Zerssa et al. (2021b)

Table 2. Characteristics of soil and compost used in the field experiment

Parameters	Compost	Soil
C (g kg^{-1})	92.9 ± 0.8	24.0 ± 4.0
N (g kg^{-1})	12.0 ± 0.7	2.2 ± 0.1
Ca (g kg^{-1})	25.1 ± 1.5	2.3 ± 0.2
S (g kg^{-1})	2.2 ± 0.08	0.5 ± 0.02
K^* (g kg^{-1})	1.9 ± 0.02	0.4 ± 0.1
Mg^* (g kg^{-1})	1.3 ± 0.04	0.2 ± 0.01
P^* (mg kg^{-1})	718.2 ± 7.5	2.1 ± 0.1
Fe (mg kg^{-1})	44.4 ± 0.2	66.6 ± 1.4
Zn (mg kg^{-1})	188.9 ± 2.3	98.1 ± 3.2
Cu (mg kg^{-1})	39.8 ± 1.6	22.3 ± 1.2
Mn (g kg^{-1})	1.9 ± 0.05	0.4 ± 0.02
pH	7.1 ± 1.0	4.9 ± 0.9
EC (µS cm^{-1})	6.1 ± 0.5	0.3 ± 0.01
CEC (cmole kg^{-1})	118.0 ± 4.8	42.7 ± 5.3
Moisture content (%)	9.7 ± 1.1	32.2 ± 3.2
Texture	-	Silty clay loam
Bulk density (g cm^{-3})	-	1.6 ± 0.3

*P, K, and Mg in the compost are given as total contents and in the soil as bio-available nutrients. Adopted from Zerssa et al. (2021)

The maize Bako hybrid (BH_661) variety was used, since it is commonly cultivated in the study area. During both growing seasons twelve maize plants per row were grown at 0.75 m inter-row and 0.30 m intra-row spacing in each plot (4 m × 2.5 m). Agronomic practices, such as sowing, weeding, and harvesting were applied manually. Irrigation was not applied. During maturity (July 2019 and August 2020), the two central rows in each subplot were harvested in order to determine the maize yield and the grain composition (Testa, Reyneri, and Blandino 2016).

4.2.2. ***Soil and compost analysis***

Before the treatment application and after end of the experiment, composite soil samples were collected from the surface layer (0–20 cm). The collected soil samples and the compost were analyzed for nutrient composition (Table 2). Total element concentrations were measured after microwave digestion (aqua regia) by using inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin Elmer). Organic C and total N were measured by the Walkley–Black oxidation method (Gelman, Binstock, and Halicz 2012) and the micro-Kjeldahl method (Calazans et al. 2018) respectively. Available phosphorus (P), potassium (K), and magnesium (Mg) contents were measured in a spectrophotometer (P) or flame photometer (K, Mg) after extraction with calcium lactate ($C_6H_{10}CaO_6 \cdot 5\ H_2O$) solution (Jones Jr 1998). Cation exchange capacity (CEC) was determined by the method of Chapman (Chapman, 1965). The pH of compost and soil were measured using a pH meter (pMX 3000) in 1:2.5 compost/soil:$CaCl_2$ ratios. Furthermore, soil texture was determined using the hydrometer method (Bouyoucos 1962) and bulk density was determined using a core sampler method (Blake and Hartge 1986).

4.2.3. ***Analysis of grain minerals***

Maize grains were oven-dried at 70 ˚C, milled by using a standard laboratory miller, and sieved with 0.5 mm mesh width. The ground tissue was analysed for N using the Kjeldahl method. To analyse the other nutrients, 2 g of plant material was placed into the muffle furnace at 550 °C for 5 hours. After cooling, the ash was digested into nitric acid. The solution was filtered and the mineral concentrations were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Perkin Elmer, Germany) (AACC 2000).

4.2.4. ***Calculations for nitrogen phosphorus and sulphur use efficiency of maize***

Nitrogen use efficiency (NUE), phosphorus use efficiency (PUE) and sulphur use efficiency (SUE) for the treatments were determined using Eq. (1), Eq. (2) and Eq. (3), respectively.

$$NUE(\%) = \frac{\text{N uptake in fertilized plots } (\text{kg ha}^{-1}) - \text{N uptake in unfertilized plots } (\text{kg ha}^{-1})}{\text{N applied} (\text{kg ha}^{-1})} \times 100 \qquad (1)$$

$$PUE(\%) = \frac{\text{P uptake in fertilized plots } (\text{kg ha}^{-1}) - \text{P uptake in unfertilized plots } (\text{kg ha}^{-1})}{\text{P applied} (\text{kg ha}^{-1})} \times 100 \qquad (2)$$

$$SUE(\%) = \frac{\text{S uptake in fertilized plots } (\text{kg ha}^{-1}) - \text{S uptake in unfertilized plots } (\text{kg ha}^{-1})}{\text{S applied} (\text{kg ha}^{-1})} \times 100 \qquad (3)$$

4.3. ***Statistical analysis***

Normality of data was checked by the Kolmogorov-Smirnov normality test (Drezner, Turel, and Zerom, 2010). The one-way analysis of variance (ANOVA) was used to determine the effect of different fertilizer treatment on grain mineral concentrations, nutrient efficiency, and soil parameters. The Tukey-test was used for the comparison of the treatment means. A multiple linear regression and Pearson correlation analysis were performed between the nutrient inputs and the yield, mineral concentration of the maize grains and nutrient inputs. All results were assessed at the 5% significance level. The statistical analyses were made with the IBM SPSS software Version 22.0. (Armonk, NY: IBM Corp).

4.4. Results

4.4.1. Mineral concentrations of maize grain

The fertilizer treatments had a significant impact ($p < 0.05$) on the grain minerals of maize with very similar patterns in both experimental years. Usually, grain mineral concentrations were higher in the combined fertilizer applications than in the control and the 100 MF treatment (Table 3 and 4). Most pronounced elevations of grain minerals in comparison to 100min were found in the 50 MF treatment for Fe (304 vs. 570 mg kg^{-1}) and Mn (36.3 vs. 70.1 mg kg^{-1}). The Mg and P concentrations were also found to be highest in the 50 MF treatment. Increasing the organic amendments from 50 to 100% did usually not result in further increases of grain minerals. One exception is the concentration of Ca which was found to be higher (1.36 g kg^{-1}, average of both years) when only compost was applied in comparison to all other treatments. The sole application of mineral NPS did not increase the concentrations of grain minerals, not even S, compared to the control.

Although the pattern of mineral concentration in the grains was similar in both years, the concentrations in the first growing season were higher than in the second, with the exception of the Zn concentration.

Table 3. Mineral concentrations of maize grains in different treatments (mean ± SE) and grain yield of maize in the field experiment in 2018/19

Treatment	Ca (g kg^{-1})	Mg (g kg^{-1})	K (g kg^{-1})	P (g kg^{-1})	N (g kg^{-1})	S (g kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Grain yield (Mg ha^{-1})
Control	1.08 ± 0.07^{ab}	1.30 ± 0.01^{a}	5.73 ± 0.14^{ab}	2.38 ± 0.02^{a}	11.60 ± 0.04^{a}	1.23 ± 0.01^{b}	302.0 ± 0.71^{ab}	2.6 ± 0.05^{a}	29.49 ± 0.55^{a}	31.9 ± 1.49^{a}	8.5 ± 0.31^{a}
100 MF	1.09 ± 0.09^{ab}	1.38 ± 0.01^{ab}	5.38 ± 0.15^{ab}	2.49 ± 0.06^{a}	12.34 ± 0.19^{b}	1.12 ± 0.03^{a}	324.8 ± 31.6^{b}	2.8 ± 0.08^{a}	31.54 ± 0.84^{ab}	36.7 ± 3.53^{a}	9.0 ± 0.11^{ab}
80 MF	1.16 ± 0.04^{ab}	1.40 ± 0.02 ^{bc}	5.68 ± 0.23^{ab}	2.84 ± 0.04^{c}	11.71 ± 0.19^{ab}	1.45 ± 0.01^{c}	300.6 ± 12.3^{a}	2.6 ± 0.25^{a}	33.85 ± 0.44^{cd}	33.7 ± 0.56^{a}	9.0 ± 0.11^{ab}
60 MF	1.25 ± 0.03^{bc}	1.44 ± 0.02^{bc}	5.10 ± 0.04^{a}	2.93 ± 0.02^{c}	11.85 ± 0.10^{ab}	1.51 ± 0.02^{c}	265.5 ± 18.4^{a}	2.8 ± 0.48^{a}	34.89 ± 0.45^{cd}	32.6 ± 0.58^{a}	10.4 ± 0.71^{c}
50 MF	1.17 ± 0.07^{ab}	1.48 ± 0.06^{c}	7.65 ± 0.09^{c}	3.10 ± 0.03^{d}	13.20 ± 0.36^{c}	1.26 ± 0.03^{b}	567.9 ± 7.82^{c}	3.3 ± 0.03^{a}	30.0 ± 0.17^{a}	57.5 ± 2.39^{b}	10.1 ± 0.21^{bc}
30 MF	1.05 ± 0.06^{a}	1.42 ± 0.02^{bc}	5.53 ± 0.04^{ab}	2.96 ± 0.04^{c}	12.90 ± 0.12^{c}	1.83 ± 0.02^{d}	342.7 ± 12.5^{b}	2.8 ± 0.22^{a}	35.63 ± 1.8^{d}	32.8 ± 0.89^{a}	9.10 ± 0.22^{ab}
100 Comp	1.40 ± 0.03^{c}	1.37 ± 0.01^{ab}	5.44 ± 0.21^{ab}	2.69 ± 0.06^{b}	11.69 ± 0.04^{ab}	1.24 ± 0.03^{b}	318.3 ± 2.01^{ab}	2.7 ± 0.06^{a}	33.04 ± 0.50^{bc}	37.1 ± 0.38^{a}	9.5 ± 0.42^{b}

Means followed by the different letters indicate significant differences among the treatments (Tukey HSD test, $p < 0.05$). Control: no fertilizer input; 100 MF: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 MF: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 MF: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 MF: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 MF: 30% mineral fertilizer + 4.9 t ha^{-1} compost; and 100 Comp: 100% compost (7 t ha^{-1} compost).

Table 4. Mineral concentrations of maize grains in different treatments (mean ± SE) and grain yield of maize in the field experiment in 2019/2020

Treatment	Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	S ($g\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)	Grain yield ($Mg\ ha^{-1}$)
Control	1.02 ± 0.03^{ab}	1.03 ± 0.02^{a}	2.76 ± 0.18^{a}	1.15 ± 0.12^{a}	10.52 ± 0.05^{a}	1.07 ± 0.06^{b}	222.9 ± 0.63^{a}	2.0 ± 0.08^{a}	31.6 ± 1.52^{a}	24.6 ± 5.03^{a}	7.5 ± 0.22^{a}
100 MF	0.95 ± 0.08^{a}	1.06 ± 0.03^{a}	2.35 ± 0.13^{a}	1.39 ± 0.13^{ab}	10.67 ± 0.27^{a}	0.93 ± 0.03^{a}	241.2 ± 31.6^{a}	2.2 ± 0.16^{a}	33.5 ± 1.61^{ab}	25.7 ± 3.18^{a}	7.6 ± 0.21^{a}
80 MF	1.08 ± 0.03^{abc}	1.08 ± 0.04^{a}	2.78 ± 0.23^{a}	2.79 ± 0.50^{bc}	10.66 ± 0.18^{a}	1.26 ± 0.01^{c}	200.1 ± 12.3^{a}	1.8 ± 0.08^{a}	37.7 ± 1.44^{cd}	31.6 ± 3.95^{a}	8.1 ± 0.32^{ab}
60 MF	1.17 ± 0.06^{cb}	1.08 ± 0.03^{a}	2.12 ± 0.03^{b}	2.56 ± 0.72^{bc}	10.77 ± 0.08^{a}	1.30 ± 0.02^{c}	162.9 ± 18.4^{ab}	2.3 ± 0.43^{a}	36.8 ± 0.56^{bc}	19.9 ± 5.03^{a}	9.2 ± 0.72^{c}
50 MF	1.18 ± 0.06^{bcd}	1.40 ± 0.03^{c}	4.57 ± 0.55^{b}	4.39 ± 0.53^{d}	12.84 ± 0.11^{c}	1.07 ± 0.03^{b}	461.8 ± 7.81^{c}	3.1 ± 0.07^{b}	40.37 ± 0.41^{d}	70.1 ± 7.55^{b}	8.6 ± 0.20^{bc}
30 MF	0.97 ± 0.05^{ab}	1.25 ± 0.01^{b}	2.61 ± 0.02^{a}	2.86 ± 0.53^{bc}	12.29 ± 0.27^{b}	1.63 ± 0.02^{d}	243.4 ± 12.47^{b}	2.6 ± 0.31^{ab}	38.6 ± 0.91^{cd}	33.1 ± 2.51^{a}	9.2 ± 0.31^{c}
100 Comp	1.32 ± 0.06^{d}	1.25 ± 0.06^{b}	2.35 ± 0.17^{a}	2.10 ± 0.17^{abc}	10.72 ± 0.04^{a}	1.04 ± 0.03^{b}	222.4 ± 1.89^{ab}	2.5 ± 0.24^{ab}	36.1 ± 0.44^{bc}	39.1 ± 9.59^{a}	7.6 ± 0.20^{a}

Means followed by the different letters indicate significant differences among the treatments (Tukey HSD test, $p < 0.05$). Control: no input; 100 MF: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 MF: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 MF: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 MF: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 MF: 30% mineral fertilizer + 4.9 t ha^{-1} compost; and 100Comp: 100% compost (7 t ha^{-1} compost).

The minerals in the grain showed predominantly positive correlations with each other (Table 5). All minerals, with the exception of S, had a significant correlation with Mg. Calcium, on the other hand, had no correlation with any of the grain minerals. Furthermore, significant correlations existed between the average grain yields of maize and the concentrations of Mg, P, S, and Zn

Table 5. Pearson correlation coefficients of minerals in the maize grains and maize grain

	Ca	Mg	N	Fe	K	S	P	Zn	Cu	Mn
Ca	---									
Mg	0.330	---								
N	-0.220	0.733**	---							
Fe	0.027	0.695**	0.771**	---						
K	0.045	0.667**	0.574**	0.907**	---					
S	-0.175	0.229	0.242	-0.201	-0.179	---				
P	0.170	0.750**	0.671**	0.578**	0.544*	0.292	---			
Zn	0.050	0.512*	-0.035	0.089	0.039	0.638**	0.586**	---		
Cu	0.223	0.569**	0.426*	0.669**	0.511*	-0.094	0.464*	0.269	---	
Mn	0.234	0.769**	0.611**	0.899**	0.858**	-0.297	0.596**	0.121	0.535*	
Maize grain	0.190	0.513*	0.423	0.176	0.193	0.483*	0.538*	0.601**	0.323	0.228

*. Correlation is significant at the 0.05 level (2-tailed)

**. Correlation is significant at the 0.01 level (2-tailed)

Interestingly, although the fertilizer treatments affected the grain mineral concentration there was almost no significant correlations between the amount of nutrients applied with the fertilizers and the grain minerals, with the exception of Ca (SI Table 5). Grain Ca concentration was negatively correlated with the N and P amounts applied and positively correlated with the S supply ($p < 0.05$). Considering only the mineral sources of nutrients negative correlations ($p < 0.01$) were found between the application of N. P, and S and the concentration of Mg, N, S, P, and Zn in grains. In contrast, amounts of nutrients applied with compost were not correlated with the concentration of grain minerals.

The maize grain yield, however, depended on the N supply with the mineral fertilizers or compost and yields of maize could be estimated using the equation Eq. (4),

$$\text{Maize yield} = 8.036 + (0.0125 \times \text{Comp. N}) + (0.00768 \times \text{MF. N}) \quad (4)$$

where comp. N is nitrogen from compost (kg N ha^{-1}) and MF. N is nitrogen from mineral fertilizer (kg N ha^{-1}).

In addition, the N to P ratio of compost and mineral fertilizer (SI Table 2) could be used to predict maize yield with the following equation Eq. (5),

$$\text{Maize yield} = 7.89 + (0.045 \times \text{Comp. N:P}) + (0.18 \times \text{MF. N:P} \quad (5)$$

where comp. N:P is nitrogen to phosphorus ratio from compost and MF. N:P is nitrogen to phosphorus ratio from mineral fertilizer.

4.4.2. Nitrogen, phosphorus, and sulphur use efficiency of maize

For the estimation of the use efficiency of N, P and S we considered the nutrients uptake in the fertilized plots with those of the non-fertilized plots considering the amount of nutrients applied (see equation 1 to 3).

The fertilizer treatments affected the nutrient uptake and nutrient use efficiency of maize in both growing seasons ($p < 0.05$) (Table 6). The N uptake was found to be highest, when 40 to 70% of the N from mineral fertilizers were replaced by compost N (treatments 30 MF, 50 MF, and 60 MF). Accordingly, the N use efficiency (NUE) was with roughly 30% clearly higher in these treatments compared to 100 MF, which had a NUE of only 11.8% in the first and 1.06% in the second growing season. However, the sole application of compost (100 Comp) seemed neither suitable for an efficient use of N with a comparable

NUE as for 100 MF. In contrast to NUE, the P use efficiency (PUE) in the 100 Comp treatment was clearly higher than in the 100 MF. Highest uptakes of P were found in 30 MF, 50 MF, and 60 MF treatments. Similar to NUE, low S use efficiencies (SUE) were found in both the 100 MF and 100 Comp treatment. Highest S uptakes and SUE were found in the 30 MF treatment in both growing seasons.

Table 6. Nutrient uptake in maize grains (nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), and sulphur use efficiency (SUE)) in dependence of the fertilizer treatments (mean ± SE).

Treatment	Nutrient applied (kg ha^{-1})			Nutrients in harvested grain (kg ha^{-1}) 2018/19			Nutrients in harvested grain (kg ha^{-1}) 2019/20			Nutrient use efficiency (%) 2018/19			Nutrient use efficiency (%) 2019/20		
	N	P	S	N	P	S	N	P	S	NUE	PUE	SUE	NUE	PUE	SUE
Con	0	0	0	98.8 ± 0.34^{a}	20.3 ± 0.17^{a}	10.76 ± 0.24^{abc}	79.3 ± 2.44^{a}	8.65 ± 0.41^{a}	7.99 ± 0.04^{a}	–	–	–	–	–	–
100 MF	100	33.3	14.0	110.7 ± 0.54^{abc}	22.3 ± 0.07^{a}	10.03 ± 0.29^{a}	80.7 ± 0.91^{a}	10.6 ± 1.61^{a}	7.0 ± 0.06^{a}	11.83 ± 3.31^{ab}	6.06 ± 0.41^{a}	-5.18 ± 3.80^{a}	1.06 ± 2.07^{a}	5.88 ± 4.80^{a}	-5.93 ± 2.2^{a}
80 MF	96.8	27.7	14.3	105.7 ± 5.46^{ab}	26.5 ± 0.80^{b}	13.12 ± 0.76^{c}	86.3 ± 1.10^{a}	22.6 ± 0.42^{abc}	10.18 ± 0.33^{b}	7.15 ± 5.90^{a}	22.28 ± 3.50^{ab}	16.5 ± 3.98^{b}	6.91 ± 2.64^{a}	50.4 ± 2.6^{ab}	16.4 ± 2.90^{bcd}
60 MF	93.6	22.0	14.6	123.5 ± 4.0^{cd}	29.7 ± 0.60^{d}	15.71 ± 0.71^{d}	99.2 ± 0.60^{b}	23.6 ± 0.60^{abc}	12.0 ± 0.71^{c}	26.39 ± 4.58^{bc}	42.7 ± 3.3^{bc}	33.9 ± 2.70^{c}	20.9 ± 2.26^{b}	68.0 ± 2.5^{abc}	28.6 ± 0.57^{d}
50 MF	92	19.2	14.7	132.8 ± 3.25^{d}	31.3 ± 0.40^{d}	12.72 ± 0.43^{bc}	109.7 ± 2.33^{c}	37.2 ± 8.19^{bc}	9.17 ± 0.61^{b}	36.96 ± 3.35^{c}	57.4 ± 2.10^{c}	13.3 ± 4.50^{b}	32.67 ± 2.37^{bc}	149.9 ± 44.3^{c}	9.10 ± 3.10^{bc}
30 MF	88.8	13.5	15.0	117.7 ± 0.92^{bcd}	26.9 ± 0.46^{b}	16.7 ± 0.47^{d}	113.3 ± 1.83^{c}	26.5 ± 1.67^{bc}	14.98 ± 0.33^{d}	21.29 ±0.77^{abc}	49.2 ± 4.41^{c}	39.7 ± 4.10^{c}	37.96 ± 4.13^{c}	132.1 ± 13.7^{bc}	47.6 ± 3.60^{e}
100 comp	84	5.04	15.4	110.6 ± 0.74^{abc}	25.5 ± 0.46^{b}	11.76 ± 0.24^{ab}	80.6 ± 2.49^{a}	15.8 ± 1.09^{ab}	7.86 ± 0.08^{a}	14.0 ± 0.51^{ab}	103.1 ± 10.8^{d}	6.51 ± 0.44^{ab}	1.20 ± 0.81^{a}	142.4 ± 17.9^{c}	0.16 ± 1.69^{ab}

Means followed by the different letters indicate significant differences among the treatments (Tukey HSD test, $p < 0.05$). Con: no fertilizer input; 100 MF: 100% mineral fertilizer N (100 kg N ha^{-1}) and P (33.3 kg P ha^{-1}), 80 MF: 80% mineral fertilizer + 1.4 t ha^{-1} compost; 60 MF: 60% mineral fertilizer + 2.8 t ha^{-1} compost; 50 MF: 50% mineral fertilizer + 3.5 t ha^{-1} compost; 30 MF: 30% mineral fertilizer + 4.9 t ha^{-1} compost; and 100Comp: 100% compost (7 t ha^{-1} compost).

4.4.3. Soil characteristics after two years experimental time

The soil characteristics were only partly affected by the fertilizer treatments and the soil nutrient contents were usually not increased after application of the fertilizers (Table 7). The C content increased with application of the compost in the 30 MF and 100 Comp treatment in comparison to the control and also the pH values and CEC were higher when organic matter was applied.

Table 7. Soil minerals and chemical properties after harvest of the second experimental year 2019/2020 (mean ± SE)

Soil parameters	Treatment						
	Cont.	100 MF	80 MF	60 MF	50 MF	30 MF	100 comp
Fe (mg kg^{-1})	71.3 ± 0.91^{a}	70.7± 0.83^{a}	70.7 ± 1.37^{a}	73.1 ± 0.83^{a}	72.6 ± 1.02^{a}	71.5 ± 2.46^{a}	69.9 ± 0.54^{a}
Ca (g kg^{-1})	3.08 ± 0.06^{a}	3.03 ± 0.01^{a}	3.24 ± 0.08^{a}	3.3 ± 0.06^{a}	3.2 ± 0.07^{a}	3.44 ± 0.08^{a}	3.11 ± 0.04^{a}
Mg* (g kg^{-1})	0.25 ± 0.01^{a}	0.24 ± 0.02^{a}	0.24 ±0.01^{a}	0.26 ± 0.01^{a}	0.27 ± 0.01^{a}	0.28 ± 0.01^{a}	0.26 ± 0.01^{a}
K* (g kg^{-1})	0.29 ± 0.02^{a}	0.34 ±0.03^{a}	0.31 ± 0.02^{a}	0.39 ± 0.02^{a}	0.36 ± 0.04^{a}	0.36 ± 0.01^{a}	0.38 ± 0.02^{a}
Cu (mg kg^{-1})	21.98 ± 1.15^{a}	22.28 ± 0.68^{a}	20.93 ± 0.55^{a}	22.94 ± 0.57^{a}	20.97 ± 0.07^{a}	22.66 ± 0.37^{a}	22.98 ± 0.78^{a}
N (g kg^{-1})	2.48 ± 0.08^{a}	2.58 ± 0.06^{a}	2.48 ± 0.14^{a}	2.6 ± 0.04^{a}	2.6 ± 0.06^{a}	2.6 ± 0.04^{a}	2.6 ± 0.09^{a}
P* (mg kg^{-1})	1.57 ± 0.16^{a}	1.58 ± 0.34^{a}	1.17 ± 0.09^{a}	1.16 ± 0.32^{a}	1.28 ± 0.11^{a}	2.24 ± 0.16^{a}	1.26 ± 0.14^{a}
S (g kg^{-1})	0.53 ± 0.02^{a}	0.56 ± 0.04^{a}	0.58 ± 0.06^{a}	0.58 ± 0.13^{a}	0.61 ± 0.06^{a}	0.51 ± 0.02^{a}	0.53 ± 0.06^{a}
C (g kg^{-1})	25.8 ± 19^{a}	27.3 ± 0.49^{ab}	26.6 ± 1.27^{ab}	27.6 ± 0.6^{ab}	27.6 ± 0.52^{ab}	29.4 ± 0.70^{b}	28.4 ± 0.58^{b}
Zn (g kg^{-1})	0.11 ± 0.03^{a}	0.12 ± 0.01^{a}	0.11 ± 0.01^{a}	0.12 ± 0.01^{a}	0.11 ± 0.01^{a}	0.12 ± 0.01^{a}	0.11 ± 0.04^{a}
Mn (g kg^{-1})	3.11 ± 0.06^{ab}	3.58 ± 0.09^{c}	3.01 ± 0.04^{a}	3.5 ± 0.04^{bc}	3.13 ± 0.07^{ab}	3.59 ± 0.05^{c}	3.08 ± 0.05^{a}
pH	4.98 ± 0.05^{a}	5.0 ± 0.06^{a}	5.05 ± 0.04^{ab}	5.28 ± 0.04^{c}	5.23 ± 0.03^{abc}	5.25 ± 0.05^{bc}	5.18 ± 0.03^{abc}
Ec (µS cm^{-1})	0.22 ± 0.01^{a}	0.25 ± 0.02^{a}	0.23 ± 0.05^{a}	0.24 ± 0.06^{a}	0.24 ± 0.02^{a}	0.28 ± 0.02^{a}	0.24 ± 0.02^{a}
CEC (cmole kg^{-1})	39.4 ± 0.06^{a}	39.9 ± 0.20^{ab}	40.23 ± 0.3^{b}	41.33 ± 0.22^{c}	41.53 ± 0.09^{c}	41.6 ± 0.11^{c}	41.6 ± 0.23^{c}

Different letters within the same column indicate significant differences among the treatments using the Tukey HSD test ($p < 0.05$). *P, K, and Mg are in the soil as bio-available nutrients.

4.5. Discussion

4.5.1. Fertilizer application and concentration of grain minerals

The study results showed that the combined application of mineral fertilizers and compost can increase the concentration of grain minerals in maize. In particular, when 70% of the mineral nitrogen supply was replaced by compost nitrogen (30 MF treatment), high concentrations of almost all grain minerals were found. This is especially important for smallholder farming systems facing a shortage of micronutrients in the form of mineral fertilizers on the market (Gashu et al. 2021). Among all grain minerals, iron (Fe) and manganese (Mn) were most affected by the treatments, with the highest concentrations found for the 50 MF treatment. This is interesting because Nitisol soils have relatively high Fe and Mn contents (Negassa and Gebrekidan 2003). Apparently, a certain ratio of fertilizers can increase the availability of these nutrients to plants. Compost application also increased the concentration of calcium (Ca), magnesium (Mg), and zinc (Zn), which are important for maize consumers in Ethiopia (Gashu et al. 2021). Consequently, the results suggest that combined fertilizer applications have potential as an agronomic biofortification for essential minerals for maize consumers. According to our results, combinations in which approximately 50% of the nitrogen supply is provided by compost would be particularly suitable, and the additional nutrients added with the compost can positively influence the quality of maize grains.

Except for Zn, all other minerals showed lower concentrations in the second growing season than in the first year, which was mainly true for Fe and K. This might be related to the unfavorable weather conditions with extreme rainfall events in the second season (see suppl. information), which affected grain yield and quality. Multiple linear regression analysis revealed that maize yield was well explained by compost N and mineral N; however, compost N application had a more pronounced impact on maize than mineral N application (Eq. 4). One have to consider that organic fertilizer not only provides N but also all the essential plant nutrients which will certainly have an influences on the yields (Pasley et al. 2019). Furthermore, organic fertilizers, like compost, also improves physical soil characteristics like aggregate stability and porosity (Iqbal et al. 2019), which in turn increase microbial activities and microbial nutrient turnover (Ejigu et al. 2021; Mahmood et al. 2017). However, application of only compost as nutrient source was shown to be not superior to the control or the only mineral treatment. This is probably related to the slow N release from compost which limits the biomass production (Zicker et al. 2018). Furthermore, application of large amounts of compost is not applicable for smallholder farmers in Ethiopia, as they need to utilize organic resources for various purposes (Zerssa et al. 2021a).

4.2 Nutrient use efficiency

The study on nutrient use efficiency focused on N, P, and S as these are most economically important nutrient in Ethiopia's maize growing system. In accordance with the yields, the nutrient use efficiency increased, when mineral fertilizers were combined with compost. Mainly regarding the NUE these outcomes have importance for farmers, as N fertilization causes the highest costs (Afreh et al. 2018; Agegnehu, Nelson, and Bird 2016b). Furthermore, increasing the NUE can contribute to reduce environmental pollutions by N losses.

The NUE was lower when either only compost or only mineral fertilizer was applied in comparison to the combinations. For the 100 Comp treatment, this can be explained by the relatively stable N compounds in compost and the consequently gradually release of N (see above). On the other hand, high application amounts of readily available N as in the 80 MF or 100 MF treatments can result in relevant to N losses in the form of nitrous oxide (N_2O) or leaching of nitrate (Afreh et al. 2018), which also reduce the efficiency of N use. Correspondingly, in a previous study at this site highest N losses through gas emission were found in the 100 MF treatment (Zerssa et al. 2021b).

In contrast to NUE, highest PUE was found when only compost was applied, which was related to the relatively high P uptake combined with a relatively low amount of P applied in the 100 Comp treatment. This means that the P availability in soil increased with application of organic material and that the crops were not reliant of high soluble P sources as provided with the NPS fertilizer. Other studies confirmed that organic matter in the soil is positively associated with the availability of P (Eichler-Löbermann, Köhne, and Köppen 2007; Iqbal et al. 2019; Yu et al. 2013). Among other reasons, this is due to the competition of organic molecules with P ions for sorption sites resulting in a reduced P adsorption (Agegnehu, Nelson, and Bird 2016a; Gichangi and Mnkeni 2009; Iqbal et al. 2019). Furthermore, compost can be especially suitable as a P source as it contains both, mineral P compounds as well as stable organic P forms (Frossard et al. 2002). The applied mineral P fertilizer at this Nitisol site exhibited relatively low PUE. This fact is probably related to the high Al and Fe concentration of this soil, which usually result in high P fixation and formation of Al- and Fe-phosphates, especially under low pH values (Abebe, Gebremedin, and Endalkachew, 2013; Elias 2017).

The highest SUE was observed in the 30 MF treatment in both growing seasons. The result indicates compost provides a positive effect on plant S nutrition and efficient use of S. This might be related to the correlation of organic matter and heterotrophic microorganisms that can oxidize S compounds (Chapman 1989; Rezapour 2014). Also Haq et al. (2021) suggested that the application of compost is one of the most effective strategies to enhance the availability of S in soil, but without suggesting concrete ratios of organic and mineral S sources. Our study showed that compost is more suitable than mineral fertilizers to contribute to the efficient use of S in Nitisols.

4.5.2. Soil characteristics

After two years of combined application of compost and mineral fertilizer, significantly higher soil pH, organic C, and CEC, were observed compared to control treatment. This was especially true in the treatments with more than the half of the N supply given with compost (50 MF, 30 MF, and 100 Comp). Thus, despite the relatively short duration of the study of two years, we were able to show that mixed fertilizer applications affected soil parameters, which are also crucial to build soil resistance for drought. Especially an increase in the organic C content ensure a more sustainable and resilient crop production based on higher water-holding capacity of the soil (Derbile 2013; Smith et al. 2019). Surprisingly, most of the soil nutrients did not significantly increase, when the fertilizers were applied. It is likely that the increased grain nutrient concentrations (see section 4.1) and consequently increased nutrient uptakes after application of the fertilizers counteracted the effect of the nutrient supply on soil nutrient pools. However, for most soil nutrients, there was a tendency for fertilizer treatments to increase compared to the control. Furthermore, we found that, with the exception of P and K nutrients, most nutrients increased modestly in the soil compared to the initial soil. This could be linked to the fact that P is the most vulnerable nutrient for fixation, which may reduce the available form of P in the soil (Bekele et al. 2022). The K nutrient has a monovalent ion that may be more susceptible to leaching than other divalent and trivalent ions in the soil and hence reduces the available form of K (Brhane, Mamo, and Teka 2017; Wolde 2016).

Conclusion

The combined application of organic and mineral fertilizers can improve the nutritional quality of maize grains and increase nutrient use efficiency. However, it is important to determine suitable combination ratios for each cropping site. In a Nitisol soil in Southwest Ethiopia, the application of mineral fertilizer with compost accounting for 40-70% of the total nitrogen supply was found to be a suitable option for increasing both grain mineral concentrations and NUE, PUE, and SUE in maize production. This finding could be particularly beneficial for smallholder farmers who are facing rising prices and limited availability of mineral fertilizers on the market.

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Chapter 5: General discussion

General discussion

The short description of the current study

To provide a comprehensive and shared understanding of the roles of climate-smart agriculture in smallholder farming systems and the contribution of soil nutrient management to CSA in a Nitisol, the findings of chapters 2-4 are discussed together in this chapter. In addition, this chapter briefly discusses the urgent need for Ethiopia to shift from exclusive application of mineral fertilizers to a mixed application of compost and mineral fertilizers to achieve food and nutritional security. The results of each individual study, as well as the evaluation of the research as a whole, will be used to create baseline information for future research and policy makers. Conclusions are drawn for practical applications of appropriate compost and mineral fertilizer combinations and well-established information to improve maize production without damaging the soil's ability to sustain future generations.

The findings in chapters 2 to 4 are linked by the role of CSA for sustainable agriculture in smallholder farming systems without damaging the soil or the environment. The literature search and assessments in chapter 2 clearly describe the role of CSA in helping smallholder farmers improve their productivity. Chapter 2 also discussed the challenges and opportunities available for improving CSA. The study identified various CSA practices that have been practiced in different parts of Ethiopia. Due to its great influence on crop production, the impact of soil nutrient management on CSA was chosen among all CSA practices for further field and laboratory investigations (Chapter 3). The results showed a remarkable difference in maize yield and GHG emissions for different rates and types of fertilizer applications (Chapter 3). In order to find the same fertilizer rate with optimal yield and higher maize quality, grain mineral concentrations were analyzed because often grain mineral concentration is not correlated with yields (Chapter 4). The type and rate of fertilizer that improve maize yield and quality should also improve soil quality and increase nutrient use efficiency. Consequently, soil parameters were examined before and after the field experiment to determine their balance and to recommend appropriate mixtures of compost and mineral fertilizer.

Effect of combined nutrient application on GHG emissions

Various anthropogenic activities increase the three most important GHGs (CO_2, N_2O and CH_4) that contribute to global warming potential (GWP), particularly inadequate soil nutrient management practices. Excessive application of organic and mineral fertilizers on farms can increase GHG emissions; particularly during the wet season, N_2O losses are expected due to the microbial denitrification process (Chapter 3). The present study confirms that N_2O losses are significantly higher in mineral fertilizer application alone in 75% of the WFPS soils. When soil microorganisms obtain a sufficient amount of N and C through soil fertilizer application, this provides a conducive environment for microbial activities (decomposition, mineralization and denitrification) and thus increases GHG emissions. During mineral fertilizer application alone, crops cannot absorb all the applied N from the soil solution and the extra N in the soil solution is lost through leaching or N_2O emissions. In addition, mineral fertilizer application alone in the wet season can emit more than half of the N_2O in a week due to its significant amount of readily available nutrient N compared to organic and combined fertilizer applications. The study showed that within six days of mineral fertilizer application, approximately 90% of the N_2O was released in 75% of the WFPS. The finding suggests that special care should be taken when applying mineral fertilizers during the wet season to avoid N losses through gas formation. In this study, combined fertilizer applications reduced N_2O emission by up to 80% and CO_2 emission by up to 22% compared to single mineral fertilizer in wet Nitisol due to lower N application in the combined application (Chapter 3). In particular, substitution of about 50-70% of mineral N by compost could significantly reduce N_2O emission in rainy seasons. A multiple linear regression analysis was conducted to understand how compost and mineral fertilizer affected N_2O and CO_2 emissions and to understand the strength of their relationship. The regression equation showed that mineral fertilizer application significantly increased N_2O and CO_2 emissions compared to organic fertilizer application (Equations 1 to 4). The regression result indicates that mineral fertilizers contributed more to N_2O and CO_2 emissions than organic inputs. A readily available type of N that rapidly promotes microbial denitrification may be the source of the highest GHG emissions from mineral N fertilizer. In addition, limiting the amount of mineral N added to the soil could promote soil C stocks and sequestration by preventing the decomposition of organic matter, which could reduce the impact of GWP and mitigate CO_2 emission. However, previous research by Li et al., (2017) reported opposite results, that N fertilization decreases SOM decomposition and increases soil C sequestration efficiency. The author argued that under low soil N levels, microbes met their N demand by increasing an acquisition from accelerated decomposition of organic sources, leading to increased CO_2 emissions. For future understanding of the relationships between SOM decomposition and mineral N applications in a Nitisol, a systematic research approach is required. Overall, the GHG experiment of the present study had some drawbacks. As the first experiment on Ethiopian soil, direct field measurements were a good way to obtain accurate data on GHG emissions. However, since it was not possible to install static chambers in the field and GC was not available to measure gas fluxes, for these reasons a laboratory incubation experiment was chosen. Therefore, the study suggests conducting a field experiment with various parameters in the future.

$$N_2O \text{ at } 40\% \text{ WFPS} = 4.57 + 0.01 \times Org\_N + 0.024 \times min\_N \quad (1)$$

$$N_2O \text{ at } 75\% \text{ WFPS} = 5.72 + 0.007 \times Org\_N + 0.083 \times min\_N \quad (2)$$

where, N_2O at 40% WFPS and N_2O at 75% WFPS are nitrous oxide emission at 40% and 75% water-filled pore spaces, Org_N nitrogen from organic sources, min_N nitrogen from mineral sources

$$CO_2 \text{ at } 40\% \text{ WFPS} = 3.45 + 0.007 \times Org\_N + 0.021 \times min\_N \quad (3)$$

$$CO_2 \text{ at } 75\% \text{ WFPS} = 5.86 + 0.014 \times Org\_N + 0.035 \times min\_N \quad (4)$$

CO_2 at 40% WFPS and CO_2 at 75% WFPS are carbon oxide emission at 40% and 75% water-filled pore spaces, Org_N nitrogen from organic sources, min_N nitrogen from mineral sources.

The finding has not only made a scientific contribution, but also provides valuable information for the country's policy makers regarding the GHG inventory. For the past decades, Ethiopia has not had any reports for direct measurement of GHGs from croplands, neither by field measurements nor by laboratory incubations. Few studies have previously used the IPCC Tier 1 technique to report GHGs from mineral fertilizer applications (Evangelista et al., 2020; WORKU, 2020). However, the Tier 1 methodology assumes a linear response to fertilizer, which may not accurately reflect emissions in low-input systems, and also GHG emissions are site-specific and limited in several factors. Furthermore, in recent years, evidence suggests that N_2O emissions often increase as an exponential function of N input rate rather than a linear response (Scheer et al., 2016; Takeda et al., 2021); because of this, application of the Tier 1 methodology may not provide accurate data on GHG emissions from fertilized cropping systems. Another critical finding regarding this study is the N_2O emission factor (EF) for fertilizer applied on wet and dry soils. According to IPCC guidelines for national GHG inventories, the default value for N_2O EF is 1% for mineral N inputs; however, this study found an EF of 3.85%, which is almost three times higher than the default value suggested by IPCC 2006 for the EF of mineral fertilizer applications. The EF values of N_2O from this study suggest that using international default EF values to estimate national GHG emissions from cropland will lead to inaccurate results. There will either be a low estimate or a high estimate when we use the IPCC international default values. Therefore, this study recommends the application of site-specific EF values for the national GHG inventory.

Effect of combined nutrient application on maize production

Sustainable yield intensification is one of the pillars of the CSA, and in chapter 3 we demonstrated in detail how the joint use of compost and mineral fertilizer increased corn yields in two consecutive growing seasons. Higher corn yields were observed when we applied 40–70% compost with a combination of mineral fertilizer instead of single fertilization (compost or mineral) for two consecutive growing seasons. Although all treatments had lower yields in the second season due to unfavorable weather, fertilizers combined with 40–70% compost combinations still had higher yields compared to single fertilizers. The present study confirmed that the combination of low rate of compost and mineral fertilizers obtained higher maize yields than previous researches conducted under various growing conditions (Habtamu et al., 2015; Ejigu et al., 2021; Mamuye et al., 2021). For example, due to the rising cost of mineral fertilizer, poor farmers, particularly those in sub-Saharan Africa, cannot afford to use 10 t ha^{-1} compost/manure with 120 kg N ha^{-1} of mineral fertilizer as suggested by Habtamu et al., (2015). Therefore, it is vital to recommend resource-poor farmers to use low rates of fertilizer blends, which could provide higher yields compared to conventional rates. The present study also provided an alternative combination with almost the same average maize yields. For example, the combined use of the 30 min and 50 min treatments provided almost similar amount of grain yield with lower GHG emissions. This implies that farmers with sufficient organic fertilizer can apply up to 70% N from compost/manure, while farmers with little organic fertilizer can apply 50% N from compost for optimal corn yields with optimal quality. Overall, the study observed that the use of a mixed fertilizer of 30-50 kg N ha^{-1} from mineral fertilizer and 50–70% compost was a suitable fertilizer treatment to improve maize yield without increasing GHGs in the smallholder farming system. Since this combination could promote the formation of favorable soil properties that would, in turn, accelerate nutrient use efficiency and reduce nutrient losses compared to mineral application alone. The current combined ratios would also provide the N needed for vegetative and reproductive organ growth throughout the growing season due to its slow release for N, thus increasing yield. In addition, it could maintain soil pH, decrease the rate of soil acidification, improve the rhizosphere environment, and increase the soil's ability to maintain fertilizer supply to crops.

The application of combined fertilizers, as illustrated in the previous section, not only meets the three pillars of the CSA, but also increases corn grain mineral concentrations and increases plant nutrient use efficiency. The results in chapter 4 show that combined fertilizer application significantly increased grain mineral concentrations compared to sole mineral application. In particular, Fe and Mn were significantly elevated in the combined application compared to the single mineral application. In addition, other essential minerals (Ca, Mg and Zn), which are important for corn consumers, increase in the combined applications compared to the single applications. This is useful for the rural population, which relies heavily on maize-based diets. Maize is a staple food in Ethiopia and about 88% of the maize produced in Ethiopia is consumed as food, both green and dry grain. Consumers get more calories and few minerals because maize is inherently low in most minerals of nutritional value. This condition can cause malnutrition if not supplemented by other mechanisms. For example, the results of the present study showed that 24% additional Ca concentrations are obtained in maize grain after supplying 70% N from compost compared with mineral fertilizers alone. Therefore, this finding suggests that compensation of lost micronutrients through 50–70% compost application in the maize field could increase the concentrations of valuable minerals in maize grain compared to mineral fertilizer application alone.

Effect of combined nutrient management on soil resistance to drought

Balanced soil nutrient management could increase soil resilience and enhance the potential for adaptation to climate change impacts in cereal cropping systems, particularly drought resistance. Some soil properties that may be affected by climate change and related to soil resilience are: organic matter, nutrient dynamics, soil pH and cation exchange capacity (CEC) (Brevik, 2013; Song et al., 2015). In the present study, the combined application of 70% compost with mineral fertilizers increased organic C, pH and CEC compared to the single mineral application. Although the study was short-term, the amended field with 70% N supplied by compost showed higher organic carbon value than mineral fertilizer. Soils with adequate organic C, good structure and high plant nutrient content could be more resilient to climate change than soils with low organic C and other properties. Compost up to 70% and mineral fertilizer will increase soil organic matter, fertility, stabilize soil aggregates and increase the water holding capacity of the soil to supply more water for crop development during the dry season. Crop root development and water storage in deep soil layers are favored by the lower bulk density and higher porosity.

Due to the fact that compost contains almost all nutrients, it has been found that its application has an impact on micronutrient content in soil, particularly on Mn. As a result, the amount Mn is higher in fields that received 70% of compost combinations as opposed to sole mineral fertilizer. Furthermore, the amount of Ca, Mg, K, TN, Av.P and S were somewhat increased in the experimental field, which was amended with combined fertilizer compared to sole application. Despite the short duration of the experiment, current research shows that replacing compost with N by 70% improves soil macro- and micronutrients, which further increases the soil's ability to adapt to climate change impact (i.e. drought). Ogundijo et al. (2015), was suggested the combined application of 10 t ha^{-1} poultry manure with (120 kg ha^{-1} NPK) to enhance organic carbon over sole fertilizer application (120 kg ha^{-1} NPK). However, due to the scarcity of organic resources and the high cost of mineral fertilizer, 10 t ha^{-1} of poultry manure with 120 kg ha^{-1} NPK could not be applied in smallholder farming systems. The current study's findings suggest that less compost and mineral fertilizer may be required than Ogundijo et al. (2015) suggested in order to increase soil organic carbon.

Furthermore, CEC was significantly increased in all combined application except 80 min compared with the sole mineral fertilization. This may be as a result of compost's impact on the soil's colloidal surface, as the presence of organic matter raises the negative charges on the surface of soil colloids, increasing the soil's CEC (Ejigu et al., 2021; Nešić et al., 2015; Ogundijo et al., 2015). The result confirmed that the replacing of mineral fertilizer by compost increased CEC, further demonstrating the impact of organic matter on soil colloids. This might increase nutrient retention for plants and increase the buffering capacity of the soil to resist pH change. Furthermore, by applying a combined ratio of 30 to 50% mineral fertilizers together with 50 to 70% of compost, the Mn shortage in the cereal production system could be alleviated. Because of the lack of a market for mineral fertilizer for micronutrients, cereal production has been affected significantly. Even though the study was conducted over a short period, the results indicate that adding compost to mineral fertilizer may increase the levels of macro- and micronutrients in the soil, which could improve soil productivity and maize yield in low-input systems.

Overall achievements of the study

Prior to conducting field and lab experiments, the study analyzed about 208 peer-reviewed literature in order to synthesize and identify the CSA practices in Ethiopia. Furthermore, among all CSA techniques, integrated nutrient management was selected for additional research. The influence of nutrient inputs on CSA was examined in the current study using a combination of compost and mineral fertilizers, in particular NPS and urea. The three nutrients (NPS) were purposively selected since they have been used extensively for cereal production in Ethiopia. The goal of the study was to suggest suitable combinations of compost and mineral fertilizer to provide the best possible maize yield with the least amount of GHG emissions. The compost was composed with all essential nutrients with optimum quality as other study used. The NPS were applied in large quantity in all treatments compared with other essential nutrients. However, the yield and quality of maize were affected not only by these elements, but also by other essential elements from compost, although they were applied in small quantities (Chapter 3 and 4). For instance, the N (100 vs 88.8 kg N ha^{-1}) and P (33.3 vs 13.5 kg P ha^{-1}) amount applied in 100 min treatment were greater than in 30 min treatment, but the average yield and grain mineral concentrations for most minerals were significantly higher in 30 min treatment. This suggests that the soil type (Nitisol) responds strongly to the other essential nutrients and that the best yield could not be obtained with the use of NPS alone. For the production of cereals, micronutrients should be provided, either in the form of mineral fertilizer or compost/manure. Micronutrient application is particularly important for producing nutritionally quality maize. Since maize is a staple meal in most rural areas of Ethiopia, malnutrition issues may arise for the consumers due to maize's naturally low concentration for most essential minerals.

The unique finding of this study was that identifying suitable fertilizer combinations, which could meet the the three pillars of CSA. While other studies had reported different findings regarding the effects of fertilizer on individual pillars separately. The study also gave a general overview of the amount of GHGs emitted by Ethiopian fertilizer applications. Moreover, could fill the gap for low and limited nutrient application in smallholder farming systems. In general, substituting mineral N with 50–70% N from compost could compensate for the missed micronutrients, increases maize production up to 18%, mitigate N_2O emissions up to 80%, increase soil resilience for drought, increase the nutritional quality and nutrient use efficiency of maize grain compared to sole mineral fertilizer application as discussed in detail in each chapter.

Conclusions and recommendations for future research direction

The challenges and possibilities that revealed in the current study should be considered to increase CSA practices in Ethiopia. Fertilizer management can be a primary factor that affects the sustainable agriculture in Ethiopia. Ethiopia cannot feed its growing population under the sole mineral and low-rate nutrient application trend; hence, a move to integrated nutrient management is required. Based on a two-year field and laboratory incubation experiments, combining 50–70% of compost with 30– 50% of mineral fertilizer is more effective in ensuring maximum maize production, reducing GHGs, and increasing plant nutrients than sole mineral fertilization in a Nitisol. The current combined ratio application could significantly increased maize yields than mineral fertilizer at 100 kg N ha^{-1}. Mineral fertilizer at a rate of 100 kg N ha^{-1} is may be non-responsive for maize yield in a Nitisol for a field with 2.4% of C and 0.22% of N since non-significant yield was observed with control treatment. The study also conclude that soil moisture could significantly increase N_2O and CO_2 in Nitisol, so especial consideration should be paid to fertilizer applications during wet seasons to balance nutrient uptake and losses. Emission of CH_4 is not affected by fertilizer types and rates from 40 to 75% WFPS in Nitisol as the study confirmed a non-significant difference in control and other treatments. The saturation point for CH_4 emission could be higher WFPS than 75% WFPS. Combined fertilizer application of 50–70% of compost with 30–50% of mineral fertilizer significantly increased some soil nutrients at the end of the experiment. It also enhance grain mineral concentrations that are nutritionally important, reducing malnutrition among consumers of maize-based foods in rural Ethiopia. In the current study, the combined fertilizer at a rate of 50–70% of compost with 30–50% of mineral fertilizer fulfilled the three pillars of CSA and simultaneously increased grain mineral concentrations and nutrient use efficiency compared with other combinations.

The development of particular finance plans and policies for smallholder farming systems is recommended in order to encourage the adoption of CSA in Ethiopia. Farmers and extension workers should also get training, education, and capacity-building. Although the current study focuses on the situation in Ethiopia, its results may also be applicable to other east African countries**.** The results of this study could be used to formulate the best nutrient management practices to promote sustainable agriculture that is environmentally friendly for smallholder farming systems elsewhere. In order to ensure food security, the Ethiopian government should place more emphasis on the use of mixed fertilizers than only mineral fertilizers. Policymakers should also focus on sustainable crop production rather than increasing short-term production by increasing the rate of mineral fertilizer application alone.

The GHGs emissions experiment was conducted in the laboratory conditions with a known range of temperature and moisture; therefore, future studies under the field conditions will be recommended. Since the amount of GHG emissions from fertilizer application is depended on several external conditions (soil moisture, temperature, amount of rainfall, plant type, pH, C/N ratio, microbial activities). To know the actual amount emitted from croplands, study must include the above factors. Therefore, a field study could consist of the above factors and might determine nearly the substantial amount of GHG emitted from croplands to provide factual information for the policymakers. Furthermore, cereal-cultivating fields with other soil types (Lithosols, Vertisols, Cambisols, Solonchaks, Fluvisols, and Luvisols) should be investigated because soil types are crucial factors that determine GHGs emissions.

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September, 2011, to September, 2013	**M.Sc**. in Physical land resources (Soil Sciences), Ghent University, Belgium. **Graduated with distinction**.
September, 2006 to June, 2009	**B.Sc**. in Natural Resources Management, Jimma University, Ethiopia. **Graduated with great distinction**.

Work Experience

Since 2009 up to present	Working at Jimma University in various positions (Graduate assistant, lecturer and assistant professor in soil science)

Training Experience (Awards: Certificates in):

- Grant proposal writing at Jimma University June, 2021
- Training on Statistical Data Analysis for Post-Graduate Students and Staff using R Programming Language from MaRCCI, has attended on 7th - 19th February 2022.
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Conference paper and poster presentations

- Oral presentation at the MSM academic conference on private sector development in emerging economies, contributing to a climate smart and inclusive society in Maastricht School of Management, on 1 December 2021, the Netherlands.
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Sep 2011–Sep 2013	VLIR-UOS Scholarship for International Master Programmes (ICP), Belgium (MSc)
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A) Proceedings paper:

1. **Zerssa, G. W**., Koal, P., & Eichler-Löbermann, B. (2022). Fertilizer Management Strategy to Reduce Global Warming Potential and Improve Soil Fertility in a Nitisol in Southwestern Ethiopia. *Chemistry Proceedings, 10*(1), 51.

B) Journal Articles

2. **Zerssa, G. W**., Kim, D. G., Koal, P., & Eichler-Löbermann, B. (2023). Grain Mineral Concentrations in Maize (Zea Mays L.) and Nutrient Use Efficiency as Affected by Fertilizer Management on a Nitisol in Southwestern Ethiopia, Communications in Soil Science and Plant Analysis.

3. **Zerssa, G. W**., Kim, D. G., Koal, P., & Eichler-Löbermann, B. (2021). Combination of Compost and Mineral Fertilizers as an Option for Enhancing Maize (Zea mays L.) Yields and Mitigating Greenhouse Gas Emissions from a Nitisol in Ethiopia. *Agronomy*, *11*(11), 2097.
4. **Zerssa, G**., Feyssa, D., Kim, D. G., & Eichler-Löbermann, B. (2021). Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. *Agriculture*, *11*(3), 192.
5. Wakweya, T., Nigussie, A., **Worku, G**., Biresaw, A., Aticho, A., Hirko, O., ... & Ahmed, M. (2021). Long-term effects of bone char and lignocellulosic biochar-based soil amendments on phosphorus adsorption–desorption and crop yield in low-input acidic soils. *Soil Use and Management*.
6. Tadele, K. T., & **Zerssa, G. W.** (2021). Specific Plant Nutrients and Vitamins that Fortify Human Immune System. In *Traditional Herbal Therapy for the Human Immune System* (pp. 363-396). CRC Press.
7. De Waele, J., Vandecasteele, B., Elsen, A., Haesaert, G., Wittouck, D., Horemans, D., **Zerssa, G. W**, & De Neve, S. (2020). Risk assessment of additional nitrate leaching under catch crops fertilized with pig slurry after harvest of winter cereals. *Agriculture, Ecosystems & Environment*, *304*, 107113.
8. **Gebeyanesh W. Z**., Bahilu B. and Birhanu D., 2017. Assessment of farmers' perception towards soil and water conservation in Obi Koji Peasant Association, Woliso District, South West Shewa Ethiopia. Journal of Ecology and the Natural Environment. Vol. 9(3), pp. 45-52,
9. **Gebeyanesh W.Z**., Debela H.F., 2016. Natural Resource Use Conflicts: Gender Opportunities and Constraints in Conflict Management. A review. Journal of Biological and Chemical Research. 33(2): 836-846.

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Proof of individual contribution

Article and manuscript included in the thesis	**First-author**	**Co-author**
Zerssa, G., Feyssa, D., Kim, D. G., & Eichler-Löbermann, B. (2021). Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. **Agriculture**, 11(3), 192 **Chapter 2**	Generating research idea, generating and evaluating data, writing the manuscript	Feyssa, D. (Correcting the manuscript), Kim, D.G (Correcting the manuscript), Eichler Löbermann, B (Correcting the manuscript)
Zerssa, G. W., Kim, D. G., Koal, P., & Eichler-Löbermann, B. (2021). Combination of Compost and Mineral Fertilizers as an Option for Enhancing Maize (Zea mays L.) Yields and Mitigating Greenhouse Gas Emissions from a Nitisol in Ethiopia. **Agronomy**, 11(11), 2097 **Chapter 3**	Generating research idea, generating, evaluating and analyzing data, writing the manuscript	Kim, D.G (Correcting the manuscript) Koal P. (Correcting the manuscript) Eichler Löbermann, B (Evaluating data and correcting the manuscript)
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Declaration of primary authorship

I declare, that I have written the present thesis for doctorate and without help of others. Other than, the presented references were not used and quoted results were always marked with the relevant reference. The present thesis was never either abroad or in Germany submitted for examination in the present or a similar version.

Selbständigkeitserklärung

Ich erkläre, dass ich die eingereichte Dissertation selbständig und ohne fremde Hilfe verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Die vorgelegte Dissertation wurde bisher weder im Ausland noch im Inland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

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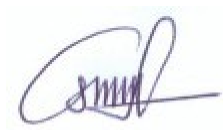

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APPENDIX

Table A1. Daily emission of nitrous oxide (N_2O) at 40% water-filled pore space in different fertilizer treatments (incubation experiment). Only the days with significant differences between the treatments are listed.

Treatment	Day 2	Day 3	Day 4	Day 5	Day 6	Day 9	Day 10
	(g N_2O-N ha^{-1})						
Cont	1.01 ± 0.04^{a}	0.76 ± 0.14^{a}	0.41 ± 0.05^{a}	0.54 ± 0.02^{a}	0.42 ± 0.10^{a}	0.14 ± 0.01^{a}	0.15 ± 0.02^{a}
100 min	1.35 ± 0.08^{ab}	0.84 ± 0.09^{ab}	0.95 ± 0.09^{b}	0.95 ± 0.14^{b}	0.55 ± 0.08^{ab}	0.30 ± 0.01^{b}	0.35 ± 0.02^{b}
80 min	1.38 ± 0.21^{ab}	0.99 ± 0.21^{b}	0.60 ± 0.05^{b}	0.78 ± 0.10^{ab}	0.64 ± 0.10^{b}	0.21 ± 0.01^{ab}	0.36 ± 0.02^{b}
60 min	1.47 ± 0.20^{b}	1.01 ± 0.21^{b}	0.60 ± 0.09^{b}	0.78 ± 0.12^{ab}	0.60 ± 0.06^{ab}	0.21 ± 0.01^{ab}	0.24 ± 0.01^{ab}
50 min	1.29 ± 0.20^{ab}	0.94 ± 0.14^{ab}	0.51 ± 0.04^{ab}	0.65 ± 0.08^{a}	0.49 ± 0.05^{ab}	0.23 ± 0.01^{ab}	0.34 ± 0.01^{b}
30 min	1.20 ± 0.20^{ab}	0.92 ± 0.10^{ab}	0.51 ± 0.10^{ab}	0.66 ± 0.09^{a}	0.56 ± 0.12^{ab}	0.23 ± 0.01^{ab}	0.26 ± 0.01^{ab}
100 comp	1.03 ± 0.05^{ab}	0.86 ± 0.20^{ab}	0.48 ± 0.02^{ab}	0.59 ± 0.10^{a}	0.48 ± 0.05^{a}	0.19 ± 0.02^{ab}	0.23 ± 0.01^{ab}

Different letters within the same column indicate significant differences among the treatments using the Tukey HSD test ($p < 0.05$).

Table A2. Daily emission of nitrous oxide (N_2O) at 75% water-filled pore space in different fertilizer treatments (incubation experiment). Only the days with significant differences between the treatments are listed.

Treatment	Day 1	Day 2	Day 3	Day 4	Day 5	Day 8	Day 9	Day 10	Day 12
	($g\ N_2O\text{-}N\ ha^{-1}$)								
Cont	0.39 ± 0.06^{a}	1.16 ± 0.08^{a}	0.81 ± 0.10^{a}	0.44 ± 0.07^{a}	0.72 ± 0.08^{a}	0.24 ± 0.06^{a}	0.23 ± 0.06^{a}	0.26 ± 0.06^{a}	0.16 ± 0.06^{a}
100 min	1.07 ± 0.11^{b}	2.71 ± 0.21^{cd}	3.03 ± 0.22^{b}	2.42 ± 0.30^{b}	2.14 ± 0.22^{b}	0.49 ± 0.11^{a}	0.48 ± 0.10^{b}	0.60 ± 0.10^{b}	0.65 ± 0.11^{b}
80 min	1.03 ± 0.11^{b}	1.70 ± 0.11^{abc}	1.15 ± 0.11^{a}	1.25 ± 0.11^{a}	0.9 ± 0.03^{ab}	0.27 ± 0.03^{a}	0.36 ± 0.05^{ab}	0.36 ± 0.05^{ab}	0.21 ± 0.01^{ab}
60 min	1.0 ± 0.20^{b}	3.17 ± 0.40^{d}	1.55 ± 0.40^{ab}	1.55 ± 0.21^{ab}	1.48 ± 0.21^{ab}	0.67 ± 0.10^{b}	0.41 ± 0.11^{ab}	0.52 ± 0.10^{ab}	0.60 ± 0.10^{b}
50 min	1.10 ± 0.20^{b}	2.21 ± 0.30^{abcd}	1.37 ± 0.20^{a}	1.05 ± 0.20^{ab}	0.77 ± 0.11^{a}	0.43 ± 0.06^{a}	0.40 ± 0.10^{ab}	0.37 ± 0.10^{ab}	0.21 ± 0.06^{ab}
30 min	1.07 ± 0.21^{b}	2.52 ± 0.30^{bcd}	1.08 ± 0.21^{a}	1.19 ± 0.21^{ab}	0.91 ± 0.11^{ab}	0.35 ± 0.06^{a}	0.34 ± 0.06^{ab}	0.40 ± 0.07^{ab}	0.26 ± 0.04^{ab}
100 comp	0.67 ± 0.03^{a}	1.32 ± 0.10^{ab}	0.91 ± 0.11^{a}	0.54 ± 0.03^{a}	0.80 ± 0.05^{a}	0.25 ± 0.06^{a}	0.21 ± 0.05^{a}	0.29 ± 0.06^{a}	0.18 ± 0.05^{a}

Different letters within the same column indicate significant differences among the treatments using the Tukey HSD test ($p < 0.05$).

Table A3. Daily emission of carbon dioxide (CO_2) at 40% water-filled pore space in different fertilizer treatments (incubation experiment). Only the days with significant differences between the treatments are listed.

Treatment	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
			(kg CO_2 –C ha^{-1})			
Cont	0.68 ± 0.06^{a}	0.59 ± 0.05^{a}	0.31 ± 0.05^{a}	0.41 ± 0.04^{a}	0.33 ± 0.05^{a}	0.15 ± 0.02^{a}
100 min	1.04 ± 0.10^{abc}	0.91 ± 0.14^{abc}	0.62 ± 0.15^{d}	0.77 ± 0.12^{c}	0.53 ± 0.06^{b}	0.23 ± 0.04^{b}
80 min	1.09 ± 0.10^{bc}	1.18 ± 0.10^{c}	0.60 ± 0.06^{cd}	0.57 ± 0.06^{b}	0.47 ± 0.06^{ab}	0.19 ± 0.06^{ab}
60 min	1.17 ± 0.09^{c}	1.21 ± 0.10^{c}	0.57 ± 0.06^{bcd}	0.55 ± 0.06^{b}	0.44 ± 0.05^{ab}	0.19 ± 0.06^{ab}
50 min	1.06 ± 0.2^{bc}	1.09 ± 0.20^{bc}	0.44 ± 0.05^{abc}	0.48 ± 0.06^{ab}	0.34 ± 0.06^{a}	0.17 ± 0.06^{a}
30 min	0.89 ± 0.2^{abc}	0.92 ± 0.10^{abc}	0.42 ± 0.04^{ab}	0.46 ± 0.05^{ab}	0.39 ± 0.06^{ab}	0.17 ± 0.06^{a}
100 comp	0.73 ± 0.06^{ab}	0.73 ± 0.05^{ab}	0.40 ± 0.04^{ab}	0.44 ± 0.04^{ab}	0.37 ± 0.04^{a}	0.18 ± 0.03^{a}

Different letters within the same column indicate significant differences among the treatments using the Tukey HSD test ($p < 0.05$).

Table A4. Daily emission of carbon dioxide (CO_2) at 75% water-filled pore space in different fertilizer treatments (incubation experiment). Only the days with significant differences between the treatments are listed.

Treatment	Day 1	Day 2	Day 3	Day 4
		(kg CO_2 –C ha^{-1})		
Cont	0.28 ± 0.07[a]	0.92 ± 0.10[a]	1.22 ± 0.20[a]	0.65 ± 0.07[a]
100 min	0.95 ± 0.08[c]	2.27 ± 0.21[d]	2.20 ± 0.21[b]	0.97 ± 0.10[ab]
80 min	0.86 ± 0.08[c]	1.41 ± 0.10[abc]	1.69 ± 0.10[ab]	1.03 ± 0.07[b]
60 min	0.79 ± 0.08[c]	1.99 ± 0.20[cd]	1.47 ± 0.11[a]	0.94 ± 0.11[ab]
50 min	0.90 ± 0.08[c]	1.70 ± 0.10[bcd]	1.55 ± 0.10[ab]	0.90 ± 0.06[ab]
30 min	0.86 ± 0.08[c]	1.78 ± 0.20[bcd]	1.29 ± 0.14 [a]	1.01 ± 0.11[b]
100 comp	0.54 ± 0.08[b]	1.10 ± 0.20[ab]	1.44 ± 0.20[a]	0.84 ± 0.20[ab]

Different letters within the same column indicate significant differences among the treatments using the Tukey HSD test ($p < 0.05$).

Table A5. Multiple linear regression analysis for maize grain and coefficient of N nutrient applied from organic and mineral fertilizers.

	Coefficient	Std. Error	t value	p value
Constant	8.036	0.326	24.624	0.001
comp. N	0.0125	0.00494	2.538	0.01
min. N	0.00768	0.00401	1.915	0.05

COMP. N: nitrogen from compost; min. N: nitrogen from mineral fertilizer.

Table A6. Multiple linear regression analysis for maize grain and coefficient for nitrogen to phosphorus ratios (N:P) (organic and mineral)

	Coefficient	Std. Error	t value	p value
Constant	7.88761	0.22578	34.934	0.001
N:P_comp	0.04543	0.01427	3.183	0.01
N:P_min	0.17659	0.07928	2.227	0.05

N:P_comp: nitrogen to phosphorus ratio in compost; N:P_min: nitrogen to phosphorus ratio in mineral fertilizer

Table A7. Multiple linear regression analysis for grain minerals and coefficient of total nutrient applied from compost and mineral fertilizer

S-g	Coefficient	Std. Error	t value	p value
Constant	-164.898	42.143	-3.913	0.001
P-tot	0.518	0.133	3.895	0.001
S-tot	10.622	2.691	3.947	0.001
Mn-g				
Constant	7471.782	2844.140	2.627	0.019
P-tot	-23.698	8.968	-2.642	0.018
S-tot	-474.387	181.628	-2.612	0.020

S-g = sulphur in grain, Mn-g = manganese in grain, P-tot = phosphorus from compost plus mineral fertilizer, S-tot = sulphur from compost plus mineral fertilizer.

Table A8. Multiple linear regression analysis for grain minerals and coefficient of nutrient supplied from mineral fertilizer

Mg-g	Coefficient	Std. Error	t value	p value
Constant	1.450	0.048	30.055	0.001
S-min	-0.017	0.005	-3.316	0.006
P-g				
Constant	3.854	0.440	8.767	0.001
S-min	-0.114	0.046	-2.479	0.028
N-g				
Constant	13.294	0.446	29.837	0.000
S-min	-0.153	0.047	-3.287	0.006
S-g				
Constant	1.821	0.122	14.885	0.001
S-min	-0.054	0.013	-4.243	0.001
Zn-g				
Constant	38.471	1.140	33.753	0.001
S-min	-0.356	0.119	-2.989	0.010

Mg-g = magnesium in grain, P-g = phosphorus in grain, N-g = nitrogen in grain, S-g = sulphur in grain, Zn-g = zinc in grain, S-min = sulphur from mineral fertilizer.

Table A9. Pearson's correlation coefficients of applied nutrients (total, organic and mineral separately) and grain mineral concentrations

	Ca	Mg	N	Fe	K	S	P	Zn	Cu	Mn
N-tot	-0.531*	-0.467	-0.152	-0.085	-0.045	-0.262	-0.185	-0.310	-0.264	-0.203
P-tot	-0.531*	-0.467	-0.153	-0.086	-0.046	-0.261	-0.186	-0.310	-0.264	-0.204
S-tot	0.531*	0.459	0.145	0.067	0.031	0.284	0.187	0.325	0.254	0.185
N-min	-0.088	-0.677**	-0.674**	-0.291	-0.282	-0.762**	-0.567*	-0.638*	-0.376	-0.284
P-min	-0.088	-0.677**	-0.674**	-0.291	-0.282	-0.762**	-0.567*	-0.638*	-0.376	-0.284
S-min	-0.088	-0.677**	-0.674**	-0.291	-0.282	-0.762**	-0.567*	-0.638*	-0.376	-0.284
N-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
P-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
S-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Ca-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Mg-omp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
K-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Fe-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Zn-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Cu-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083
Mn-comp	0.423	0.213	0.055	0.033	-0.135	-0.133	-0.289	-0.251	0.236	0.083

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed). N-tot = Nitrogen from compost plus mineral, P-tot = Phosphorus from compost plus mineral, S-tot = Sulphur from compost plus mineral, N-min = Nitrogen from mineral, P-min = Phosphorus from mineral, S-min = Sulphur from mineral sources, N-comp to Mn-comp = Nitrogen and other nutrients from compost.