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Effects of Combined Application of Compost and Mineral Fertilizer on Soil Carbon and Nutrient Content, Yield, and Agronomic Nitrogen Use Efficiency in Maize-Potato Cropping Systems in Southern Ethiopia

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Abstract: Low nutrient input and low soil fertility are limiting agricultural productivity in Ethiopia. The main objectives were therefore to evaluate the effects of combined compost and mineral fertilizer (MF) application on soil properties, yield, agronomic nitrogen use efficiency, and adoption of compost application in maize (*Zey mays* L.)—potato (*Solanum tuberosum* L.) cropping systems. Yield data were collected from 20 smallholders applying (i) compost and MF at a total rate of 110 kg N ha^{-1}, with 6 Mg compost ha^{-1} + MF (6CF), 12 Mg compost ha^{-1} + MF (12CF), and 16 Mg compost ha^{-1} + MF (16CF; compost on a fresh weight basis), (ii) MF application of 108 kg N ha^{-1} (F), and (iii) zero fertilization. Soil from 0–20 and 20–40 cm depths was collected from 16 farms using compost and MF. Compost + MF treatments showed significantly lower soil bulk density and iron contents, while pH, electrical conductivity, and cation exchange capacity were higher compared to F treatments. The 6CF, 12CF, and 16CF showed 22, 43, and 54% higher maize grain yield and 8, 16, and 18% higher potato tuber yield compared to F, respectively. The scarcity of organic material was a major socioeconomic constraint for smallholders for producing and applying compost.

Keywords: compost; nutrient depletion; smallholder agriculture; socio-economic constraints; yield; agronomic nitrogen use efficiency; soil properties; Ethiopia

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1. Introduction

The combined effects of global population increase, climate change, and progressive soil degradation are threatening food security around the world [1,2]. With 65% of all agricultural land in Sub-Saharan Africa (SSA) being degraded (10% very severely degraded and another 15% severely degraded), SSA is one of the most severely affected subcontinental regions by soil degradation worldwide [3]. The fast-growing population has increased the demand for food not only in SSA, but also particularly in Ethiopia [4]. Furthermore, the increasing costs of mineral fertilizers, land grabbing, and climate variability and change will continue to exacerbate the problem of food security [4–6].

To date, the majority of the increase in SSA food production has been achieved by agricultural expansion at the expense of natural land. However, as land is becoming scarce, it is important to stop this process and increase food security by sustainably improving the productivity and efficiency of agriculture, with smallholder agriculture being at the forefront [7–9]. One means of enhancing food security is the use of organic fertilizers, inorganic fertilizers, and their combined use to increase soil fertility and nutrient inputs to crop fields [8,10].

Agriculture in SSA is dominated by smallholder subsistence farms with low adaptive capacity to climate change and variability, which farm on land and soil resources prone to degradation. In Ethiopia, for example, over 80% of all farms are smaller than 2 ha [11–13]. They are farming on land that is low in soil fertility, nutrient contents, and nutrient-use efficiency, particularly nitrogen (N), but also other macro- and micronutrients, as a result of soil degradation [14,15]. A decline in the soil fertility in cropland occurs when there is inadequate recycling of crop residues, and when insufficient amounts of mineral and organic fertilizers are used to compensate for the depletion of extracted nutrients and soil organic matter [3,16,17]. Ethiopia's soil nutrient balance shows that nutrient resources have decreased in most cropping systems, except for areas under permanent vegetation and vegetable crops [18]. Continuous cropping and the inadequate replacement of nutrients removed with harvested materials or loss through erosion and leaching are the major cause of nutrient depletion in Ethiopia [19]. This is particularly evident in intensively cultivated areas, known as high-potential zones, which are largely located in the country's highlands [20].

Mineral fertilizers are widely used globally to overcome nutrient deficiencies; their use, however, remains very low in SSA due to economic constraints [21,22]. Furthermore, commonly available mineral fertilizers only contain some of the macronutrients required for sustainable plant production, namely N, P, and S or K, but run short in providing further macro- and micronutrients. Due to a lack of economic resources and a lack of availability of macro- and micronutrient-containing complex fertilizers, smallholder agriculture is mostly unable to replace all nutrients removed from agricultural land by crop production [23,24]. Furthermore, these types of mineral fertilizers are not able to replenish soil humus and therefore fall short in restoring soil fertility in the long term [25]. Yield benefits are thus more apparent when mineral fertilizer application is accompanied by crop rotation, green manuring, crop residue management, manure, or compost amendments [19,26,27].

Low productivity and climate change impacts require climate-smart agricultural (CSA) practices in order to improve food security by sustainably increasing crop productivity, enhancing the resilience or adaptive capacity of agricultural systems, and offsetting greenhouse gas emissions [28,29]. In this context, high-quality organic soil amendments, such as compost, can provide most essential nutrients in the short term and build up soil organic matter in the long term [25,26,30,31]. However, due to limited availability and varying quality, a sufficient supply of organic amendments to satisfy crop nutrient requirements remains challenging at a larger scale [8,32]. In low-input crop production systems, such as in smallholder farming in Ethiopia, mineral fertilizers are neither available nor affordable in sufficient quantities [33]. The addition of organic resources can complement or even replace mineral fertilizer and therefore reduce the dependence on mineral fertilizers [19,33–35]. Therefore, the combined application of organic resources and mineral fertilizers are among the most viable approaches to mitigating soil fertility decline in SSA, and are increasingly gaining recognition [19,33,34]. However, there is still a need to explore ways to optimize the impact of compost–mineral fertilizer combinations on soil fertility, crop production, and agronomic nitrogen use efficiency (ANUE), and to explore adoption constraints, as little on-farm research has been conducted on smallholder farming systems in SSA.

The objectives of this study were therefore (i) to assess the effects of the practiced combined application of compost and mineral fertilizer on soil properties, maize (*Zea mays* L.) grain yield (MGY), and ANUE of maize, as well as potato (*Solanum tuberosum* L.) tuber yield (PTY) in the subsequent growing season of a common maize–potato rotation of typical smallholder farms, and (ii) to identify the socioeconomic constraints of compost production and application. This study was carried out at 20 smallholder farms with maize–potato cropping systems in southern Ethiopia with regard to yield assessment, and at a subset of

16 farms with regard to soil fertility evaluation. We hypothesized that the complementary addition of compost to the application of mineral fertilizers will increase the soil fertility and productivity of smallholder farming systems due to the compost's higher content of organic matter and further macro- and micronutrients compared to the sole application of mineral NPS (i.e., nitrogen, phosphorus, and sulfur) and urea fertilizer.

2. Materials and Methods

2.1. Site Description

The study area was located in the Wondo district, West Arsi zone of Oromia Regional State, Ethiopia (between 7°12′71.60″ and 7°14′71.44″ N, and 38°56′96.48″ and 38°59′81.01″ E), at an altitudinal range from 1948 to 2010 m a.s.l. (Figure 1). The study sites are characterized by a sub-humid tropical climate with an average annual rainfall of 1247 mm. The rainfall has a bimodal distribution pattern with a short rainy season from March to May accounting for approximately 30% of the total rainfall, and a long rainy season from July to October, accounting for over 50% of the total rainfall. The average annual temperature is 19.5 °C, with maximum and minimum values of 26.3 °C and 12.4 °C, respectively [36]. The study sites were located in an undulating to mountainous terrain at a mid-slope position, with a slope of 2–5%. The soil of all smallholder farmers' fields was classified as Mollic Andosol with a sandy-loam texture [37]. Particle size fractions of sand, silt, and clay, and soil textural classes are presented in Supplementary Table S1.

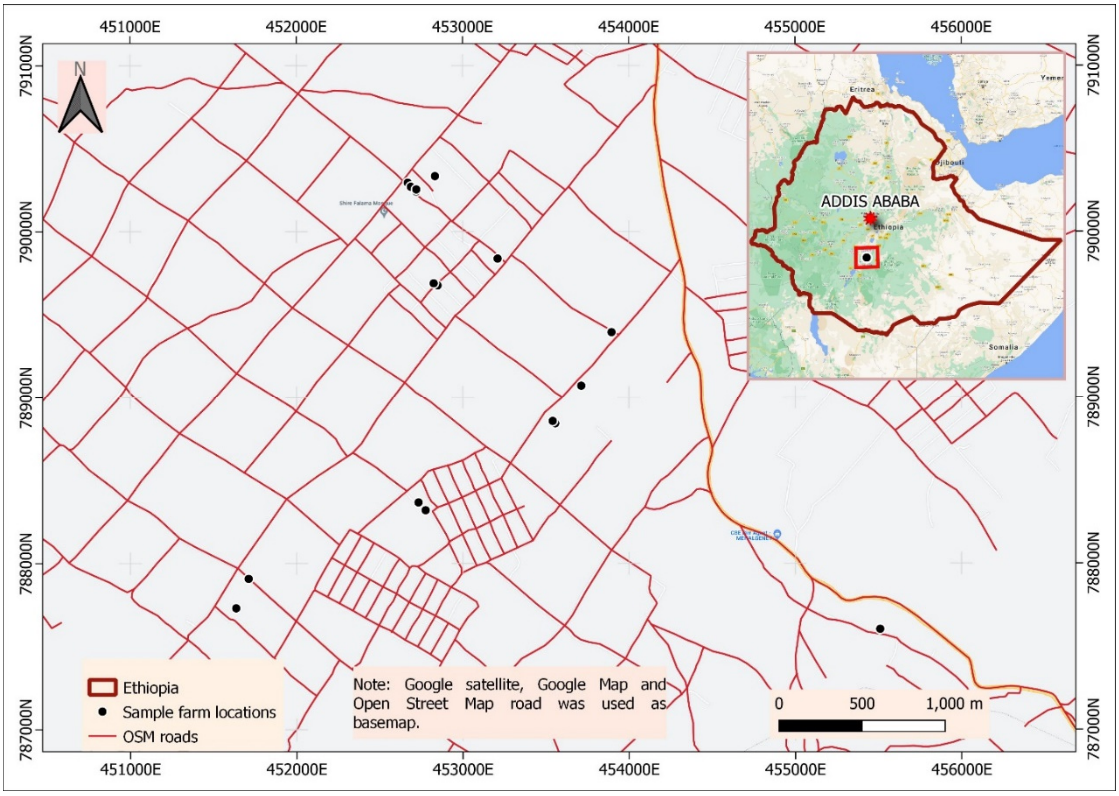

Figure 1. Map of the study area, showing the studied smallholder farmers' fields (black dots) at Wondo District, Oromia Region, Southern Ethiopia (map provided by M. Gebrehiwot on the basis of Google Earth, Google Maps, and Open Street Map) OSM = Open Street Map.

2.2. Household Survey on Compost Management

Shire Borara and Mado, two kebeles (lowest administrative units) in the Wondo district, Oromia, southern Ethiopia, were selected for their compost and mineral fertilizer use experience in their rain-fed, mixed farming (crop and cattle rearing)-based farming system. Sixty farmers who had been applying a maize–potato cropping system for at least three consecutive years were interviewed to obtain information on the state of the art of compost management at the household (HH) level, in order to understand the reasons that farmers adopt or reject compost use, assess the socio-economic conditions, and identify the constraints for compost production and the impact of compost on soil and crop yields. The baseline information gathered through this assessment was used for the selection of farms, treatment arrangement, and sample size determination for further study on fertilization management practices and their impact on yields, soil fertility, and ANUE.

2.3. Farm Management Practices

The study sites (different smallholder farmers' fields in Shire Borara and Mado Kebeles) had been cropped with a maize–potato rotation sequence by the smallholders (maize from April to July and potato from August to November) for at least the last three years. Maize crop residues are usually removed from the fields and used both as fuel and fodder for livestock [19,33], whereas the potato residues are returned to the soil. Most farmers fertilize their farmland with combinations of organic and mineral fertilizers at different application rates. Some farmers use mineral fertilizer (NPS and urea) at a varying rate together with compost. Farmers use either a combination of organic and mineral fertilizer, or mineral fertilizer only. Due to a lack of organic waste for composting and high compost prices, farmers usually do not use full-dose compost fertilization to satisfy the nutrient demand of the crops, while resource-poor farmers do not even apply any fertilizer to their cropland at all.

Compost, produced from locally available materials (i.e., crop residues, green leaves, weeds, tree pruning material, animal manure, organic HH waste, ashes, and mineral soil), was prepared following the traditional practices described in Tulema et al. [38]. Three composting methods, i.e., (i) heaps, (ii) pits, and (iii) the preparation of compost in pits with further maturation in heaps, are commonly used in the study area. Mature compost is usually applied once per year during land preparation before sowing maize in March by broadcasting it on the surface and incorporating it into the soil by tillage. NPS fertilizer is applied at sowing for both maize and potato, with half of the dose of urea applied at sowing, and the other top-dressed 40–45 days after sowing of maize. Urea was not applied to potato.

2.4. Experimental Design

Based on their willingness to participate in the research, 20 farms with 5 different application rates of compost and mineral fertilizer for maize cultivation, including a zero-fertilization variant, were selected, as listed below, for assessing yield parameters (Table 1):

(1) Application of 5.7 $\pm$ 0.5 Mg ha^{-1} compost on fresh weight (FW) basis, i.e., 2.3 $\pm$ 0.2 Mg ha^{-1} dry weight (DW) (equivalent to 31.6 $\pm$ 2.6 kg N ha^{-1}) + mineral fertilizer (72.8 $\pm$ 5.6 N kg ha^{-1}): 6CF (compost + mineral fertilizer).
(2) Application of 12 Mg ha^{-1} compost on FW basis, i.e., 4.8 $\pm$ 0 Mg ha^{-1} DW (equivalent to 67.2 $\pm$ 0.0 kg N ha^{-1}) + mineral fertilizer (39.4 $\pm$ 2.6 kg N ha^{-1}): 12CF.
(3) Application of 16 Mg ha^{-1} compost on FW basis, i.e., 6.4 $\pm$ 0 Mg ha^{-1} $\pm$ DW (equivalent to 89.6 $\pm$ 0.0 kg N ha^{-1}) + mineral fertilizer (19.5 $\pm$ 3.0 kg N ha^{-1}): 16CF.
(4) Application of a full dose of mineral fertilizer equivalent to 108.3 $\pm$ 3.4 kg N ha^{-1} (100 kg NPS + 200 kg urea ha^{-1}): F.
(5) No compost or fertilizer input for maize: Control.

However, since those smallholder farmers applying no fertilizer to maize were not willing to participate in the assessment of soil fertility analyses, no samples could be taken for soil analyses.

Table 1. Application period, rates, carbon and nitrogen contents of compost, and mineral fertilizer for maize; n = 4 replicates for each treatment (means ± SD).

Treat-ment	Appl. Period	Application Rate			Total Carbon and Nutrient Contents from All Applications	
		Comp FW	NPS	Urea	C	N
	years	Mg ha^{-1}	kg ha^{-1}			
6CF	3 to 10	6 ± 0.5	129 ± 49	105 ± 19	432 ± 36	104 ± 4
12CF	3 to 10	12 ± 0	72 ± 34	56 ± 20	917 ± 0	107 ± 3
16CF	3 to 10	16 ± 0	76 ± 43	11 ± 13	1222 ± 0	109 ± 3
F	3 to 10	0	110 ± 35	190 ± 20	0	108 ± 3
Control	3	0	0	0	0	0

CF = compost + mineral fertilizer; F = mineral fertilizer only: NPS (19% N, 38% P_2O_5 and 7% S) and Urea (46% N); n = number of replicates, C = Carbon; N = Nitrogen; SD = standard deviation.

To reach the recommended dose of mineral fertilizer of around 110 kg N ha^{-1} for high-producing varieties of hybrid maize in the study area [39], 100 kg of commercially available NPS fertilizer (19% N, 38% P_2O_5, and 7% S) and 200 kg urea (46% N) are commonly used. The substitution of mineral fertilizer N with compost N in the different combined compost treatments (6CF, 12CF, 16CF) was calculated based on the amount of total N in the compost (assumed availability of 100% during the first year), supplemented with NPS fertilizer and urea to satisfy the crop requirement of around 110 kg N ha^{-1}. For the subsequent crop, i.e., potato, all farmers (including those that did not apply any fertilizer to maize) used mineral N fertilization at a rate of 100 kg NPS ha^{-1} (i.e., 19 kg N ha^{-1}) uniformly for all of the treatments according to their local practice.

The moisture content of the compost was measured by drying the compost at 105 °C for 24 h. Compost total nitrogen (TN) was determined using the Kjeldahl technique [40], total organic carbon (TOC) was determined using the Walkley–Black oxidation method [41], and the carbon-to-nitrogen (C/N) ratio was calculated from TOC and TN. The average values (±standard error) of moisture, TOC, TN, the C/N ratio, and pH of the compost at the study sites were 60 ± 1%, 191.0 ± 23.0 g kg^{-1}, 14.4 ± 3.0 g kg^{-1}, 13.3±0.5, and 8.2 ± 0.1, respectively.

2.5. Crop Yield Data Collection and Analysis

Maize grain yield (MGY; for farmers using F, 6CF, 12CF, 16 CF, and no fertilization) and potato tuber yield (PTY; for farmers using F, 6CF, 12CF, and 16 CF, as stated above there was no zero fertilization treatment for the potato growing season) were determined for the inner 4 m × 4.5 m area of a farm plot at the end of each season. This area comprised six rows of plants with a row spacing of 75 cm for maize and potato. Data for the MGY and PTY analysis were averaged across farms and treatments.

The Agronomic Nitrogen Use Efficiency (ANUE) of the combined addition of organic N plus mineral N fertilizer, or mineral N fertilizer alone, was calculated as the increase in yield in kg ha^{-1}, compared to the control per kg N ha^{-1} applied [34,42], using the equation:

$$ANUE = (Y_{trt} - Y_{con})/(\text{total N applied})$$

where Y_{trt} represents the yield of the different treatments, Y_{con} represents the yield of the control, and total N applied represents N applied in the compost (assuming availability of total N of 100%) + mineral N fertilizer treatment or the mineral N fertilizer-only treatment; all units are expressed in kg ha^{-1}.

2.6. Soil Sampling and Analysis

In the region, smallholder farmers practice ploughing with an oxen-pulled plough, resulting in a ploughing horizon of 0–20 cm soil depth. After maize harvest, 192 soil samples were collected from two soil depths (0–20 and 20–40 cm), for four treatments, four replications, and six sampling spots per treatment replicate. For each plot and soil depth, the six samples taken were combined into composite samples for soil chemical analyses, resulting in a total of 32 composite samples. To determine soil bulk density (BD), another set of soil samples was collected in the middle of the 0–20 cm (i.e., from 7.5–12 cm) and 20–40 cm (i.e., from 27.5–32.5 cm) soil layers with a soil core sampler (diameter of 5 cm, length of 5 cm). One set of soil samples was collected per plot, i.e., four replicates per treatment. Soil samples were air-dried, homogenized carefully, and passed through a 2-mm sieve before analysis. Soil texture was determined using the Bouyoucos hydrometer method [43]. Dry soil BD was determined by a standardized core method [44], in which the soil was oven-dried at 105 °C for 24 h. Soil pH was measured with a pH meter (HI99121 Hanna Instruments Inc., Woonsocket, RI, 02895, USA.) in a 1:5 soil-water (*w*/*v*) suspension. Electrical conductivity (EC) was analyzed in an aqueous extract of soil (soil–water mixture 1:2 *w*/*v*) with an EC instrument (EC250 Oakton Instruments 625 East Bunker Court, Vernon Hills, IL, 60061, USA), corrected to 25 °C [45]. Cation exchange capacity (CEC) was determined by flame photometry as described in Castro Herrera et al. [46] following the method of FAO [47]. The dry matter fraction was determined using the respective DIN method [48]. Soil organic matter (SOM), TOC, and total N contents were determined by dry combustion [49,50]. Total Fe, phosphate (P_2O_5), potassium oxide (K_2O), Mg, Na, and S were determined after aqua regia digestion using inductively coupled plasma optical emission spectrometry (ICP-OES) according to DIN [51]. Plant-available Ca was estimated by shaking the soil with 1% ammonium chloride solution (1:10, *w*:*v*) for one hour, and measuring the filtrate with ICP-OES. Mineral nitrogen (ammonium-N and, nitrate-N) was determined by the respective VDLUFA method [52]. Exchangeable P and K were measured according to the VDLUFA method [53]. Exchangeable S, Fe, Na, Al, and Mg were determined according to the VDLUFA method [54].

2.7. Statistical Analysis

The normality of the data distribution was first analyzed using the Anderson–Darling normality test [55] for all datasets. One-way analysis of variance (ANOVA) was used to test the significance of fertilization type and soil depth effect on soil properties, yield, and ANUE with Minitab 17.0 Software (Minitab Inc., State College, PA, USA). Two-way ANOVA, following the general linear model (GLM), was used to test fertilization type, soil depth, and their interaction effect with SPSS 20.0 for Windows (SPSS Inc., Chicago, IL, USA). Tukey's honest significance difference (HSD) test was used for mean separation when the analysis of variance showed statistically significant differences ($p < 0.05$). Pearson correlation was employed to examine the relationships between soil organic matter (SOM), soil pH, nitrate-N, and exchangeable Mg, Ca, P, K, S, Fe, Na, and Al.

3. Results

3.1. Soil Bulk Density

Fertilizer type, soil depth, and their interaction had a significant effect on soil BD ($p < 0.001$, Supplementary Table S2). In 0–20 cm depth, soil BD was 3%, 8%, and 11% lower in 6CF, 12CF and 16CF, respectively, compared to F (Table 2), with a significance of $p < 0.001$ for 12CF and 16 CF. In contrast, in the 20–40 cm soil depth, there was no significant difference in soil BD between treatments. For all compost treatments, soil BD at the 0–20 cm soil depth was significantly lower ($p < 0.001$) compared to the 20–40 cm soil depth (Table 2).

Table 2. Soil physical and chemical properties in 0–20 and 20–40 cm soil depths of smallholder farmers' fields applied with different rates of compost and mineral fertilizer (n = 4, mean ± SD).

Parameter	Soil Depth (cm)	Type of Compost and Mineral Fertilizer Use			
		6CF	12CF	16CF	F
BD (g cm^{-3})	0–20	0.818 ± 0.004 ^{ABb}	0.770 ± 0.004 ^{BCb}	0.744 ± 0.002 ^{Cb}	0.840 ± 0.004 ^{Aa}
	20–40	0.843 ± 0.01 ^{Aa}	0.842 ± 0.004 ^{Aa}	0.840 ± 0.002 ^{Aa}	0.844 ± 0.004 ^{Aa}
pH	0–20	6.2 ± 0.3 ^{Aa}	6.6 ± 0.4 ^{Aa}	6.2 ± 0.7 ^{Aa}	5.9 ± 0.1 ^{Aa}
	20–40	6.3 ± 0.2 ^{Ba}	6.8 ± 0.3 ^{Aa}	6.5 ± 0.1 ^{ABa}	6.2 ± 0.2 ^{Bb}
EC (mS cm^{-1})	0–20	185 ± 32 ^{Aa}	171 ± 17 ^{Aa}	201 ± 42 ^{Aa}	128 ± 17 ^{Ba}
	20–40	106 ± 15 ^{BCb}	141 ± 27 ^{ABa}	175 ± 39 ^{Aa}	80.0 ± 6.4 ^{Cb}
CEC (cmol kg^{-1})	0–20	23.1 ± 2.5 ^{Bb}	32.1 ± 1.2 ^{Aa}	31.5 ± 1.8 ^{Aa}	25.3 ± 1.5 ^{Bb}
	20–40	20.9 ± 2.2 ^{Bb}	22.5 ± 2.1 ^{Bb}	28.6 ± 1.5 ^{Aa}	22.2 ± 3.1 ^{Bb}
SOM (g kg^{-1})	0–20	36.3 ± 3.4 ^{Aa}	47.8 ± 8.0 ^{Aa}	41.0 ± 11.9 ^{Aa}	41.5 ± 5.5 ^{Aa}
	20–40	30.3 ± 4.6 ^{Aa}	29.8 ± 9.6 ^{Ab}	28.5 ± 20.5 ^{Aa}	34.8 ± 17.2 ^{Aa}
TOC (g kg^{-1})	0–20	21.0 ± 1.9 ^{Aa}	27.7 ± 4.6 ^{Aa}	23.8 ± 7.0 ^{Aa}	24.1 ± 3.2 ^{Aa}
	20–40	17.6 ± 2.7 ^{Aa}	17.3 ± 5.5 ^{Ab}	16.5 ± 11.9 ^{Aa}	20.2 ± 10.0 ^{Aa}
Total N (g kg^{-1})	0–20	2.2 ± 0.2 ^{Aa}	2.6 ± 0.2 ^{Aa}	2.3 ± 0.6 ^{Aa}	2.4 ± 0.4 ^{Aa}
	20–40	2.1 ± 0.3 ^{Aa}	1.9 ± 0.1 ^{Ab}	1.6 ± 0.6 ^{Aa}	1.9 ± 0.4 ^{Aa}
Total P (g kg^{-1})	0–20	0.30 ± 0.02 ^{Aa}	0.48 ± 0.10 ^{Aa}	0.44 ± 0.20 ^{Aa}	0.34 ± 0.11 ^{Aa}
	20–40	0.27 ± 0.03 ^{Aa}	0.28 ± 0.10 ^{Ab}	0.27 ± 0.04 ^{Aa}	0.24 ± 0.02 ^{Ab}
Total K (g kg^{-1})	0–20	1.7 ± 0.2 ^{Aa}	1.8 ± 0.6 ^{Aa}	1.9 ± 0.9 ^{Aa}	2.1 ± 0.1 ^{Aa}
	20–40	1.3 ± 0.1 ^{Ab}	1.1 ± 0.4 ^{Aa}	1.0 ± 0.3 ^{Aa}	1.3 ± 0.2 ^{Ab}
Total Mg (g kg^{-1})	0–20	1.4 ± 0.1 ^{Aa}	1.5 ± 0.2 ^{Aa}	1.4 ± 0.3 ^{Aa}	1.7 ± 0.1 ^{Aa}
	20–40	1.3 ± 0.1 ^{Aa}	1.1 ± 0.3 ^{Aa}	1.3 ± 0.0 ^{Aa}	1.4 ± 0.1 ^{Ab}
Total S (g kg^{-1})	0–20	0.20 ± 0.00 ^{Aa}	0.23 ± 0.10 ^{Aa}	0.25 ± 0.10 ^{Aa}	0.23 ± 0.06 ^{Aa}
	20–40	0.20 ± 0.0 ^{Aa}	0.15 ± 0.10 ^{Aa}	0.10 ± 0.14 ^{Aa}	0.18 ± 0.12 ^{Aa}
Total Na (mg kg^{-1})	0–20	317 ± 56 ^{Aa}	373 ± 176 ^{Aa}	497 ± 162 ^{Aa}	511 ± 89 ^{Aa}
	20–40	431 ± 241 ^{Aa}	321 ± 121 ^{Aa}	430 ± 30 ^{Aa}	281 ± 69 ^{Ab}
Total Fe (g kg^{-1})	0–20	16.0 ± 0.8 ^{Ba}	14.2 ± 1.2 ^{Ba}	15.7 ± 2.3 ^{Ba}	21.9 ± 1.8 ^{Aa}
	20–40	14.3 ± 0.9 ^{Bb}	10.8 ± 2.0 ^{Cb}	12.5 ± 2.6 ^{BCa}	18.2 ± 1.0 ^{Aa}
C/N-Ratio	0–20	9.7 ± 0.4 ^{Aa}	10.8 ± 1.4 ^{Aa}	10.3 ± 1.4 ^{Aa}	10.0 ± 0.8 ^{Aa}
	20–40	8.4 ± 1.2 ^{Aa}	9.0 ± 3.0 ^{Aa}	9.7 ± 5.8 ^{Aa}	10.0 ± 3.4 ^{Aa}

Means followed by different uppercase superscript letters indicate a significant difference between treatments, means followed by different lowercase superscript letters indicate a significant difference between soil depths (see also Supplementary Table S2). n = number of replicates, SD = standard deviation, 6CF = 5.7 Mg ha^{-1} of compost on fresh weight (FW) basis and 72.8 N kg ha^{-1} of mineral fertilizer; 12CF = 12 Mg ha^{-1} of compost (FW) and 39.4 kg N ha^{-1} of mineral fertilizer; 16CF = 16 Mg ha^{-1} of compost (FW) and 19.5 kg N ha^{-1} of mineral fertilizer; F = 108.3 kg N ha^{-1} of mineral fertilizer only.

3.2. *Soil pH*

There was a trend of higher pH values for all treatments using compost (6CF, 12CF, 16CF); however, differences were not statistically significant for a soil depth of 0–20 cm (Table 2). In contrast, for a soil depth of 20–40 cm, treatments using higher compost amendments (12CF and 16CF) showed significantly ($p < 0.05$) higher soil pH compared to treatments with no (F) or only low compost amendments (6CF; Supplementary Table S2, Table 2).

3.3. *Electrical Conductivity*

Similar to soil pH, for EC there was also a significant variation with fertilizer type. In the 0–20 cm soil depth, EC was significantly ($p < 0.001$) higher for all treatments using compost (6CF, 12CF, and 16CF) compared to the one using mineral fertilizer only (F). This effect was even more pronounced for the soil depth from 20–40 cm, where EC increased with the amount of compost used (F < 6CF < 12CF < 16CF) and was significantly different ($p < 0.001$) for all treatments using compost (6CF, 12CF, 16 CF) compared to F (Table 2, Supplementary Table S2).

3.4. Cation Exchange Capacity

Increasing amounts of compost amendment resulted in a significant increase in CEC ($p < 0.001$; Supplementary Table S2). In the 0–20 cm soil depth, treatments with the highest compost application rates (12CF and 16CF) had significantly (27% and 24%) higher CEC values compared to F (Table 2). For the 20–40 cm soil depth, however, only for 16CF was CEC significantly (29%) higher than F, whereas all other compost treatments showed similar CEC values compared to F ($p < 0.01$; Table 2).

3.5. Soil Organic Matter, Organic Carbon, and Total Nutrient Contents

No significant differences between treatments could be observed for SOM, SOC, and total nutrient contents. Consequently, there was also no significant difference in the C/N ratio between the treatments (Table 2). Only for total Fe did the compost treatments (6CF, 12CF, 16CF) show significantly ($p < 0.001$) lower contents in the 0–20 cm soil depth compared to F (Table 2; Supplementary Table S2).

3.6. Available Nutrient Contents

Among all available soil nutrients, analyzed as exchangeable nutrient contents, only sulfur (S), iron (Fe), and sodium (Na) exhibited significant differences between the treatments (Table 3). This can be partly attributed to large standard deviations. For example, this was the case for exchangeable P contents, for which a trend toward higher P contents could be observed for the compost treatments in the 0–20 cm soil depth compared to the F treatment (F; Table 3). Contents of exchangeable S were eleven times, and thereby significantly ($p < 0.01$; Supplementary Table S2), higher in the 6CF treatment than in the F treatment at the 0–20 cm soil depth. In contrast, the two other compost treatments (12CF and 16CF) did not show significantly higher contents of exchangeable S compared to the F treatment (Table 3). Compost treatments showed lower exchangeable Fe contents compared to the F treatment. In the 0–20 cm soil depth, the lowest Fe content could be observed for the 12CF treatment, which was 33% and significantly ($p < 0.001$) lower compared to F. In the 20–40 cm soil depth, both 12CF and 16CF showed significantly (40% and 44%) lower exchangeable Fe contents compared to F (Table 3, $p < 0.001$). In contrast, the highest exchangeable Na content could be found in the 0–20 cm layer in the 6CF treatment, being significantly ($p < 0.01$) larger than in the 12CF and F treatments (Table 3).

3.7. Crop Yield and Agronomic N Use Efficiency

3.7.1. Maize Grain Yield and Agronomic N Use Efficiency

As expected, all fields amended with combined compost–mineral fertilizer (6CF, 12CF, 16CF) as well as the mineral-fertilizer-only treatment (F) had significantly higher maize grain yields (MGY) than the control fields with no N input (Figure 2). There was significantly higher MGY in 6CF ($p < 0.05$), 12CF, and 16CF ($p < 0.001$), respectively, compared to F (Supplementary Table S4). The addition of mineral N fertilizer (F) resulted in a 150% higher MGY than in the control with no fertilizer input, whereas in 6CF, 12CF, and 16CF, the combined application of compost and mineral fertilizer increased the mean MGY by 205 %, 257%, and 284%, respectively, compared to the unfertilized control (Figure 2). Compared to F, the combined application of compost and mineral fertilizers increased MGY by 28% (i.e., by 1.07 Mg ha^{-1}) in 6CF, 46% (i.e., by 1.77 Mg ha^{-1}) in 12CF, and 55% (i.e., by 2.14 Mg ha^{-1}) in 16CF. The differences in MGY between fertilizer types were all significant, except for the difference between 16CF and 12CF (Figure 2).

Table 3. Soil exchangeable nutrient contents and C/N ratio for the different compost and mineral fertilizer treatments in 0–20 cm and 20–40 cm soil depths (n = 4, mean ± SD).

Parameter	Soil Depth (cm)	Type of Compost and Mineral Fertilizer Use			
		6CF	12CF	16CF	F
Mineral Nitrogen (Ammonium + Nitrate) (mg kg^{-1})	0–20	16.8 ± 6.2 ^{Aa}	17.8 ± 3.9 ^{Aa}	19.4 ± 10.6 ^{Aa}	15.0 ± 3.5 ^{Aa}
	20–40	5.4 ± 4.2 ^{Ab}	1.4 ± 1.7 ^{Ab}	0.0 ± 0.0 ^{Aa}	0.0 ± 0.0 ^{Ab}
Nitrate-N (mg kg^{-1})	0–20	16.8 ± 6.2 ^{Aa}	17.8 ± 3.9 ^{Aa}	19.4 ± 10.6 ^{Aa}	13.5 ± 3.2 ^{Aa}
	20–40	5.4 ± 4.1 ^{Ab}	1.4 ± 1.7 ^{Ab}	0.3 ± 0.5 ^{Aa}	0.0 ± 0.0 ^{Ab}
Exchangeable Mg (mg kg^{-1})	0–20	147 ± 17 ^{Aa}	197 ± 57 ^{Aa}	168 ± 80 ^{Aa}	145 ± 3.2 ^{Aa}
	20–40	106 ± 29 ^{Aa}	150 ± 64 ^{Aa}	101 ± 91 ^{Aa}	117 ± 22 ^{Ab}
Exchangeable Ca (mg kg^{-1})	0–20	1288 ± 38 ^{Aa}	1501 ± 107 ^{Aa}	1319 ± 129 ^{Aa}	1410 ± 268 ^{Aa}
	20–40	1301 ± 110 ^{Aa}	1142 ± 108 ^{Ab}	1128 ± 413 ^{Aa}	1318 ± 311 ^{Aa}
Exchangeable P (mg kg^{-1})	0–20	20.5 ± 4.6 ^{Aa}	110 ± 114 ^{Aa}	109 ± 161 ^{Aa}	13.0 ± 6.0 ^{Aa}
	20–40	10.0 ± 5.4 ^{Ab}	23.1 ± 16.0 ^{Aa}	13.7 ± 0.4 ^{Aa}	7.7 ± 2.0 ^{Aa}
Exchangeable K (mg kg^{-1})	0–20	332 ± 114 ^{Aa}	575 ± 502 ^{Aa}	480 ± 692 ^{Aa}	204 ± 126 ^{Aa}
	20–40	178 ± 81 ^{Aa}	313 ± 259 ^{Aa}	85.5 ± 68.0 ^{Aa}	133 ± 76 ^{Aa}
Exchangeable S (mg kg^{-1})	0–20	25.5 ± 13.2 ^{Aa}	8.5 ± 1.6 ^{Ba}	10.5 ± 5.4 ^{Ba}	9.0 ± 3.2 ^{Ba}
	20–40	13.0 ± 10.6 ^{Aa}	7.5 ± 2.0 ^{Aa}	5.0 ± 2.0 ^{Aa}	6.0 ± 0.8 ^{Aa}
Exchangeable Fe (mg kg^{-1})	0–20	100 ± 11 ^{Aa}	81.0 ± 18.2 ^{Ba}	88.9 ± 24.8 ^{ABa}	120 ± 8 ^{Aa}
	20–40	93 ± 6 ^{ABa}	70.4 ± 7.2 ^{Ba}	65.9 ± 18.4 ^{Ba}	118 ± 22 ^{Aa}
Exchangeable Na (mg kg^{-1})	0–20	63.5 ± 22.4 ^{Aa}	29.6 ± 7.2 ^{Bb}	38.8 ± 7.8 ^{ABa}	35.2 ± 6.2 ^{Ba}
	20–40	61.6 ± 18.2 ^{Aa}	52.3 ± 15.4 ^{Aa}	45.1 ± 16.2 ^{Aa}	42.0± 5.4 ^{Aa}
Exchangeable Al (mg kg^{-1})	0–20	74.8 ± 4.8 ^{Aa}	55.2 ± 10.2 ^{Aa}	65.7 ± 29.0 ^{Aa}	66.4 ± 9.8 ^{Aa}
	20–40	77.0 ± 7.4 ^{Aa}	73.2 ± 24.2 ^{Aa}	74.0 ± 8.8 ^{Aa}	74.4 ± 15.2 ^{Aa}

Means followed by different uppercase superscript letters indicate a significant difference between treatments; means followed by different lowercase superscript letters indicate a significant difference between soil depths (see also Supplementary Table S2); n = number of replicates, SD = standard deviation; 6CF = 5.7 Mg ha^{-1} of compost on fresh weight (FW) basis and 72.8 N kg ha^{-1} of mineral fertilizer; 12CF = 12 Mg ha^{-1} of compost (FW) and 39.4 kg N ha^{-1} of mineral fertilizer; 16CF = 16 Mg ha^{-1} of compost (FW) and 19.5 kg N ha^{-1} of mineral fertilizer; F = 108.3 kg N ha^{-1} of mineral fertilizer only.

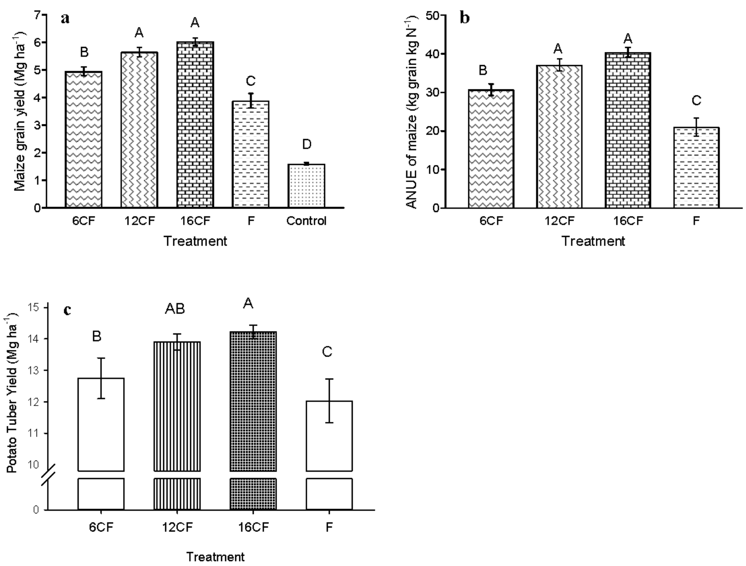

Figure 2. (**a**) Maize grain yield (MGY, dry weight), (**b**) agronomic nitrogen use efficiency (ANUE) of maize, and (**c**) potato tuber yield (PTY, fresh weight) in the different treatments of the study, 6CF = 5.7 Mg ha^{-1} compost on fresh weight (FW) basis and 72.8 kg N ha^{-1} mineral fertilizer; 12CF = 12 Mg ha^{-1} compost (FW) and 39.4 kg N ha^{-1} mineral fertilizer; 16CF = 16 Mg ha^{-1} compost (FW) and 19.5 kg N ha^{-1} mineral fertilizer; F = 108.3 kg N ha^{-1} mineral fertilizer only; Control = no input. Different letters above columns indicate significant differences between treatments ($p < 0.05$).

The ANUE was significantly higher in 12CF and 16CF compared to 6CF and significantly higher for all compost treatments (6CF, 12CF, and 16CF) compared to F (Figure 2, Supplementary Table S4). This means that compared to F, ANUE was 53% higher for 6CF, 81% higher for 12CF, and 93% higher for 16CF (Figure 2, Supplementary Table S4). Fertilizer-specific ANUE for total N supplied by the compost was in the order of 6CF > 12CF > 16CF, while for mineral fertilizer N, it was in the order of 16CF > 12CF > 6CF > F, i.e., the ANUE of the CF treatments increased with an increasing compost-N-to-fertilizer-N ratio (Supplementary Table S4).

3.7.2. Potato Tuber Yields

Compared to the F treatment, mean potato tuber yields (PTY) were higher by 8% in 6CF, 16% in 12CF, and 18% in 16CF. 16CF and 12CF were significantly higher compared to 6 CF. All treatments with compost showed significantly higher yields compared to the treatment using mineral fertilizer only (F; Figure 2, Supplemental Table S4).

3.8. Correlation between Compost and Mineral Fertilizer Inputs, Soil Properties, and Crop Yields

Soil BD, total Fe, and exchangeable Fe were positively correlated ($p < 0.01$) with the amount of N and P applied by mineral fertilizer. As the amount of mineral fertilizer increased with decreasing compost amendments, this result also indicates a negative correlation with the amount of compost applied. For BD, this is reflected in a significant positive correlation for the amount of C and N applied by compost ($p < 0.01$), whereas for total and exchangeable Fe, the correlation is not significant (Supplementary Table S5). MGY, ANUE, and PTY were all positively correlated ($p < 0.01$) with soil bulk density and total and exchangeable Fe contents (Supplementary Table S5).

3.9. Reasons for Smallholder Farmers to Use Compost

Approximately 62% of the respondents indicated that decreasing soil fertility and yields were the main reasons for the adoption of compost application. Farmers commonly stated that the traditional practice of fallow, which allows the accumulation of organic matter and nutrients, was not sufficient to produce the required yields. Approximately 26% of the respondents indicated that they were motivated by other farmers who were already producing and applying compost. Approximately 12% of the respondents indicated that the high cost and inaccessibility of mineral fertilizers were their main reasons for the adoption of compost application. Few farmers (8%) stated that they had access to credit to purchase mineral fertilizers, but most of the time, they were not able to pay back their loans. In general, farmers tended to apply their compost to fields where they grew crops with high nutrient requirements, mostly maize, but also wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), teff (*Eragrostis tef* (Zucc.) Trotter), and other crops (Figure 3). Moreover, economic returns were taken into consideration when farmers applied compost. Some farmers (7%) supplemented cereal production with vegetables, for which they could achieve higher revenues on the market (Figure 3).

The lack of organic waste was mentioned by the vast majority of farmers as a major constraint for producing and applying compost (Figure 4). In contrast, the required time, labor, and investment, as well as land tenure and lack of tools and equipment, played a subordinate role in hindering them from adopting composting and compost applications (Figure 4).

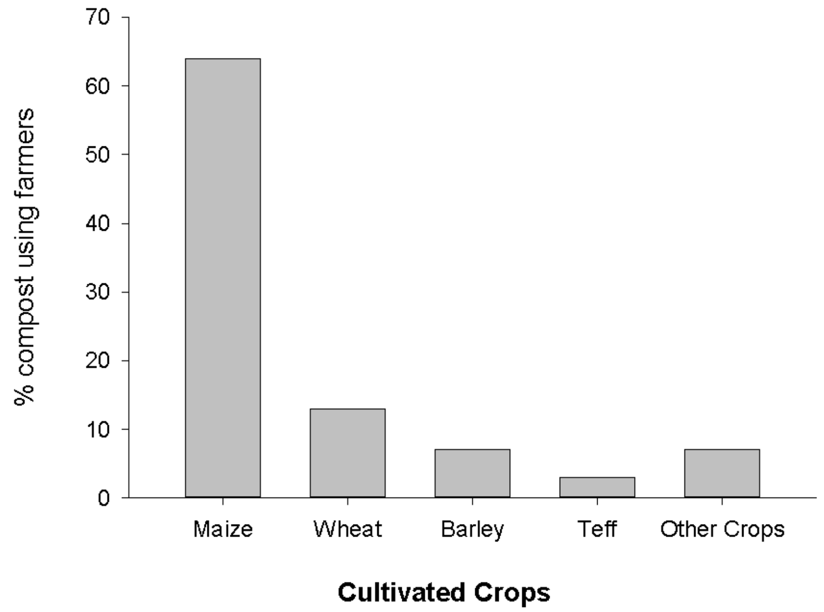

Figure 3. Compost use by smallholder farmers in Southern Ethiopia depending on the cultivated crop.

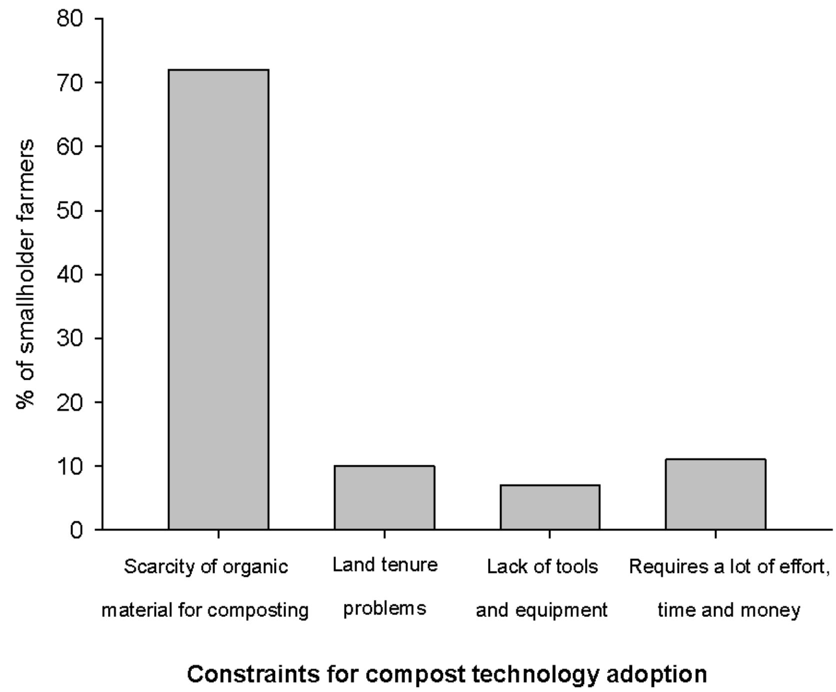

Figure 4. Constraints of smallholder farmers in Southern Ethiopia for producing and applying compost.

4. Discussion

4.1. Changes in Soil Physical and Chemical Properties

Soil from fields amended with a mixture of compost and mineral fertilizer had lower BD compared to the soil from fields amended with mineral fertilizer only (Table 2). This is in accordance with comparable studies on mid-term compost amendments and can be attributed to the mixing of low-density organic matter into the soil [56,57]. Resulting beneficial effects include, e.g., an increase in soil porosity, an improved soil structure, and aggregate stability due to interactions between organic and inorganic soil fractions [19,56–58]. These changes in physical soil properties that occur when applying compost also enable the easier penetration of plant roots and percolation of rainwater into the soil [30,57]. Furthermore, the soil will be easier to plough, due to its reduced stickiness, thereby requiring less energy for machine or animal traction [30,57]. The mixed application of compost and mineral fertilizer led to a significantly higher EC than the application of mineral fertilizer only. Organic amendments can affect soil EC by regulating several characteristics of soil fertility, such as pH, SOM, cation exchange capacity (CEC), solute concentration, and organic ligands [59,60].

However, in our smallholder study, in which compost application rates of 2.3 Mg ha^{-1}, 4.8 Mg ha^{-1}, and 6.4 Mg ha^{-1} (dry matter basis) were used by the smallholders, we could not observe any significant changes in SOM, SOC, and nutrient contents related to compost application, compared to the treatment using mineral NPS and urea fertilizer only. This was not even the case for the highest compost application rate, except for total and plant available Fe contents (Tables 2 and 3). This is in contrast to comparable studies with medium to low compost amendment for at least three years. For example, Bolduan et al. [56] reported an increase in SOM content by 0.02 to 0.05% per year for compost application rates of 2.5–3 Mg compost ha^{-1} (dry matter basis) in southern Germany. As with the study of Bolduan et al. [56], most long-term studies with medium to low compost amendment have been conducted in temperate climate regions [26,27]. However, the SOM level is a function of climate, the cropping system (including soil cultivation and crop rotation), soil N content, humus management (e.g., the use of organic amendments, green manure, etc.), and soil type [61]. Usually, a decline in SOM content is reported for intensively managed agricultural soils when applying mineral fertilizer only [62,63]. The SOM contents of home gardens and agricultural fields on Mollic Andosols in the study area, which had been converted to agricultural land only a few years ago, showed significantly higher contents of SOM of up to 6% [64] compared to the soils studied in this study. We, therefore, attribute our observation of equally high amounts of SOM (of 3.6–4.8%) and SOC (of 2.1–2.8%) for all fertilized treatments to the fast mineralization of humus in humid tropical regions due to higher average moisture and temperature favoring the microbial turnover of organic matter [65]. In addition, the lack of difference in SOM content may be related to the intensive soil cultivation during the two growing seasons of maize and potato each year combined with the removal of crop residues [60,66,67]. In this case, the increased ploughing frequency leads to increased exposure of SOM to oxidation [63]. Hence, for low to medium compost applications under tropical conditions and intensive soil cultivation, the high mineralization of organic matter, which releases nutrients and carbon, and the high nutrient uptake by potato and maize [68,69], led to no significant difference in nutrient, SOC, and SOM contents between treatments using compost and those using mineral NPS and urea fertilizer only. We therefore conclude that higher amounts of compost are necessary to significantly increase the SOM content of tropical smallholder agriculture with intensive soil management and cultivation of crops with high nutrient demand [26,70].

It also has to be considered that the longer agricultural fields are fertilized with compost, the more pronounced the increase in TOC and total N contents will be. Mayer [71] compared 18 different studies on long-term compost application. He showed that for field trials lasting three years, an increase in TOC and total N contents could not always be observed, whereas for studies lasting 4–10 years, an increase in TOC content was always reported, for total N sometimes. In contrast, for studies lasting more than 10 years, an increase in both TOC and total N contents was always reported [71]. In our study, some of the smallholder farms were practicing compost fertilization for only three years and it may be for this reason that for SOM, TOC, and nutrients contents, differences between treatments were not significant due to high standard deviations between the replicates. This observation was most obvious for exchangeable nutrient contents, especially for exchangeable K and P, with standard deviations of up to 144% and 147% of the reported mean values for K and P, respectively (Table 3).

According to Jones [72], Andosols develop from materials ejected from volcanoes, which produce allophane, imogolite, ferrihydrite, and halloysite as specific clay minerals in the course of weathering. In more humid climates, such as in the area of our study site, many Andosols develop thick and dark topsoil as a result of the fixing of organic substances by aluminum (Al) that is released from the weathering clay minerals. Andosols found along the Rift Valley in Eastern Africa have a high potential for agricultural production, but many suffer from strong P fixation due to high levels of active Fe and Al [72]. In this study, total and available Fe contents were significantly lower in fields that had been fertilized with compost, especially at a soil depth of 20–40 cm (Tables 2 and 3). Similar observations were made by Liu et al. [73], who report decreased total Fe contents in soils amended with compost.

As Carstens et al. [74] explained, the mobility of colloidal Fe-oxides is governed by soil conditions such as pH and organic matter content. For ferrihydrites, potentially present in the Andosol soils of the study site, this pH-dependent mobility is related to their point of zero charge (PZC). Below neutral pH, Fe-oxides are usually positively charged due to their relatively high PZC, which ranges between pH 7 and 9 for synthetic ferrihydrites and between 5.3 and 7.5 for naturally occurring ferrihydrites [74,75]. As most other soil minerals are negatively charged below neutral pH, Fe-oxide colloids are immobilized under these conditions [76]. Considering the trend in pH increase for soils with compost application in this study (Table 2), a change in surface charge of the ferrihydrite minerals may have occurred, thereby leading to increased mobility and therefore to leaching of Fe from the upper soil layers from 0–40 cm to deeper soil layers. Furthermore, Carstens et al. [74] and Yan et al. [77] observed increased Fe-oxide-colloid mobility with increasing dissolved organic matter (DOM) content. They explained this finding with a coating of colloids with humic acids, which reverse the surface charge to negative, thereby increasing the mobility of the colloids. We therefore attribute the lower total and available Fe contents in fields with compost application compared to fields fertilized with mineral fertilizer only, to the effect of colloid dynamics, strongly altered by the change in pH. Furthermore, we hypothesized that an increase in DOM contents in the fields amended with compost may be responsible for the increased mobility and leaching of Fe-containing colloids, at least in the first 40 cm of the soil.

The significantly higher CEC in the combined compost–mineral fertilizer treatments 12CF and 16CF compared to mineral fertilizer only (F) can be attributed to the compost amendment, which increased CEC as a result of the input of stabilized organic matter rich in functional groups. SOM contributes 20–70% of CEC in many soils [78,79]. However, worldwide SOM contents tend to decline due to continuous mineral N-fertilizer application without any additional input of organic material [62,63]. In the ploughing horizon, with its higher SOM content, CEC is usually higher, whereas in the subsoil, SOM content, and thereby CEC, decreases [63], which is also in accordance with our findings (Table 2). CEC is one of the most important indicators of soil fertility, especially for nutrient retention, as a high adsorption capacity prevents nutrient cations from leaching into the groundwater [63].

For treatment using mineral fertilizer only (F), total and plant-available Fe contents were significantly higher compared to the treatments with combined compost and mineral fertilizer application (Tables 2 and 3). In line with comparable studies [56,80], the pH in soil amended only with mineral fertilizer tended to be lower compared to soils additionally fertilized with compost (Table 2). This is important to note because, in Andosols, plant-available P is limited due to sorption and fixation with Al and Fe components, particularly in soils with low pH [72,81,82]. Nobile et al. [82] reported that after 10 years of organic fertilization of Andosol, pH had increased in all organic fertilizer treatments, resulting in a decreased P sorption and an increasing P concentration in the soil solution. Furthermore, Takeda et al. [83] showed that even short-term compost application improved the mineralization of organically bound P in Andosols. Therefore, it is in accordance with the above-cited literature that the treatments fertilized with compost (especially CF12 and CF16) tended to have higher exchangeable P contents (Table 3). It can thus be concluded that compost application was beneficial for the soil fertility of smallholder farmer fields, as it led to decreased soil bulk density and Fe contents, as well as increased pH, CEC, and plant available P (even though this increase was not significant).

4.2. Maize Grain and Potato Tuber Yields

The ANUE of cereal crops is a function of their ability to obtain N from the available supply and the efficiency with which N is used to produce grains [84]. ANUE in this study ranged from 29.4 kg (kg N)$^{-1}$ in 6CF to 40.1 kg (kg N)$^{-1}$ in 16CF, which was similar to previous observations of an increase in ANUE for fields with combined fertilization of organic amendments and mineral fertilizer in SSA (34.3 kg (kg N)$^{-1}$ [85] and 36 kg (kg N)$^{-1}$ [34].

Although the total N input was similar in all fertilizer treatments, the combined application of compost and mineral fertilizer increased MGY (23.3–55.3%) and ANUE (36.5–81.3%) compared to the application of mineral fertilizer only. This is even more remarkable, given that only 25–34% of the total N in the compost is plant-available in the first year after application, even at the higher temperatures prevailing in the tropics [61]. In temperate regions, this range is even lower; here a maximum of 15% of total N are mineralized in the first year, and 3–8% in the following years [61]. In the long-term, however, mineralization rates will increase, as Diez and Krauss [86] suggest. They found that in a 21-year field experiment with waste compost, 16% of the total compost N was taken up by plants, but in the final year, this figure rose to over 40% of the applied total N, suggesting that this amount can be attributed to the effect of the enhanced mineralization potential after 20 years of compost application in addition to the effect of fresh compost addition [61]. Hence, considering that not all N of the compost is available in the first year after application, but only a maximum of 25–40% of total N (depending on the number of years of compost application before; [61]), the long-term ANUE of the compost treatments will very likely be even higher. Assuming the maximum possible N availability (N_{av}) of 40% of total N applied in our study by compost in the first year after application, the following amounts of N would become available in the different mineral fertilizer and compost treatments: 108.3 kg N_{av} ha^{-1} for F, 85.4 kg N_{av} ha^{-1} for 6CF, 66.3 kg N_{av} ha^{-1} for 12CF, and 55.3 kg N_{av} ha^{-1} for 16CF (Supplementary Table S4). Hence, all compost-amended treatments were only providing a sub-optimal supply of available nitrogen, with decreasing N_{av} contents and increasing compost amendments. Calculating the ANUE, which takes into account the amount of N_{av} from organic and mineral fertilizer, would provide the following results: 21.0 kg grain (kg N_{av})$^{-1}$, 39.2 kg grain (kg N_{av})$^{-1}$, 61.1.4 kg grain (kg N_{av})$^{-1}$, and 123 kg grain (kg N_{av})$^{-1}$, for F, 6CF, 12 CF, and 16 CF, respectively (Supplementary Table S4).

Bearing this in mind, the yield increase for both maize and potatoes, with increasing compost and decreasing mineral fertilizer application (Figure 2), is even more astonishing, as those yields were produced with decreasing amounts of available N (due to the low mineralization of total N from compost). One reason could be the potentially better P supply in the compost treatments (Table 3). Andosols tend to fix P, especially under acidic soil conditions [72]. Hence, the rise in pH upon increasing compost amendments and the resulting increased contents of exchangeable P, together with the potentially increased abundance of arbuscular mycorrhizal fungi, could have increased plant availability of P significantly [72,81,82,87].

As displayed by our findings, compost application in sufficient quantities and sufficient periods of time could be an effective nutrient management strategy to (i) improve maize yields [80,88,89], (ii) improve soil fertility by enhancing nutrients contents, CEC, and pH, and reducing soil bulk density [61,80], and by (iii) improving soil structure and soil aggregates, thereby facilitating root growth [90]. With regard to ANUE based on the available nitrogen contents (Supplementary Table S4), it is suggested that even higher compost amounts could be applied for further yield increases and in order to increase nutrient and humus contents of smallholder farmer fields.

The MGY, ANUE, and PTY were significantly ($p < 0.05$) negatively correlated ($p < 0.01$) with BD, total Fe, and exchangeable Fe (Supplementary Table S4). On the basis of our previous discussion, these results can be explained in two ways. First, changes in soil biological and physical properties, mediated by compost application, could have increased crop performance. Compost applications directly enhance crop growth by improving the availability of soil nutrients [19,80,89] and increase root growth by improving soil structure, soil aggregation, and increasing CEC [90]. Second, the application of compost (plus mineral fertilizer) can improve soil water availability due to organic matter accumulation and increased root zone exploitation of water by healthier plants [91]. Hence, due to these changes in soil biological and physical properties as well as water availability, ANUE was positively affected.

4.3. Socioeconomic Constraints on the Use of Compost

Farmers were well aware of the compost's function in maintaining yield and improving soil quality. After learning from other farmers' experiences, 26% of the farmers in the study area adopted the composting practices, demonstrating the critical role of experience sharing from farmer to farmer. The adoption of compost applications was constrained by several factors. First, land tenure was considered an important factor influencing the adoption of compost applications, especially for women and young people. Compost production requires investment in time, organic resources, and labor, so farmers are willing to apply compost only if they have the appropriate land tenure rights [33]. Second, some farmers cannot afford to buy the equipment required for producing compost, such as pickaxes, wheelbarrows, and donkey carts. Third, compost production is very labor-intensive, hindering the adoption of compost application by farmers, in particular those with a limited workforce [30]. Fourth, there is usually not enough organic material available to produce sufficient amounts of compost, as organic wastes are often used as fodder for livestock or fuel for cooking [33]. It is thus common that farmers frequently prioritized compost use for vegetables over cereals due to their high market value. All these points suggest that the facilitation of an alternative credit system and/or subsidy would help farmers to increase their compost production and acquisition of equipment for transport [30,33].

The scarcity of organic material is the primary constraint to compost production at smallholder farms. However, organic resources for composting could be obtained by smallholder farmers in adjacent towns or cities. Increasing waste generation was reported, for example, for the town of Shashemene, which is close to the study area. This waste consisted of up to 76–84% of organic waste, mainly vegetable and fruit wastes, as well as animal manure and human excreta [92]. If organic wastes are processed safely, e.g., by thermophilic composting, even human excreta can be considered a nutrient-rich resource that can help to meet the need for low-cost complete fertilizers for smallholder farmers [46,93–95]. During composting, organic waste will be transformed into humus, while pathogens and weed seeds will be destroyed, and organic pollutants will be degraded by microbial activity and the high temperatures of the thermophilic composting process [95–97].

The transportation of bulky material to agricultural fields is a major difficulty associated with organic waste recycling in rural agricultural communities. The advantage of composting is its reduction of the amount and volume of organic waste because the fresh materials lose about 50% of their mass during thermophilic composting [98]. This point thus highlights the importance of compost production in the cities, where the majority of waste is produced and dumped [92], in order to reduce transportation costs.

The potential amount of compost made from human excreta and organic wastes from Shashemene was estimated at approximately 11,732 Mg compost year^{-1} (on a dry weight basis) [92]. This amount would be sufficient for fertilizing 460 ha year^{-1}, when used at an application rate that completely substitutes mineral fertilizer [92]. When combined with mineral fertilizer, this area could even be increased. Recycling nutrients from urban organic waste could thus be a way to close the nutrient cycle between urban and rural areas. This strategy could help smallholders not only to improve soil fertility and food security but also combat climate change because humus that is built up in the course of composting is sequestered after soil application if applied in sufficient quantities [26,99].

5. Conclusions

The combined long-term use of compost and mineral fertilizers at smallholder farms increased soil fertility, ANUE and maize as well as potato crop yields, compared to mineral fertilizer application only. However, the lack of a significant change in soil organic matter and carbon contents suggests suboptimal compost management in view of the humid tropical environment, intensive soil cultivation, and high nutrient demanding crops. Hence, higher compost applications of more than 6.4 Mg ha^{-1} compost (dry weight basis) could bring additional benefits. Farmers were aware of the benefits of compost application and indicated a lack of adequate organic material, intensive labor, and facilities required for compost production as major socioeconomic constraints that hindered the adoption of compost production and application at a larger scale.

Making appropriate use of organic resources and/or wastes by composting is critical for increasing soil fertility and food production. Therefore, creating an enabling environment is required to address constraints hindering increased compost production. Furthermore, it is necessary to strengthen linkages between rural and urban dwellers in terms of high-grade compost production for agricultural use. Our findings highlight the importance of local urban compost production as a strategy to supplement mineral fertilizer application. By this means, the dumping of organic waste in cities could be reduced, while tackling the lack of organic resources for composting simultaneously. Further integrated research and development activities are needed to overcome shortages in organic fertilizer and to investigate further site-adapted methods for increasing soil fertility, such as crop rotation, green manuring, or crop residue management, in order to increase yields while sequestering carbon in the form of humus. In this regard, intensive monitoring of plant performance reflecting the nutritional and water status of the plants, e.g., by using chlorophyll fluorescence or hyperspectral imaging of plant stands, will also help to assess the efficacy of organic fertilizers. Finally, adapting smallholder agriculture to the adverse impacts of climate change, soil degradation, and increasing mineral fertilizer prices by the increased use of organic fertilizers could be a sustainable solution for ensuring food security.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11060784/s1, Supplementary Table S1. Soil particle size fraction and soil textural classes in 0–20 and 20–40 cm soil depth; Supplementary Table S2. Summary of two-way analysis of variance (ANOVA), results for physicochemical soil properties in relation to treatment (6CF, 12CF, 16CF, and F) and soil depth (0–20 cm and 20–40 cm) and their interaction; Supplementary Table S3. Summary of Pearson correlation of carbon from compost amendments, nitrogen from mineral fertilizer and compost amendments, and phosphorus inputs from mineral fertilizer amendments related to soil properties; Supplementary Table S4. Total and available nitrogen applied with mineral fertilizer and compost, potato tuber and maize grain yield, and agronomic nitrogen use efficiency of maize; Supplementary Table S5. Summary of Pearson correlation between soil properties and crop yields.

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