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Combined Use of Organic and Inorganic Fertilizers Improved Maize (*Zea mays*) Yield and Soil Organic Carbon Stock in Lowland Dry Areas of Ethiopia

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Abstract

Organic fertilizers can improve soil organic matter and enhance the productivity of agricultural soils. Ten treatments consisting of various combinations of vermicompost (VC) or bioslurry compost (BSC) with Urea as sources of recommended N rate, were evaluated to determine the best combination of organic and Urea fertilizers for maize production and soil organic carbon (SOC) stock. The treatments, laid down in randomized complete block design with three replications, were evaluated on fixed-plot during 2020-2022 cropping seasons in Melkassa Agricultural Research Center. Analysis of variance revealed significant ($P<0.05$) seasonal and treatment differences. The combined application of N equivalence-based 25:75 VC to Urea demonstrated significantly higher above-ground biomass yield. Comparable grain yield was obtained for combined application of VC or BSC with Urea in various proportions as compared to entire application of recommended N rate from Urea. This was in contrast to application of the entire recommended N rate solely from organic sources. Application of organic sources, either alone or in different combinations with Urea, resulted in a 12-14% enhancement in SOC stock compared to using inorganic fertilizer exclusively. Partial budget analysis indicated the highest net benefits (ETB 228,284.1 per ha) and Marginal Rate of Return (MRR=1049.9%) for N equivalence-based 25:75 VC to Urea combinations followed by the entire N application from urea. Thus, combined use of organic and inorganic fertilizers is advised not only for yield improvements but also for their added benefits for soil health and climate change adaptation that are not accounted in the current economic analysis.

Key words: Bioslurry compost, vermicompost, maize yield, soil organic carbon stock, dryland, Melkassa Agricultural Research Center

Introduction

Inorganic fertilizers have significantly boosted crop yields by supplying essential plant nutrients in the form that is readily available to plants. However, the continuous use of mineral fertilizers without recycling organic matters to farmlands has caused negative impacts on farmland productivity and has also constrained other ecosystem functions (Hasler, 2017; Liu et al., 2017; Nsengimana et al., 2023; Wang et al., 2016). On the other hand, organic inputs are vital not only for increasing agronomic yield, but also for improving nutrient cycling and use efficiencies, as well as regulating ecosystem services in general (Diacono & Montemurro, 2010; Zhu et al., 2023).

Most small holder farmers in Ethiopia apply suboptimal rate of inorganic fertilizers due to escalating prices. In cereal based production of the central highlands of Ethiopia, depletion of soil nitrogen ranging from -23 to -28 kg ha^{-1} $year^{-1}$ (Amare et al., 2006; van Beek et al., 2016) has been reported. Depletion of SOC has also become among evident contributing factors to low productivity of agricultural soils in Ethiopia. Average negative balance, reaching about 3.7 t ha^{-1}, was reported for SOC in cereal based farming systems (Van Beek et al., 2019). Nutrient removal with crop yield and crop residue removal on top of low or no addition of organic resources to farm lands have contributed to the negative balances. The SOC depletion is identified as the most important soil level bottleneck in the strategy document for the Transformation of Soil Health and Fertility in Ethiopia.

The SOC is cross-linked with other multiple soil related problems such as degradation of soil physical, chemical and biological properties (Skinner et al., 2023). Soil organic carbon is of crucial importance to improve soil nutrient stocks and its productivity, soil moisture holding capacity, soil biological activities and other various ecosystem services (Milne et al., 2015). Carbon stocks in dryland soils are generally low due to high temperature and evapotranspiration, low moisture and coarse textured sandy soils common to those areas. These factors generally limit the primary productivity (Skinner et al., 2023; Tondoh et al., 2016) and hence the level of soil carbon stock and yields. The SOC depletion is also reported to result in low fertilizer use efficiencies (Lulseged et al., 2017; Tang et al., 2022) and generally impart a serious concern to the sustainability of agricultural production.

Interventions to alleviate SOC depletion have potential link to solve other multiple bottlenecks related to soil physical, biological, and chemical properties (Sharma, 2022; Voltr et al., 2021). Studies conducted in the highland areas of Ethiopia have shown the potential and benefits of using organic fertilizers in combination with inorganic fertilizers (Girma and Gebreyes, 2017; Habtamu, 2015; Melkamu et al., 2021; Teklu and Teklewold, 2009; Zerssa et al., 2021). The authors recommended integrated use of properly managed organic sources and low rates NP fertilizers to get yield advantages reaching up to 14.2% in crop production in the studied areas. They also demonstrated considerable improvement in SOC due to application of organic sources in combination with mineral fertilizers. Proper management practices are, therefore, needed to favor soil's sustainable productivity to adapt to the changing climate and enable provision and regulation ecosystem services. However, there is dearth of research results on proper proportions of the combined use of organic and urea as N source for optimum agricultural production and soil quality in lowland areas of Ethiopia. Hence, this experiment was conducted to identify the best combination of vermicompost or bio-slurry compost and urea as N source for maize production, and its effect on SOC content at Melkassa Agricultural Research Center, Ethiopia.

Materials and Methods

Description of the study area

The experiment was conducted on a fixed plot during 2020 to 2022 cropping seasons at Melkassa Agricultural Research Center (MARC) in east Shewa zone of Oromia region, Ethiopia. The experimental plot in the MARC is located at coordinates of 8.41515N and 39.32112E with an elevation of 1549 meters above sea level. The long term mean annual total rainfall from MARC weather station was 818 mm with erratic distribution. The main rainy season is from June to September. The annual average minimum and maximum temperatures are 14.1 and 29.1 ^{o}C, respectively (Fig 1). The soil type of the experimental site is well drained loam soil genetically classified as Mollic Andosols (Abayneh et al., 2005).

The land-use system of the smallholder farmers surrounding MARC is mainly crop-livestock mixed farming under open canopy of remnant acacias. Crop production is both under rain-fed and irrigation, and the major crops produced in the area include tef, maize, wheat and common bean.

Treatment setup and experimental design

The experiment evaluated the following ten treatments (Table 1).

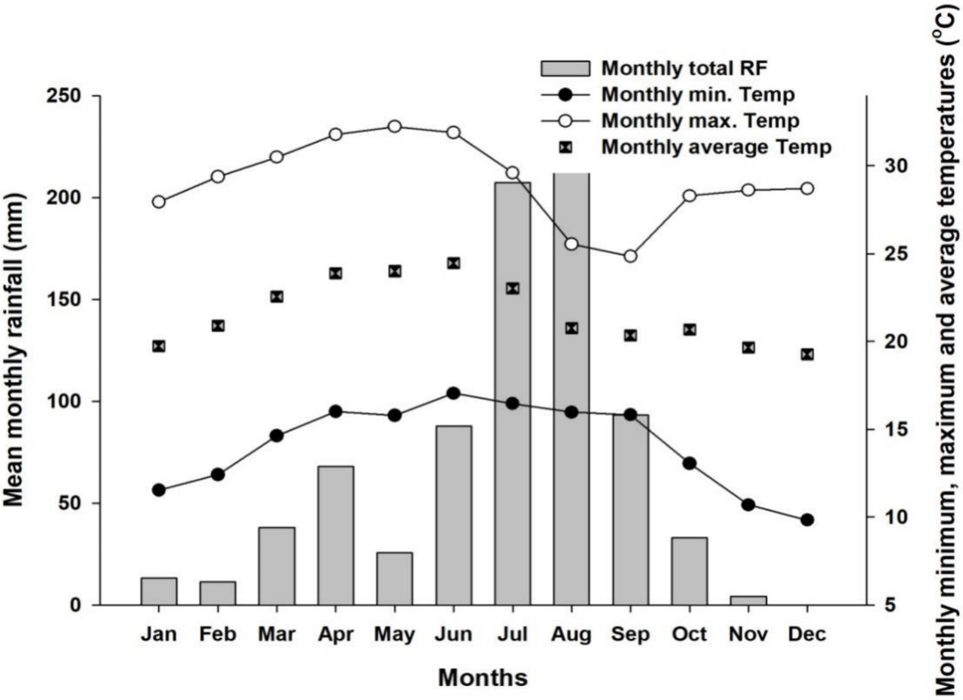

Figure 1. Mean monthly total rainfall (RF), and mean monthly minimum (min), maximum (max) and average temperatures (Temp) at MARC.

Data source: MARC: Climate, Geospatial and Bio-metrics Research Process (2019-2022), Ethiopia.

Table 1. Treatment setup and amount of nitrogen applied from different sources.

Treatments	**N sources**		**Total N (kg ha^{-1})***
	VC or BSC (kg ha^{-1})	Urea (kg ha^{-1})	
No N fertilizer (Negative control)	0.0	0.0	0.0
Rec. N: 100% Urea (Positive control)	0.0	46.0	46.0
Rec. N: 25% from VC+75% from Urea	11.5	34.5	46.0
Rec. N: 50% from VC+50% from Urea	23.0	23.0	46.0
Rec. N: 75% from VC+25% from Urea	34.5	11.5	46.0
Rec. N : 100% from **VC**	46.0	0.0	46.0
Rec. N: 25% from **BSC+75%** from **Urea**	11.5	34.5	46.0
Rec. N: 50% from **BSC+50%** from **Urea**	23.0	23.0	46.0
Rec. N: 75% from **BSC+25%** from **Urea**	34.5	11.5	46.0
Rec. N: 100% from **BSC**	46.0	0.0	46.0

Rec. N = recommended nitrogen rate, VC = vermicompost, BSC = bio-slurry compost

*The recommended rate of fertilizer for Maize in the study area was 46 kg ha^{-1} N and 20 kg ha^{-1} P.

Treatments were arranged in randomized complete block design and replicated three times. Prior to application of the organic fertilizers, their moisture content and nitrogen concentration were determined following standard laboratory procedures. Then, the amount of organic sources to be applied to each plot was calculated for both organic fertilizers based on the recommended mineral N equivalence. Maize MH-140 hybrid variety was used in 2020 cropping season while open pollinated Melkassa-2 variety was used during 2021 and 2022 cropping seasons based on onset of the rainy season. Both maize varieties are released for low-moisture stressed areas except MH-140 is preferred for its higher yield when sufficient rainfall is received and the soil moisture is adequate for early May planting (MoA, 2013; MoARD, 2004).

A 3.75 m x 4.00 m plot was used. Two seeds per hole were planted at 25cm and 75cm spacing between plants and rows, respectively. The spacing between plots and blocks were 0.50m and 1.00m, respectively. Then, thinning down to one plant per hole was done in two to three weeks' time after emergence.

Each year, the vermicompost and bioslurry compost were manually applied three weeks before sowing and mixed in to the soil to a depth of 15 to 20 cm. Urea, as source of mineral N, was applied at the respective rate to each plot in two splits: 1/3rd at sowing and the remaining 2/3rd at about 35 days after sowing (knee height stage). The recommended rate of P, 20 kg ha^{-1}, was uniformly applied to all plots in the form of triple super phosphate (TSP) as basal application at planting. In the first year of the experiment, primary and secondary tillage was done by tractor before organic inputs were applied. For the following two years, hand hoeing was used to avoid the mixing or transfer of soils from one plot to the next. Hand weeding and other agronomic management practices were applied uniformly to all plots as per the recommendation for the test crop.

Preparation and application of vermicompost and bioslurry compost

The inputs used for the preparation of vermicompost were chopped maize straw and common bean residues mixed with animal manure. These materials were used as bedding and feedstock to *Esneai fetida* earthworm. Bioslurry compost was purchased from a farmer. According to the information obtained from the farmer and observation made on the preparation of bioslurry compost at farmer site, crop residue mainly bread wheat straw was mixed with bioslurry produced from a biogas plant fed with animal manure. Some of the chemical properties of vermicompost and bio-slurry compost are shown in Table 2.

Table 2. pH, OC and N (%), and C:N ratio of the vermicompost and bioslurry compost used for the experiment

Organic source	Cropping seasons	pH (1:2.5 soil to H_2O) (Jackson, 1958)	OC (%) (Walkley and Black, 1934)	Kjeldahl total N (%) (Bremner, 1996)	C:N ratio
Vermicompost	2020	7.1	11.3	1.72	6.57
	2021	7.6	11.5	1.66	6.93
	2022	7.4	12.1	1.37	8.83
Bioslurry compost	2020	7.6	12.4	0.49	25.31
	2021	7.9	12.2	0.49	24.96
	2022	7.7	13.0	0.51	25.51

The amounts of organic sources applied to maintain the recommended N rate were based on their moisture and N contents. Accordingly, to maintain 46 kg N ha^{-1}, 9.01, 9.01 and 9.33 t ha^{-1} of bioslurry compost was applied in 2020, 2021 and 2022 cropping seasons, respectively. For the vermicompost, 2.77, 3.02 and 3.34 t ha^{-1} was applied to fulfill the same recommended rate of N in 2020, 2021 and 2022 cropping seasons, respectively.

Data collection

Soil sampling and laboratory analysis

Prior to treatment applications, a soil sample composed of 10 sub-samples from surface layer (0-20 cm) was collected from the entire experimental site and prepared. After the 3rd year crop harvest, 5 soil sub-samples were collected from the same depth for each plot to make one composite sample per plot. The collected composite soil samples were air dried and ground to pass through a 2 mm sieve, and subjected to laboratory analysis. Standard laboratory analytical techniques used and the laboratory analysis results for the selected soil parameters prior to treatment application are shown (Table 3).

Table 3. Selected soil properties of the study site before treatment application in 2020 cropping season

Selected soil parameters	Values	References for laboratory analysis procedures
pH (1:2.5 soil to H_2O)	6.69	Jackson, 1958
Electrical conductivity (1:2.5 soil: H_2O) (dSm^{-1})	0.17	Sonmez et al., 2008
Soil organic carbon (%)	1.61	Walkley and Black, 1934
Kjeldahl total N (%)	0.13	Bremner, 1996
Clay (%)	16	Bouyoucos, 1962
Silt (%)	34	
Sand (%)	50	
Textural class	loam	USDA, 1999
Bulk density (g/cm3)	1.2	

Composite soil samples collected after crop harvest in the third cropping season were also analyzed following the standard lab procedure (Table 3) for each plot. Bulk density was determined from undisturbed soil samples to the depth of 20 cm using core sampler (Blake and Hartge, 1986). Then, soil organic carbon percent was determined (Walkley and Black, 1934) and then soil organic carbon stock in Mg ha^{-1} was calculated for each treatment using the following formula.

$$SOC\ stock\ (Mg\ ha^{-1}) = SOC\ (mg\ per\ gram\ of\ soil) * BD\ (gram\ per\ cm^{3}) * (1 - CF) * SD\ (cm) * 0.1$$

where, BD represents soil bulk density, CF is coarse fragment factor in the soil (in %) which was zero at this experimental site and SD is soil sampling depth.

Plant growth and yield data

Plant height was measured for ten plant samples per plot from the ground surface to the tip of the plant, excluding tassel. The aboveground parts of the inner 3 rows of plant samples were harvested to determine the above ground total biomass (AGB) and grain yields. The harvested plant samples were air dried for about 15 days and weighed to determine the AGB in kg per plot. Then, ears were removed and dehusked manually and weighed using electronic balance to determine ear weight per plot. The grains were shelled manually and weighed to determine grain yield. Grain moisture contents were determined for three samples for each plot and the average was used to adjust grain yields to 12.5% moisture content. Stover/straw harvest was calculated by subtracting grain yield from the AGB. All yield and yield related parameters were calculated per hectare base using plot level determined data.

Yield harvest relative to the negative control (%) was determined for each treatment using the following formula:

$$HRC\ (\%) = \frac{Yield_{trt}}{Yield_{ctrl}} * 100\%$$

where HRC represents yield harvest relative to the control (%), $Yield_{trt}$ is mean yield harvest from N fertilizer applied plots in either organic or mineral, or in combination, and $Yield_{ctrl}$ is mean yield harvest from the negative control plots. The yield harvests considered in this calculation are grain and above ground biomass yields.

Data analysis

The soil laboratory analysis results, plant growth and yield data were subjected to statistical analysis using R (R development core team, 2023). A model of analysis of variance (ANOVA) for F fertilizer treatments, S cropping seasons and r replications of the following forms were considered.

$$Y = \mu + F + S + (F * S) + \varepsilon$$

where Y is the measured value, μ is the grand mean of the measured value, F is the fertilizer treatment based on the source and rate of application (kg ha^{-1}), S is cropping season, F*S is interaction effect of fertilizer and cropping season, and ε is the error term. Then, treatment mean separations were done using least significant difference (LSD) test at 0.05 level of probability (Gomez and Gomez, 1984) when significant differences are observed between treatments. Pearson correlation analysis was also done among yield component parameters and grain yield to confirm relationship among the selected plant parameters.

Economic analysis

Partial budget analysis was done following the procedure indicated by CIMMYT (CIMMYT, 1998) to identify the rewarding treatments based on the economic benefits and help farmers to make decisions either to shift their current practice or not. To account for management differences, the grain and straw yields from each treatment were adjusted down by 10% to reflect the yield that farmers could expect from the same treatment. The selling price of urea, bioslurry compost and vermicompost, and labor costs for their application in the field were considered as total costs that vary. The gross benefit (GB) was calculated as a product of adjusted yield (straw and grain yield) and their respective selling prices. Then, net benefit (NB) was calculated as gross benefit minus the total cost that varies. Finally, the marginal rate of return (MRR%) was determined from the marginal difference of net benefit divided by the marginal difference of total variable cost multiplied by 100%.

Three years average market prices of straw and grain (ETB 10 and 21.9 per kg, respectively), farm-gate price of urea, vermicompost and bioslurry compost fertilizers (ETB 31.58, 3 and 1 per kg) and labor cost for organic fertilizer applications (valued at ETB 800 and 1400 per ha for 100% recommended N from vermicompost and 100% recommended N from bioslurry compost, respectively) were considered for the economic analysis.

Result and Discussions

Plant growth, yield and yield related parameters

Results of analysis of variance for cropping seasons, treatments, and their interaction are presented (Table 4). For all the plant parameters considered in this analysis, there was no significant ($P>0.05$) interaction effect between years (cropping seasons) and treatments. However, treatment differences combined over the years showed highly significant ($P<0.001$) variation on above ground biomass (AGB), gain yields, and their harvest relative to the negative control (HRC). Cropping seasons differences also led to significant ($P<0.05$) differences in plant height, AGB, grain yields, and the grain HRC.

Table 4. Significance level of analysis of variance of cropping season, treatment and treatment by season interaction effect on growth, yield and yield components of maize at Melkassa during 2020-2022 cropping seasons

Source of variation	Plant height (cm)	Above ground biomass (kg ha^{-1})	Above ground biomass HRC (%)	Grain yield (kg ha^{-1})	Grain HRC (%)	Harvest Index (%)
Cropping season (S)	<0.0001	0.02295	0.64419	<0.0001	<0.0001	0.1004
Treatment (Trt)	0.10153	<0.0001	0.00284	<0.0001	<0.0001	0.2247
S*Trt	0.80320	0.07098	0.53621	0.1124	0.1023	0.7945
Mean	212.9	16281.0	126.5	6006.5	124.7	37.03
CV (%)	4.59	10.63	14.44	10.74	10.68	8.62

HRC (%) = Harvest relative to the negative control

Plant heights, AGB, grain yield, and grain HRC in 2020 were significantly ($P<0.05$) superior to that of 2022 (Table 5). However, there was no significant difference between 2020 and 2021 in AGB and grain yields. The plant height, grain yield and grain HRC of the 2022 cropping season were significantly ($P<0.05$) lower than those of 2020 and 2021. The higher rainfall received in the 2020 cropping season was responsible for the better yield recorded in the 2020 cropping season.

The amount and distribution of in-season rainfall received during the experimental periods (Fig 2) clearly depict the variety responses to rainfall. The 2020 seasonal rainfall (918.8 mm), received from May 1st to the end of September, was higher than same duration in of the 2021 or 2022, which were 468.0 mm and 516.8 mm, respectively. However, in the 2022 cropping season, rain started late (in the second week of June) unlike the earlier starting dates in 2020 and 2021 cropping seasons. There were 10 consecutive days of dry-spell with only 9 rainy days (76.9 mm) between day 82 to 113 starting from May 1 for the 2022 cropping season while there were 17 rainy days (178.8 mm) during the same period in the 2021 cropping season. The plant growth and development stages during these days are in the fast vegetative growth and sensitive reproductive stages. The observed rainfall that likely limited moisture and nutrient availabilities to the crop is critical to reduce growth and yield of the crop in the 2022 cropping season. Hence, the in-season rainfall amount and its distribution are critical and attributable factors to the significantly ($P<0.05$) low plant growth and grain yield recorded in the 2022 cropping season (Fig 2).

The different treatments did not show a consistent trend in their performance to the variation of rainfall between the seasons. However, the organic source containing treatments were expected to perform better than sole inorganic fertilizer applications in short dry-spells, as long as other conditions were not limiting their growth. In the current result, the soil improvement status could be not sufficient to offset the effects of the dry-spells and the rainfall distribution occurred in the season.

Except for plant height and harvest index (HI), the combined analysis of effects of the treatments over the cropping seasons showed that all the treatments were better than the negative control (no N fertilizer applied) (Table 5). This indicates the potential of combining organic and inorganic fertilizers to produce grain yield comparable to that obtained from applying 100% of the recommended N from urea. The combined application of 25% of the recommended N from VC and the remaining 75% N from urea was found to be significantly ($P<0.05$) better in terms of the AGB, grain yield, and AGB and grain yields HRC compared to the negative control and applying 100% of the recommended N from either of the organic sources. In contrast, the negative control and applying 100% of the recommended N from organic sources resulted in 24% and 9% yield loss, respectively, compared to applying 100% of the recommended N from urea.

Table 5. Main effect of cropping season and treatment differences on growth, yield and yield components of maize at Melkassa during 2020 to 2022 cropping seasons

Variable factors	**Growth, yield and yield components**					
	Plant height (cm)	Above ground biomass (kg ha^{-1})	AGB HRC (%)	Grain yield (kg ha^{-1})	Grain HRC (%)	Harvest Index (%)
Cropping seasons						
2020	224.0a	16802.6a	125.93	6314.6a	133.0a	37.62
2021	211.4b	16465.9ab	128.85	6135.0a	125.4b	37.48
2022	203.4c	15574.5b	124.50	5569.9b	115.6c	36.00
LSD (5% significance level)	5.05	894.72	Ns	333.5	6.88	Ns
Treatments						
No N fertilizer (negative control)	202.6	12949.7d	100.0c	4819.4d	100.0d	37.5
Rec. N: 100% Urea (positive control)	217.1	16603.2bc	129.0ab	6377.3ab	132.2ab	38.4
Rec. N: 25% from VC+75% from Urea	215.1	18333.6a	142.2a	6441.6a	133.9a	35.3
Rec. N: 50% from VC+50% from Urea	213.1	15934.1bc	123.8b	6288.1ab	130.6ab	39.6
Rec. N: 75% from VC+25% from Urea	210.2	16147.2bc	125.2ab	5947.0abc	123.5abc	36.9
Rec. N: 100% from VC	215.2	16000.5bc	124.5b	5809.4bc	120.5bc	36.5
Rec. N: 25% from BSC+75% from Urea	211.3	16753.8abc	131.0ab	6176.0abc	128.2abc	36.9
Rec. N: 50% from BSC+50% from Urea	216.9	16935.9abc	130.5ab	6246.7abc	129.7abc	37.0
Rec N: 75% from BSC+25% from Urea	212.7	17417.0ab	134.9ab	6283.8abc	130.3abc	36.0
Rec N: 100% from BSC	215.1	15735.0c	123.1b	5676.0c	117.8c	36.2
Grand mean	212.9	16281.0	126.43	6006.50	124.69	37.0
LSD (5% significance level)	ns	1633.52	17.23	608.80	12.57	Ns
P-value	0.10153	<0.0001	0.00284	<0.0001	<0.0001	0.2247
CV (%)	4.59	10.63	14.44	10.74	10.68	8.62

AGB= above ground biomass; Rec. N= recommended nitrogen; VC = Vermicompost; BSC = Bioslurry compost; HRC= Harvest relative to the negative control; NS = no significant difference; Means within same column followed by same letter(s) are not significantly different (P> 0.05)

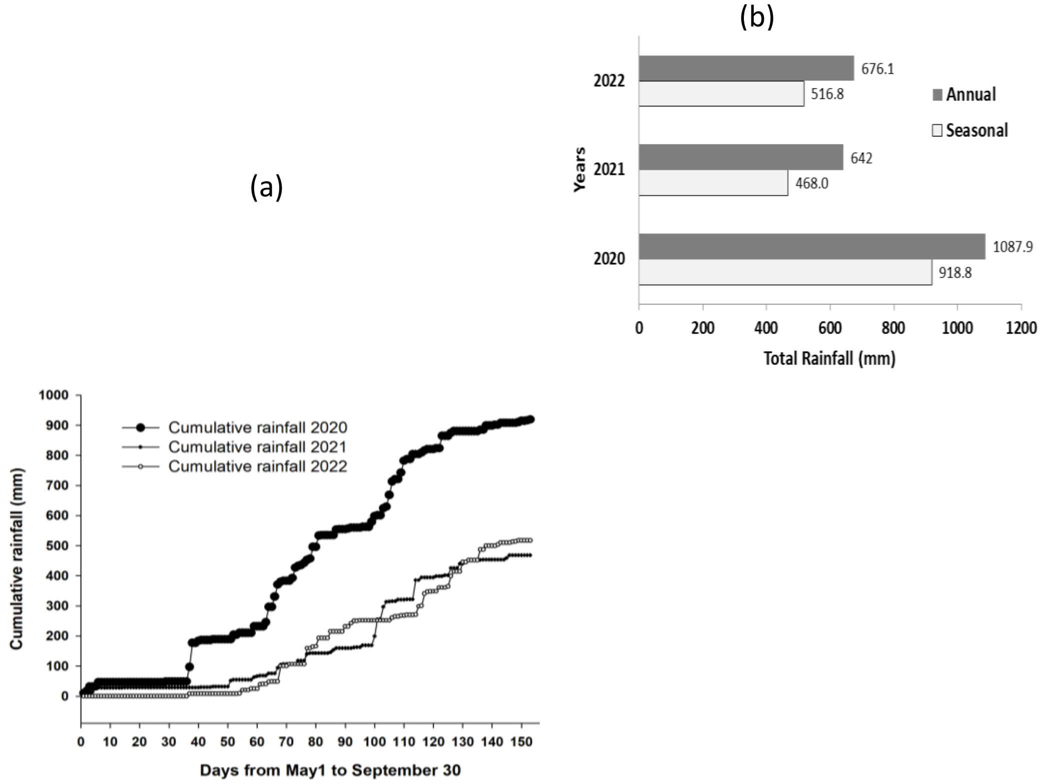

Figure 2. Cumulative, seasonal and annual total rainfall of the study site
N.B. Cumulative and seasonal refers to the rainfalls received during May 1 to September 30 for the respective cropping seasons

Previous study results reported that comparable or higher biomass and grain yields were achieved by N equivalence based combined application of various organic sources with urea at 25:75 or 50:50 ratios. A study conducted on highland Ultisols of Chelia and Nitisols of Lemu-Bilbilo districts showed comparable biomass and grain yields of barley by applying N-equivalence based combined use of either compost, farmyard manure (FYM) or vermicompost and mineral fertilizers in 50:50 proportions (Tolera et al., 2018; Kassu et al., 2018). FYM is a well-decomposed mixture of manure, urine and bedding material from various animals. The ratio of 25:75 between organic and mineral fertilizers based on an N equivalent was not evaluated in the two studies mentioned above. Similar results from Vertisols in the Ambo area showed comparable maize yield with N-equivalence based combined use of vermicompost and mineral fertilizer at a ratio of 50:50 compared to applying the recommended rate of NPS fertilizer alone (Girma et al., 2019). Other similar study results on tef and wheat crops confirmed yield benefits from N equivalence based combined application of organic and mineral fertilizers at 25:75 or 50:50 ratio (Girma et al., 2019; Girma & Gebreyes, 2017).

Analogous studies from wider study locations conducted over long period of time also revealed considerable better yield advantages from their combined use. The result from an experiment conducted on farmers' field at Arsi Negele area of Ethiopia demonstrated higher grain yield for 50:50 combined use of compost and mineral fertilizers during the first five successive cropping seasons and sole compost use on the final cropping season (Workneh et al., 2014). A study by Melkamu et al. (2021) on 10 farmers' field for two years at Bedele district of southwestern Ethiopia verified the significance of integrated use of FYM or compost with mineral fertilizer. The result demonstrated higher grain yield of maize (7.9 t ha^{-1}) from the integrated use where the nutrient inputs were 44 and 19 kg ha^{-1} N and P, respectively, against the 64 and 22 kg ha^{-1} of N and P input from the mineral fertilizer that yielded 6.0 t ha^{-1}. This is attributable to additional roles of organic sources other than sources to different nutrient elements for crop growth. A meta-analysis of combined use of organic and mineral fertilizers from 122 studies in sub-Saharan Africa country also showed increasing yield advantages when quality organic sources are used and as total N rate exceeds 100 kg per season (Gram et al., 2020). The authors reported 20% increase in agronomic efficiency over 100% sole mineral fertilizer when N equivalence based 50:50 proportions of high-quality organic sources and mineral fertilizers are used.

The yield penalty observed for nitrogen unfertilized plots and application of entire N rate from sole organic sources is considerable, despite the experiment was conducted on relatively fertile soil (research station) as compared to farmers' field. The 24% yield penalty, recorded from N unfertilized plots, was entirely caused by N-omission. The national level average maize grain yield penalty due to N-omission was over 38% on farmers' field where soil N content and fertility status is lower than at research station (unpublished data).

The treatments did not have a significant (P>0.05) impact on the average plant height and harvest index over the cropping seasons. Furthermore, the analysis of variance of the treatments within each cropping season also showed no significant (P>0.05) difference between the treatments for plant height and harvest index (data not presented).

The selected plant parameters (ear weight, 200-seed weight, above ground biomass) and grain yield of maize had highly significant (P<0.001) positive correlations (Table 6). This was in line with the expected and scientifically established fact that grain yield was positively and significantly (P<0.001) related to ear weight (r=0.822), 200-seed weight (r=0.417), above ground biomass (r=0.823) (Fig 3). This confirmed the reliability of the research result.

Table 6. Pearson correlation matrix (r) between maize yield parameters and grain yield (N= 90)

Variable	Ear weight (kg ha^{-1})	200 seed weight (gm)	Above ground biomass yield (kg ha^{-1})	Grain yield at 12.5% moisture (kg ha^{-1})
Ear weight (kg ha^{-1})	1			
200 seed weight (gm)	0.610***	1		
AGB yield (kg ha^{-1})	0.633***	0.341***	1	
Grain yield at 12.5% moisture (kg ha^{-1})	0.822***	0.417***	0.823***	1

*** represent 0.001 levels of significance.

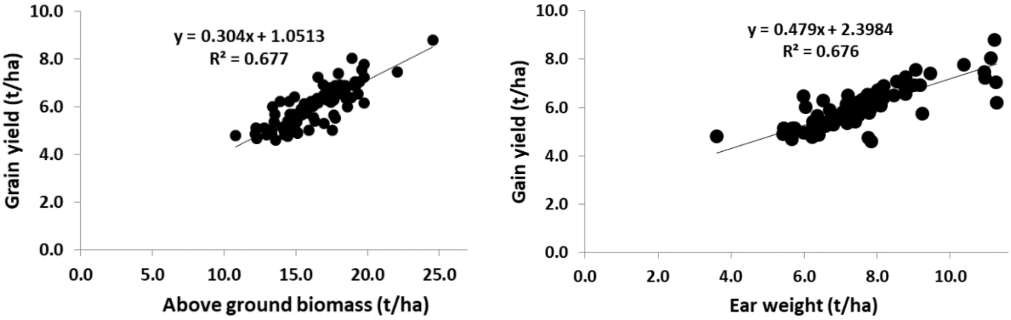

Figure 3. Regression analysis between AGB and grain yield (Left) and ear weight and grain yield (Right)

Soil improvements

The changes in soil-quality parameters due to treatment difference are presented (Table 7). Soil pH consistently increased with increasing level of bioslurry compost application. The increases in SOC were consistent with the increasing proportion of applied organic sources (Table 7 and Fig 4). When 75% of the recommended N was applied from either of the organic sources, the soil organic carbon was 12% higher than in the entire application of recommended N from urea. Similarly, the SOC was about 13 and 14% higher when 100% recommended N was applied from VC or BSC, respectively, than entire application of N from urea. The total SOC stock was generally 38.4 to 43.8 Mg ha^{-1}. The result showed about 5 Mg ha^{-1} higher total SOC stock for application of 75 or 100% recommended N from either organic source as compared to 100% N from urea. It also showed about 2 Mg ha^{-1} higher SOC stock when 25 to 50% N was applied from either of the organic sources as compared to 100% N from urea.

The increases in pH levels corresponding to higher level application of organic sources aligns with the findings from earlier studies (Girma et al., 2019; Girma & Gebreyes, 2017; Workneh et al., 2014). This trend is attributable to the higher pH levels of the organic inputs as compared to that of soils. However, the changes in N and available phosphorus were not consistent to make conclusive insights with regard to the evaluated treatments.

Similar studies have shown an increase in SOC with higher proportions of N from FYM and conventional compost (Girma et al., 2019; Girma and Gebreyes, 2017). Long-term on-farm study also demonstrated enhanced SOC stocks through exclusive use of compost or a combined application of compost and urea (Workeneh et al., 2014). An experiment conducted for four years on Vertisol soils in China demonstrated 41.15% increase in SOC content when 60% of N was derived from compost in comparison to the plot without inputs (Zhao et al., 2020). Research by Melkamu et al. (2021) also showed improved soil quality with the application of either FYM or compost combined with 50% recommended mineral fertilizer. The result demonstrated 86 and 175% higher SOC and total N stocks, respectively, over the sole application of recommended mineral fertilizer during a two-year experiment. A meta-analysis focusing on sub-Saharan Africa proved a notable 18% reduction in SOC loss over seven growing seasons when organic and mineral fertilizers were used in combination as opposed to using mineral fertilizer alone (Gram et al., 2020). This indicated the potential contribution of combined use of organic and mineral fertilizer in climate change adaptation and mitigation.

Table 7. Mean soil pH, organic carbon, Kjeldahl N, and olsen P as affected by treatment differences over the 2020 to 2022 cropping season with standard deviation

Treatments	Soil pH (1:2.5 soil to H_2O)	SOC (g kg^{-1} soil)	SOC stock (Mg ha^{-1}) in 20 cm depth	Total Kjeldahl N (%)	Available Olsen P (ppm)
No N fertilizer (Negative control)	6.69±0.06	16.50±0.15	39.61±0.34	0.13±0.01	21.86±2.15
Rec. N: 100% Urea (Positive control)	6.67±0.12	15.99±0.55	38.37±1.32	0.12±0.01	25.24±4.41
Rec. N: 25% from VC+75% from Urea	6.61±0.04	16.73±0.70	40.14±1.67	0.14±0.01	23.36±3.66
Rec. N: 50% from VC+50% from Urea	6.64±0.04	16.92±1.22	40.60±2.93	0.13±0.02	23.28±0.67
Rec. N: 75% from VC+25% from Urea	6.62±0.11	18.00±1.56	43.20±3.74	0.15±0.03	24.84±0.94
Rec. N: 100% from VC	6.67±0.06	18.03±1.13	43.27±2.70	0.16±0.01	21.33±3.40
Rec. N: 25% from BSC+75% from Urea	6.74±0.06	16.99±0.65	40.77±1.56	0.13±0.01	27.07±1.94
Rec. N: 50% from BSC+50% from Urea	6.73±0.03	16.97±1.32	40.72±3.16	0.13±0.02	23.13±1.56
Rec N: 75% from BSC+25% from Urea	6.78±0.05	17.90±1.56	42.96±3.73	0.14±0.02	25.96±1.40
Rec N: 100% from BSC	6.80±0.05	18.23±1.53	43.75±3.66	0.14±0.02	23.57±2.36
Grand mean	6.69	17.22	41.34	0.14	23.97

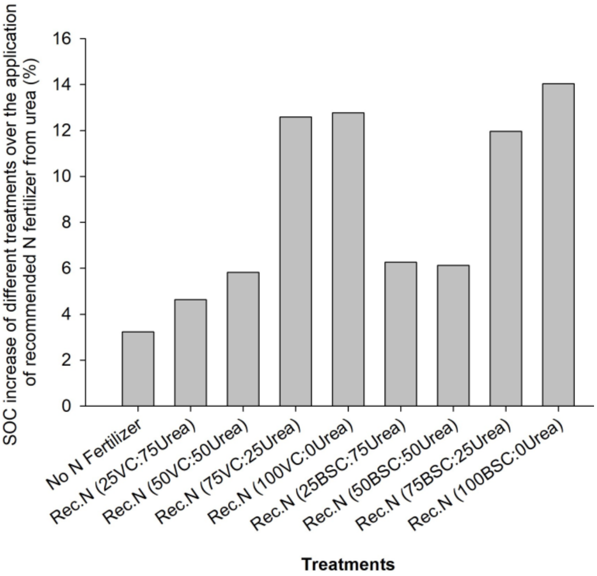

Figure 4. Relative total SOC increase (%) due to application of organic sources in different proportion with urea as compared to the recommencded N application from urea.

Economic analysis

Partial budget analysis result is presented in Table 8. The result depicted the highest net benefit (ETB 228,284.1 ha^{-1}) with MRR (MRR=1049.9) for N equivalence based replacement of 25% N by vermicompost and the remaining N applied from urea. The 100% recommended N rate application from urea was the second prefered in its net benefit with MRR =1469.6. The other combinations of N from organic and mineral fertilizers were all dominated mainly due to the current high selling price of the organic sources which was used for this analysis and labour cost for application of organic fertilizers.

There are limited number of organic fertilizer producers in the country, leading to high demand for these fertilizers for actitivities such as tree seedling raising in nursuries and high-value crop production in irrigated agriculture. Consequently, the current market prices of organic fertilizers are very high. However, farmers can produce their own organic fertilizers using locally available resources such as manure/cowdung and crop straws left over from animals feeding. As a result, various combinations of these organic fertilizers with mineral fertilizer could prove economically viable for farmers to use, and enhance agricultural production and soil health. Previous research results, utilizing production costs at the farmers' level for economic analysis, demonstrated the N equivalence based combinations of 50:50 and 25:75 oragnic sources to mineral N source are profitable with acceptable MRR for farmers to use in major cereal crop production (Girma et al., 2019; Girma & Gebreyes, 2017; Tolera et al., 2018).

The positive impact on overall SOC content resulting from the use of organic sources, sustainable restoration of soil productivity and higher economic yields in the long-term are overlooked in the present partial budget analyses. Therefore, it is crucial for agricultural experts, farmers, and policymakers to prioritize not only the immediate benefits, such as increased food supply but also sustainability. Failing to do so may result in the on-going depletion of soil organic carbon and essential nutrients in increasingly intensive agricultural systems, incurring significant and unbearable economic costs.

Recently, the government has launched a robust campaign aimed at empowering farmers to produce organic fertilizers for enhancing soil health and promoting sustainable crop production. As part of this initiative, most Farmers Training Centers (FTCs) now have vermicomposting structures for showcasing and disseminating vermiworms to farmers. In the about more than 8,000 FTCs nationwide, skilled Development Agents are available to assist farmers in the production of either vermicompost or compost alongside other improved agricultural practices. Additionally, approximately 25,000 biogas digesters have been installed in the country, and there is plan to establish more in the upcoming years for the production of biogas and hence bioslurry compost that increases the availability of organic sources for use as fertilizer in combination with mineral fertilizers.

Table 8. Economic analysis of on use of organic and mineral fertilizers for maize production in Melkassa Agricultural Research Center during 2020-2022 cropping seasons

Treatments	Adj. Straw yield (kg ha^{-1}) lower by 10%	Revenue from Straw (ETB ha^{-1})	Adj. grain yield (kg ha^{-1}) lower by 10%	Revenue from grain yield (ETB ha^{-1})	Organic fertilizer price (ETB ha^{-1})	Organic fertilizer application labour cost (ETB ha^{-1})	Urea price (ETB ha^{-1})	Gross benefit (ETB ha^{-1})	TCV (ETB ha^{-1})	Net benefit (ETB ha^{-1})	MRR (%)
No N fertilizer	7,317.2	73,172.4	4,337.5	95,004.8	-	-	-	168,177.2	-	168,177.2	-
Rec. N: 100% Urea	9,203.2	92,031.6	5,739.5	125,715.1	-	-	3,158.0	217,746.7	3,158.0	214,588.7	1469.6
Rec. N: 25% from BSC+75% from Urea	9,520.2	95,202.3	5,558.4	121,746.8	2,812.5	350.0	2,368.5	216,949.1	5,531.0	211,418.1	D
Rec. N: 25% from VC+75% from Urea	10,702.6	107,025.6	5,797.4	126,983.3	3,156.3	200.0	2,368.5	234,008.9	5,724.8	228,284.1	1049.9
Rec. N: 50% from BSC+50% from Urea	9,620.1	96,201.0	5,622.0	123,140.5	5,625.0	700.0	1,579.0	219,341.5	7,904.0	211,437.5	D
Rec. N: 50% from VC+50% from Urea	8,681.3	86,813.1	5,659.3	123,957.3	6,312.5	400.0	1,579.0	210,770.4	8,291.5	202,478.9	D
Rec N: 75% from BSC+ 25% from Urea	10,019.9	100,198.5	5,655.5	123,873.2	8,437.5	1,050.0	789.5	224,071.7	10,277.0	213,794.7	D
Rec. N: 75% from VC+25% from Urea	9,180.5	91,805.1	5,352.1	117,228.6	9,468.8	600.0	789.5	209,033.7	10,858.3	198,175.5	D
Rec N: 100% from BSC	9,053.4	90,534.0	5,108.4	111,891.0	11,250.0	1,400.0	-	202,425.0	12,650.0	189,775.0	D
Rec. N: 100% from VC	9,172.1	91,720.8	5,228.5	114,522.0	12,625.0	800.0	-	206,242.8	13,425.0	192,817.8	D

Adj = Adjusted down by 10%; TCV= total cost that vary; MRR= Marginal rate of return (%)

Conclusion

The research revealed combined that use of organic and mineral fertilizers led to enhance above ground biomass and grain yields without any yield penalty as compared to sole mineral fertilizer application. Similar to sole application of mineral fertilizer, application of N equivalence based organic and mineral fertilizer in 25:75 proportions increased grain yield by about 1.6 t ha^{-1} and high net benefit as compared to no N fertilizer application.

The finding also indicated that incorporating locally produced organic sources with mineral fertilizers can help reduce nutrient and soil organic carbon depletion in smallholder farmers. In comparison to the sole use of urea, the combined application of organic and mineral fertilizers resulted in up to 14% higher soil organic carbon content. Increased level of soil organic carbon in turn is known to improve soil microbial activities, nutrient and water use efficiencies. Hence, the combined use of organic and mineral fertilizers emerges as a climate-smart agriculture approach for future promotion, as it contributes to climate change adaptation as well as a long-term strategy for mitigation.

Promoting awareness and enhancing the capacity of farmers are crucial for encouraging the long-term adoption of organic sources. This includes developing skills in organic fertilizer production and establishing standards to ensure a minimum quality level to ensure supply of quality organic fertilizers for agricultural use. Additionally, future research on labor-saving technologies is essential for optimizing the field applications of organic sources.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors assert that they have no known conflicting financial interests or personal relationships that have perceived to impact the work reported in this paper

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