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Liquid bio-slurry enhances the productivity of N-fertilized maize under field conditions in Ethiopia

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Abstract: Enhancing maize production and productivity is critical for ensuring small-scale farmers' food security. Yet, declining soil fertility poses a substantial challenge to cereal production, including maize, in developing countries. Farmers are currently finding liquid bio-slurry to be a valuable organic amendment because it improves maize productivity and food security by altering the physicochemical properties of the soil. However, extensive research on liquid bio-slurry as an organic amendment in Ethiopia is still limited. Hence, a field experiment was conducted at two sites to identify the optimal combination of inorganic nitrogen (N) and liquid bio-slurry to improve maize productivity. The trial involved the application of two mineral N fertilizers and five different rates of liquid bio-slurry in a randomized complete block design with three replications. The results revealed that the main effects of mineral N and liquid bio-slurry were significant ($p < 0.05$) on most of the parameters examined. The interaction between mineral N x liquid bio-slurry had a significant ($p < 0.05$) effect on plant height, ear length, number of rows ear^{-1}, number of kernels ear^{-1}, above-ground dry biomass yield, hundred-grain weight, grain yield, and straw yield. The highest grain yield (8,220 kg ha^{-1}) was achieved by combining 46 kg N ha^{-1} with 18 t liquid bio-slurry ha^{-1}. Therefore, 46 kg N ha^{-1} with 18 t liquid bio-slurry ha^{-1} is highly recommended for increasing maize yield in the study sites and other areas with similar agroecological zones.

Introduction

Increasing maize productivity is crucial for ensuring the food and nutritional security of smallholder farmers in Ethiopia. Maize is the world's most important cereal, second only to wheat in terms of production (FAO, 2019). Approximately 88% of the country's maize production is used for food, in green cobs and grain (Rehman et al., 2022). In addition, it is second only to teff in terms of area under production, but first in terms of productivity among main cereals (Alemu et al., 2024), making it one of the most important crops for feeding an ever-increasing population (Dimkpa et al., 2020; Rehman et al., 2022). Nevertheless, the country's average yield is only around 4.2 t ha^{-1} (CSA, 2019), which is significantly lower than the global average of 5.8 t ha^{-1} (FAO, 2019). Multiple factors have been identified as contributing to maize productivity limitations, including insufficient external inputs, particularly N, declining soil fertility which results in poor soil quality, reduced water retention capacity, and inadequate soil permeability (Chimdi et al., 2012; Dawar et al., 2022). Among others, diminishing soil fertility in many developing countries is a major challenge that leads to widespread food insecurity and poverty (Martey et al., 2019). Implementing effective strategies to boost soil fertility is crucial in tackling these complex challenges and enhancing food and nutritional security (Martey et al., 2019; Majee et al., 2021).

Agriculture is the primary source of income for the majority of Ethiopians, and soil is critical to its success (CSA, 2016). However, as stated by Spiertz (2009),

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approximately 31% of the country's agricultural land has been degraded, affecting the capacity of resource-poor farmers to maintain their agricultural productivity in the long run (Fanta et al., 2024). Maltsev and Yermolaev (2020) found in their research that it exerts a marked influence on food security and contributes to an increase in atmospheric CO_2 emissions. According to Gelaw et al. (2014), one of the primary causes of the decline in soil fertility and productivity is the loss of soil organic matter due to topsoil erosion combined with unfavorable physicochemical characteristics. Hence, to address these issues, it is critical to implement sustainable agriculture practices that prioritize prudent and balanced use of external inputs and environmentally friendly soil management techniques (Zerssa et al., 2023). This improves the stability, quality, and long-term use of soil resources, thereby increasing crop productivity (Saliu et al., 2023).

In conventional farming, mineral fertilizers are considered the foremost option to overcome the problem of nutrient depletion and sustain food production (Elka and Laekemariam, 2020). However, excessive application of synthetic fertilizers may not necessarily lead to a corresponding boost in crop production (Powlson et al., 2008; Penuelas et al., 2023). Conversely, their continual usage has been proven to decrease crop productivity due to the deterioration of soil quality (Powlson et al., 2008; Xu et al., 2015; Chaudhary et al., 2017; Maqbool et al., 2020). It also led to the regular absorption and accumulation of heavy metals in plant tissues thereby lowering the nutritional value of crops (Maqbool et al., 2020). On the other hand, the use of organic inputs alone is not also sufficient to increase crop yields and satisfy the food needs of humankind due to their slow-release nature and will not fully deliver the required quantities of nutrients via plants (Saleem et al., 2017). It is also reported by Godara et al. (2012), that neither inorganic fertilizers nor organic sources alone can result in sustainable productivity.

Integrated use of organic inputs and mineral fertilizers improves crop yield (Fairhurst, 2013; Mugwe et al., 2019; Tadewos et al., 2022). It is also considered the best strategy for improving soil fertility and increasing crop productivity (Bedada et al., 2014; Agegnehu et al., 2016; Yoseph and Shanko, 2017). Several researchers have commented on the economic benefits of integrated nutrient management (Ashoka et al., 2008; Naik and Gupta, 2010). According to Jinwei and Lianren (2011), an integrated application of organic and chemical fertilizers lowered fertilizer costs compared to a solitary application of either fertilizer alone. Saleem et al. (2017) also observed the highest net benefit (78,419.66 ha^{-1}) of mono-cropped maize with an integrated use of organic and inorganic fertilizer (50% poultry manure + 50% PK + inoculation) compared to the sole application of either fertilizer. A significant increase in crop yield has been observed when liquid bio-slurry is applied with chemical fertilizer (Warnars and Oppenoorth, 2014). Liquid bio-slurry is a nutrient-rich organic fertilizer made from the anaerobic breakdown of organic materials in a biodigester. It contains essential plant nutrients like nitrogen, phosphorus, potassium (N, P, K), as well as organic matter (humus). It significantly improves the soil's physical, chemical, and fertility properties (Musse et al., 2022). Moreover, the positive effect of bio-slurry has been examined in different crops, including maize (Rewe et al., 2022), teff (Berihu, 2021), wheat (Warnars and Oppenoorth, 2014), rice (Islam et al., 2013), barley (Warnars and Oppenoorth, 2014), millet (Warnars and Oppenoorth, 2014), and vegetables (Islam, 2006; Islam et al., 2010; Musse et al., 2022; Shao et al., 2023). However, limited research has been conducted in Ethiopia to determine the effects of mineral N and liquid bio-slurry on soil fertility and maize productivity. Therefore, this study was conducted to determine the effect of mineral N fertilizer and liquid bio-slurry on the growth and yield response of maize at the two sites in Ethiopia.

Materials and Methods

Description of study sites

The experiment was conducted at the Wondo Genet and Hawassa University Research site (Figure 1). The site selection process considered Ethiopia's prominent and representative maize production areas. In this regard, the selected sites served as a significant hub for maize production in the country, representing maize cultivation by local farmers and thus becoming a leading center for its production. **Experimental site one:** The Hawassa site is situated at 7°3′N latitude and 38°28′E longitude, 275 km south of Addis Ababa. It is 1700 meters above sea level (m.a.s.l.). The area had a bimodal rainfall distribution pattern, expected from March to April and June to August (Kebede et al., 2014). According to Markos et al. (2023), the predominant soil in this location is classified as a vitric andosol.

Experimental site two: The Wondo Genet study site is located 14 km southeast of Shashemene town and 270 km south of Addis Ababa. The site is 1780 m.a.s.l. and is found at 7°19′N and 38°38′E. The site had a bimodal rainfall pattern, expected from March to May and June to October (Gebregeorgis et al., 2018). Mollic andosol with a sandy-loam texture dominates the site's soil (Yimer, 2017).

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The distance between Hawassa and Wondo Genet is 32 km by road. The majority of the local population generates income from mixed-subsistence farming in the study areas. Enset, haricot beans, teff, wheat, khat, and maize are the primary crops produced in the area.

Climatic data of the sites

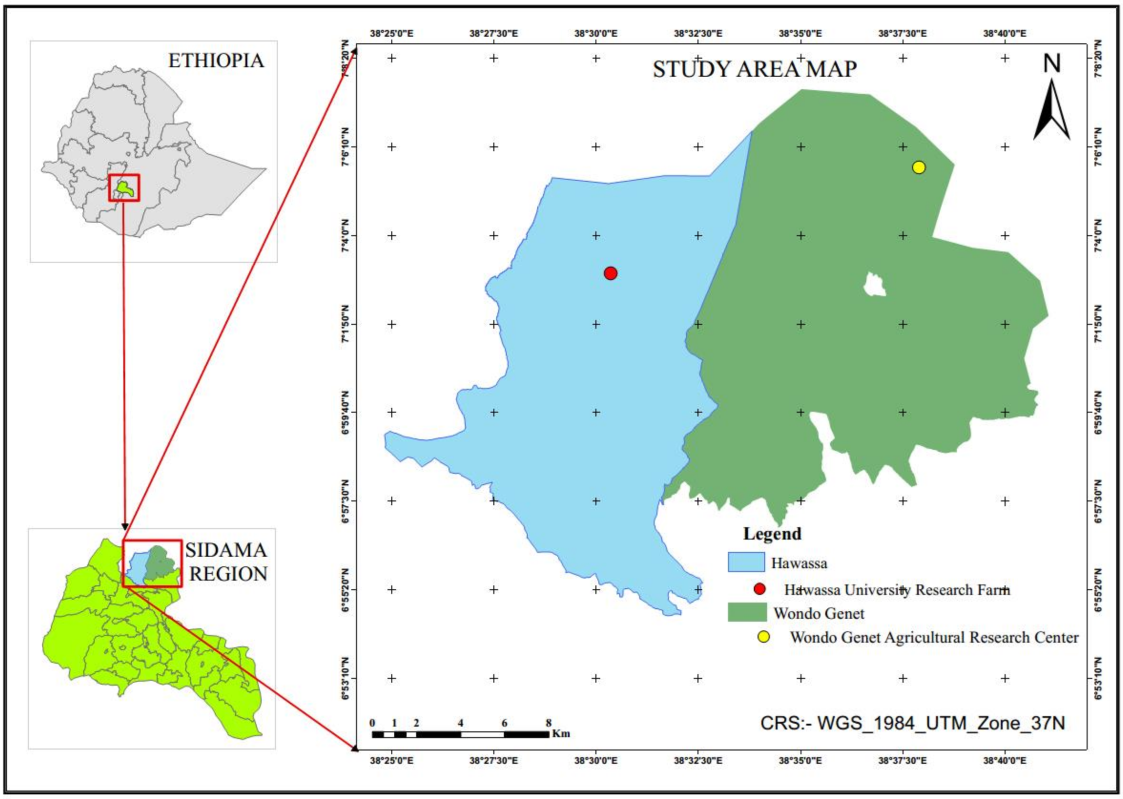

Figure 1. Physical map of two study sites (Hawassa University and Wondo Genet Research). Source: Google map from the Hawassa University College Agricultural, October 28, 2023.

Figure 2 depicts the mean monthly rainfall, and highest and lowest temperatures at the research sites for the main cropping season of 2021/22. At Wondo Genet, the highest mean monthly rainfall was recorded in September and February, whereas at Hawassa, it was higher in August and October. At Wondo Genet, the highest and lowest mean maximum and minimum temperatures were recorded in February and November. At the Hawassa, the values were higher in March and November, respectively.

Description of the experimental materials

The SBRH-2016 maize variety, released by the Bako Agricultural Research Centre in 2018, was used in this study at a seeding rate of 25–30 kg^{-1} (Golla, 2018). It demonstrated exceptional suitability to the agroecological conditions of the experimental sites and was chosen for its high potential productivity and easy seed availability to local farmers. The liquid bio-slurry was used as an organic nutrient supply, while urea, a mineral N source, was used in the study at a recommended application rate of 46 kg N ha^{-1}. Ethiopia's agricultural extension agency first implemented a nationally blanket recommendation of 100 kg diammonium phosphate (18-46-0) and 100 kg urea ha^{-1} (46-0-0) for all crops in all situations (Zelleke et al., 2019). As a result, the N amount used for this treatment followed national recommendations. To meet the crop's phosphorus (P) requirements, the recommended P in the form of TSP (Triple superphosphate) was applied uniformly to all plots. The liquid bio-slurry used for this experiment had 93% water and 7% dry matter composition, and the rates were adjusted based on the recommended rate of N respective to its N content.

Liquid bio-slurry preparation and analysis

The waste material collected from private hotels in Hawassa City was utilized to produce a liquid bio-slurry. The material underwent processing in a bio-digester tank and was stirred in a circular motion with a stick, following the procedure outlined by Musse et al. (2022). During the preparation, preventive measures were taken to avoid scraping off the bottom and corners of the tank. Then five representative liquid bio-slurry samples were collected with 2 L of sampling plastic. The samples were mixed in the plastic container, and a 1L representative sample was taken for chemical analysis such as pH, organic carbon (C), total nitrogen (N), available phosphorus (Av. P ppm), and available potassium (Av. K ppm) in the soil laboratory

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of Hawassa Agricultural Research Centre by following laboratory procedures listed in soil analysis (Table 1).

Soil sampling and analysis

calcium (Ca), potassium (K), sodium (Na), and magnesium (Mg) were estimated using the Mehlich-3 method (1984).

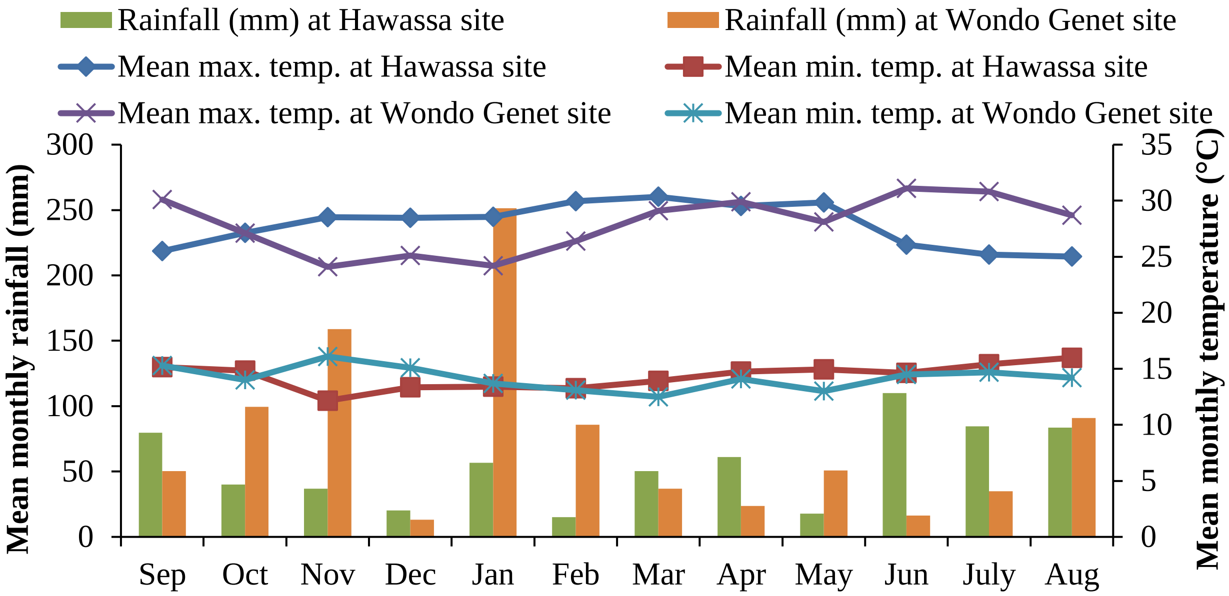

Figure 2. Mean monthly rainfall (mm) and minimum and maximum temperature (°C) data during the main cropping season of 2022 at Wondo Genet and Hawassa sites. [max. = maximum, min. = minimum, temp. = temperature].

Selected soil physicochemical properties: Before planting, soil samples were collected from 0–30cm depth from twelve points across the experimental field in a zigzag manner by using a screw auger. After removing unwanted debris, dead plants, and gravel, the soil samples were combined to form a kilogram of soil sample. The composite sample was then air-dried under shade, ground with a pestle and mortar, packed in paper bags, and labeled. The sample was pulverized and sieved through a 2mm sieve after being air-dried at room temperature. However, 0.5mm mesh wire was utilized to determine organic C and total N. Then, the selected soil physicochemical properties [soil texture, soil pH, total N, organic C content, available P, and Cation Exchangeable Capacity (CEC)] at the start of the experiment were analyzed at the Soil Laboratory of Hawassa University College of Agriculture (Table 1).

The soil's texture was measured using the Bouyoucous hydrometer technique (Day, 1965). Soil pH was determined by making a 1:2.5 soil-water solution and using a glass electrode pH meter (Jackson, 1958). The total N was determined using the Kjeldahl method (Dewis and Freitas, 1975). The organic C content was calculated using the Walkley and wet oxidation technique (Jackson, 2005). The available P was calculated using a previously described method (Olsen, 1954). CEC was assessed using the Kjeldahl technique (Ranst et al., 1999), whereas

The results presented in Table 1 showed that the soil at the Hawassa site was categorized as sandy loam, whereas the Wondo Genet site displayed a clay loam texture (Hazelton and Murphy, 2016). The soil pH at both study sites was neutral, indicating no acidity issue and adequate nutrient availability for crop production (EthioSIS, 2014). The available P contents [14.73 and 21.73 mg kg^{-1}] at both experimental sites were rated low and medium, respectively (Olsen, 1954). The low P content at the Hawassa site could be due to crop utilization or uptake due to low or no P-containing fertilizer application. Farmers are advised to use soil amendments such as P-containing fertilizers or organic sources to improve soil fertility. This will enhance maize production and productivity. The exchangeable bases were rated from medium to high at both experimental sites. The higher availability of exchangeable bases may be attributed to the sites' neutral soil reaction, which creates ideal conditions for their availability (McCauley et al., 2009). The total N contents in the soil at Hawassa and Wondo Genet were rated as medium whereas organic C was rated as low at the Hawassa site and medium at the Wondo Genet site (Landon, 1991).

Chemical composition of liquid bio-slurry

The liquid bio-slurry used for the experiment had a pH value falling within the neutral range. Its neutrality is good for agronomic practices since it reduces the acidity

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problem of experimented sites and makes it ideal for the growth of maize crops by releasing essential macro and micronutrients (Table 1). In line with this result, Mwanga (2016) reported that applying liquid bio-slurry reduces the acidity problem of the soils and improves the quality of agricultural soil by neutralizing acidic conditions. It also contains a high organic C, which is crucial for maintaining nutritional balance by limiting the movement of heavy metals and accelerating the decomposition of organic matter (Ibukunoluwa, 2015). Furthermore, it improves overall soil CEC and increases soils' ability to retain exchangeable cations, making fertilization more efficient (Wibowo and Kasno, 2021). Total N and available P contents were high in the applied liquid bio-slurry, indicating that its application can supply the soil with those essential nutrients. A similar finding was reported by Muraishi et al. (2011) and Hariadi et al. (2016). Exchangeable bases and CEC of liquid bio-slurry were classified under the high ranges this might be because of its neutral nature which in turn improves soil acidity.

Table 1. Physico-chemical properties of the soil at the two experimental sites, and of the bio-slurry.

Property	Value		
	Soil		Bio-slurry
	Wondogenet	**Hawassa**	
Chemical			
Total N (%)	0.11	1.13	1.51
Available P (mg kg^{-1} soil)	21.73	14.73	103.7
Available K (mg kg^{-1} soil)	169	174	195
Organic C (%)	1.75	1.65	17.3
Organic matter (%)	3.01	2.84	29.76
pH H_2O (1:2.5)	6.98	7.15	7.29
Exchangeable Ca^{2+} (cmol kg^{-1} soil)	9.21	13.21	14.4
Exchangeable Na^{+} (cmol kg^{-1} soil)	0.57	0.97	1.6
Exchangeable K^{+} (cmol kg^{-1} soil)	0.53	1.13	1.18
Exchangeable Mg^{2+} (cmol kg^{-1} soil)	2.93	2.63	7.2
CEC (cmol kg^{-1} soil)	20.93	23.26	61
Physical			
Sand (%)	31	58	93.13% Water
Silt (%)	32	20	6.87% Dry matter
Clay (%)	37	22	-
Textural class	Clay Loam	Sandy Loam	-

Treatments and experimental design

The treatments consisted of two N (0 and 46 N kg ha^{-1}) rates and five different rates of liquid bio-slurry (0, 6, 12, 18, and 24 t ha^{-1}). They were combined factorially, giving a total of 10 treatment combinations. The experiments were conducted using a Randomized Complete Block Design (RCBD) with three replications. A uniform plot size of 3.5 m x 2.4 m (8.4 m^2) was used for each unit, with a total experimental area of 363.4 m^2. The blocks were separated by 1 m in width, whereas the space between each plot within a block was 0.5 m. In each plot, there were five rows and 16 plants row^{-1}, for a total of 80 plants $plot^{-1}$ before thinning to the remaining one plant $hole^{-1}$. Per the specifications of the design, each treatment was assigned randomly to experimental units within a block. The middle three rows from each plot were used for yield determination, while the outermost rows were kept as border plants.

Agronomic practices

The land preparations at the two experimental sites were done by performing conventional tillage with three plowings by tractor at a depth of 30 cm. Leveling was done manually using a rake during plot preparation. Nitrogen (Urea= 46% N) was applied in two equal splits, half at planting and the other half after 40 days of plant emergence, with band application approximately 5cm away from the maize plant to control the burning effect of the plant. Phosphorus was applied at sowing. The full dose of the liquid bio-slurry was applied four weeks before sowing. All cultural and agronomic practices except fertilization, such as hoeing, disease, insect, and weed management, were performed uniformly for all plots in both study sites.

Data collection and measurements

Phenological parameters

Days to 50% tasseling were recorded from the days of emergence to when 50% of the maize plants produced tassels in each plot. Days to 50% silking were recorded from the days of emergence to when 50% of the maize plants produced silk in each plot. Days to 90% physiological maturity were recorded from the days of emergence to the days when 90% of the maize plants in a

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plot raised the formation of the black layer at the point of attachment of the kernel with the cob.

Growth parameters

Five plants were randomly selected from each plot's middle rows to measure plant height at the emergence of the flower stalk. Their average values were taken as plant height plant^{-1} and expressed in centimeters. The total number of leaves plant^{-1} was counted from the sampled plants for plant height and averaged to determine the leaf number plant^{-1}. Leaf area was measured using a leaf area meter (Model LI-3100C) at the emergence of the flower stalk. The leaf area index was determined as the ratio of the leaf area to the ground area of the plant, as described by Campbell (2012).

Yield and yield components

The number of ears plant^{-1} was determined by dividing the number of harvested ears by the number of harvested stands. Ear length was measured from the point where ears were attached to the stalk to the tip of the ear with a glass ruler after harvest. Ear diameter was measured with a caliper in the middle of the ear. To determine the kernel number ear^{-1}, the first shelled grain of the harvested maize in each plot was weighed and divided by the number of ears. The number of rows ear^{-1} was determined by dividing the number of rows by the number of harvested ears. To determine the kernel number ear^{-1}, the shelled grain of the harvested maize in each plot was weighed and divided by the number of ears. The hundred-grain weight was determined by weighing 100 sampled grains from the bulk harvest and adjusting to a 12.5% moisture level (Orebo et al., 2021). Grain and straw yield data were collected from the three harvestable rows by excluding the border plants. The harvested biomass was weighed for fresh biomass, after which the ears and the straws were separated and weighed. The grain yield was determined by adjusting the moisture content to 12.5% (Orebo et al., 2021). Straws of two stands from each plot were collected from each plot at harvest. The straw samples were oven-dried until a constant weight was attained so that it was possible to calculate the dry straw yield plot^{-1}. The dried biomass yield was determined as the sum of dry grain and dry straw yields.

Statistical data analysis

The data recorded for each of the parameters considered in this study were subjected to analysis of variance (ANOVA) using a General Linear Model in SAS software and mean separation was made based on LSD at a 5% ($p < 0.05$) level of significance (SAS version 9.0, 2004). The Hartley F_{max} test was used to evaluate the homogeneity of error variances test for all parameters before performing a mean analysis across two sites.

$$\text{Fmax} = \frac{\text{large mean square error}}{\text{smaller mean square error}}$$

The mineral N fertilizer and liquid bio-slurry were considered fixed factors, whereas the sites were random factors. The error variances were considered homogeneous because the highest error mean square (EMS) was not threefold larger than the smallest EMS, and a combined ANOVA was performed on the data from the two sites because the F_{max}<3.00 test indicated that all parameter data were homogeneous across the sites by Gomez and Gomez (1984).

Results and Discussion

Phenology Parameters

The mineral N fertilizer and liquid bio-slurry had a highly significant ($p < 0.001$) effect on the days to tasseling, silking, and maturity of maize. The longest days to tasseling, silking, and maturity were recorded from the 46 kg N ha^{-1}, and the shortest was from the control treatment (Table 2). The data on tasseling, silking, and maturity were delayed by 6.64, 7.24, and 7.94 days, respectively, when 46 kg N ha^{-1} was applied. This indicates that the applied N promotes vegetative growth, resulting in a longer duration of the tested phenological parameters and a higher rate of mineral N fertilizer over the control. In line with this finding, Kirkby (2001) found that N deficiency leads to earlier vegetative growth and leaf senescence, likely due to increased abscisic acid content and decreased cytokinin synthesis and translocation. Similarly, Karki et al. (2020) reported significant effects on tasseling, silking, anthesis silking intervals, and physiological maturity with increased N application. In addition, Shrestha (2013) and Anwar et al. (2017) also found that increasing the amount of mineral N fertilizer slowed the crop's phenological process.

Concerning the supplied bio-slurry, the control treatment yielded the shortest phenological parameters for maize, while the applications of 18 and 24 t ha^{-1} produced the longest (Table 2). The increased rate of bio-slurry led to a delay in phenology, likely by boosting levels of macro- and micronutrients in the soil, which supported the crop's regular physiological functions and extended phenology and crop growth. The ample macronutrients, particularly NPK (Table 1), found in the bio-slurry caused a delay in the phenological stages of maize, ultimately improving its overall productivity through its normal physiological processes. Similarly, Imran et al. (2015) found that the production of silk or tassel was delayed in maize plots receiving higher amounts of N fertilizer from organic or mineral sources. It was also noted by Dawadi and Sah (2012) and Jassal et al. (2017) that earlier tasseling

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and silking were recorded when higher N rates were applied.

Table 2. Effects of mineral N fertilizer and liquid bio-slurry rates on phenological parameters of maize averaged across two sites.

Parameters	Days to tasseling	Days to silking	Days to maturity
Mineral N (kg ha^{-1})			
0	82.10^{b}	85.14^{b}	125.69^{b}
46	88.74^{a}	92.38^{a}	133.63^{a}
LSD $_{(0.05)}$	1.36	0.85	3.14
Level of Significance	**	**	**
Liquid bio-slurry (t ha^{-1})			
0	80.51^{c}	82.77^{c}	123.71^{d}
6	84.63^{b}	88.68^{b}	126.07^{cd}
12	86.13^{ab}	90.23^{a}	131.28^{bc}
18	88.74^{a}	91.53^{a}	136.23^{a}
24	87.81^{a}	90.61^{a}	131.01^{ab}
LSD$_{(0.05)}$	2.16	1.35	4.97
Level of Significance	**	**	**
CV (%)	3.1	1.84	4.64

Mean values followed by the same letter (s) in the same column do not exhibit significant differences at a 5% significance level. The abbreviations LSD and CV represent the least significant difference and coefficient of variation, respectively.

Growth parameters

Plant height

The interaction effects of mineral N and liquid bio-slurry had a highly significant effect ($p < 0.01$) on the plant height (Figure 3). The combined application of 46 kg N ha^{-1} with 18 t ha^{-1}, followed by 24 and 12 t ha^{-1} liquid bio-slurry, resulted in the tallest plant height, while the shortest plant height was recorded from the control treatment. Such improvement in plant height could be attributed to a synergistic effect of mineral N and liquid bio-slurry rates. The combined application of N and bio-slurry likely improved soil aeration, root penetration, and water storage capacity by improving CEC and reducing P fixation; these effects ultimately led to an increase in plant height (Ganunga et al., 2005; Shahbaz et al., 2014; Kebede et al., 2023). This was also supported by the bio-slurry data shown in Table 1. As a result, it provides favorable conditions for maize production and promotes plant growth. The findings are also consistent with those of Woldesenbet and Tana (2014), who found a significant effect of the combined use of organic and inorganic fertilizers on plant height. Similarly, Demissie et al. (2017) found that combining lime with inorganic fertilizer and compost improved plant height in barley. Furthermore, Habtamu et al. (2019) reported significantly improved plant height in maize after applying 10 t ha^{-1} farm yard manure combined with 150 kg N ha^{-1}.

Leaf attributes

Leaf characteristics (number of leaves, leaf area, and leaf area index) play an important role in biomass yield, which is heavily influenced by soil nutrition, particularly N. The averaged results from the two experimental sites revealed that the main effects of N and liquid bio-slurry rates had highly significant ($p < 0.01$) effects on the leaf characteristics of maize. The highest values of these traits were obtained using 46 kg ha^{-1} of N, while the minimum values were recorded from the control treatment. The supplied mineral N fertilizer increased the number of leaves, leaf area, and leaf area index by 9.7, 25.3, and 24.7%, respectively, compared to the control (Table 3). Maize leaf traits improve with increased mineral N, which promotes plant growth and height, leading to more nodes and internodes and increased leaf production (Ognjenović et al., 2022). Hokmalipour and Darbandi (2011) also reported the positive effect of a higher N rate on leaf elongation, which directly affected the chlorophyll content, leaf area, and leaf area index. The current findings are also consistent with those of Chimdessa (2016), who revealed that applying mineral N fertilizer to maize crops significantly increased leaf area, leaf area index, and number of leaves plant^{-1}.

Similarly, liquid bio-slurry had a notable effect on maize leaf traits. The applications of 18 and 24 t ha^{-1} of liquid bio-slurry produced the highest leaf characteristics, and the lowest was obtained from the control. Supplying 18 t ha^{-1} of liquid bio-slurry increased the number of leaves, leaf area, and leaf area index by 15.7, 27.1, and 25.5%, respectively, compared to the control (Table 3). The availability of macro- and micronutrients in the liquid bio-slurry likely improves the soil's physico-chemical characteristics, which thereby improves the leaf characteristics of maize as the dosage of liquid bio-slurry increases. Furthermore, Feleafel and Mirdad (2014) investigated the application of 100 kg ha^{-1} of chicken

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manure to beans grown on sandy soil and found results similar to those reported here. Furthermore, the current findings are consistent with those of Wang et al. (2019), who found that liquid bio-slurry improves soil nutrient dissolution and diffusion, significantly increasing the concentration of N, P, K, and organic matter in the soil, promoting more efficient nutrient utilization, crop growth, and production, and increasing leaf length.

Mean values followed by the same letter (s) in the same column do not exhibit significant differences at a 5% significance level. The abbreviations LSD and CV represent the least significant difference and coefficient of variation, respectively.

Yield and yield component parameters

Ears plant^{-1}, ear diameter, and harvest index

The results recorded from the two study sites' revealed that the number of ears plant^{-1}, ear diameter, and harvest index were significantly ($p < 0.01$) affected by mineral N and liquid bio-slurry rates. From the result presented in Table 4, it is evident that mineral N improved maize plants' number of ears plant^{-1}, ear diameter, and harvest index by 21.6, 21.5, and 4.9%, respectively. Using mineral N fertilizer increases winter wheat production by stimulating photosynthesis and promoting vegetative growth, leading to higher yields as the amount of fertilizer applied increases (Noor et al., 2023). In agreement with this result, Rasool et al. (2016) reported that mineral N has increased the yield and cob yield with and without husk,

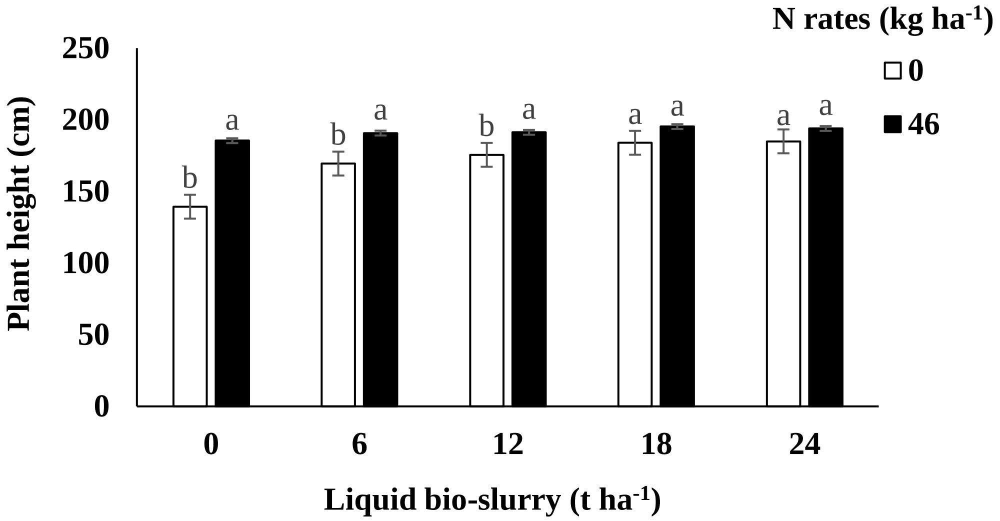

Figure 3. Interaction effects of mineral N fertilizer and liquid bio-slurry rates on plant height of maize averaged across two sites. Vertical S.E. bars followed by dissimilar letters significantly differ at *p*< 0.05.

Table 3. Effects of mineral N fertilizer and liquid bio-slurry rates on growth parameters of maize averaged across two sites.

Parameters	Number of leaves plant^{-1}	Leaf area (cm^2)	Leaf area index
Mineral N (kg ha^{-1})			
0	12.88 ^{b}	6686.90 ^{b}	3.20 ^{b}
46	14.13 ^{a}	8377.30 ^{a}	3.99 ^{a}
LSD $_{(0.05)}$	0.5454	312.33	0.1467
Level of Significance	**	**	**
Liquid bio-slurry (t ha^{-1})			
0	12.38 ^{c}	6346.10^{c}	3.06^{c}
6	13.76b^{c}	7374.3 ^{b}	3.51 ^{b}
12	13.76a ^{b}	7533.30 ^{b}	3.59 ^{b}
18	14.32 ^{a}	8067.50 ^{a}	3.84 ^{a}
24	14.14 ^{a}	8339.2 ^{a}	3.97 ^{a}
LSD $_{(0.05)}$	0.8624	493.84	0.2319
Level of Significance	**	**	**
CV $_{(\%)}$	7.73	7.93	7.81

fodder, and green biomass yield during the two cropping seasons. Similarly, Selassie (2015) found that using solely mineral N fertilizer increased the yield components of maize, including ears plant^{-1}.

Similarly, liquid bio-slurry positively influenced maize yield and yield components. The highest number of ears plant^{-1}, ear diameter, and harvest index were obtained from 18 and 24 t ha^{-1} of liquid bio-slurry, respectively, while the control treatment produced the lowest values. The number of ears plant^{-1}, ear diameter, and harvest index of maize increased by 17.3, 19.0, and 13.3% due to the application of 18 t ha^{-1} liquid bio-slurry compared to the control (Table 4). The availability of macro- and micronutrients in the liquid bio-slurry might enhance cell growth and division, membrane permeability, enzyme activation, and cell protection against acidic toxicity from other components, and thus, contribute to an increase in the yield attributes of maize. In addition, a high amount of organic N and other important nutrients can be supplied from the bio-slurry, which directly contributes to the growth and yield of maize plants, and this was supported by Gelaye and Tadele (2022), who observed improved yield attributes of plants due to the use of organic manure.

Table 4. Effects of mineral N fertilizer and liquid bio-slurry rates on yield attributes of maize averaged across two sites.

Parameters	Number of ears plant^{-1}	Ear diameter (cm)	Harvest index (%)
Mineral N (kg ha^{-1})			
0	1.02^{b}	3.99^{b}	41.00^{b}
46	1.24^{a}	4.85^{a}	43.00^{a}
LSD $_{(0.05)}$	0.06	0.17	0.01
Level of Significance	**	**	**
Liquid bio-slurry (t ha^{-1})			
0	1.04^{c}	3.90c	38.83^{c}
6	1.10^{bc}	4.37^{b}	41.50^{b}
12	1.12^{bc}	4.53^{ab}	41.70^{b}
18	1.22^{a}	4.64^{a}	44.00^{a}
24	1,17^{ab}	4.66^{a}	42.83^{ab}
LSD $_{(0.05)}$	0.09	0.27	0.02
Level of Significance	**	**	**
CV $_{(\%)}$	6.56	5.10	3.41

Mean values followed by the same letter (s) in the same column do not exhibit significant differences at a 5% significance level. The abbreviations LSD and CV represent the least significant difference and coefficient of variation, respectively.

Ear length

Ear length plays a crucial role in determining the yield of maize crops. It significantly impacts the grain yield by altering both the number of grains ear^{-1} and the size of the grains. The interaction effects of N and liquid bio-slurry had a significant ($p < 0.05$) effect on ear length. The combined application of 46 kg N ha^{-1} and 18 t ha^{-1} liquid bio-slurry resulted in the longest ear length. The shortest ear length was recorded from 0 kg N ha^{-1} and 6 t ha^{-1} liquid bio-slurry. The result indicated that ear length increases as the level of N and liquid bio-slurry increases and reaches its maximum at the maximum rate of N and 18 t ha^{-1} liquid bio-slurry (Figure 4A). The increase in ear length with the addition of both N sources might be attributed to the higher availability of nutrients, which promotes the growth and development of the maize plants. This result is consistent with the findings of Derby et al. (2005), who found that at optimal mineral N rates, ear length increased due to better solar energy consumption, increased assimilate production, and starch conversion, resulting in longer ears. Similarly, Imran et al. (2015) found that increasing the combined use of mineral N and organic fertilizer rates enhanced ear length.

Number of rows ear^{-1}

The interaction effects of mineral N and liquid bio-slurry had a significant ($p < 0.05$) impact on the number of rows ear^{-1}. The application of 18 t liquid bio-slurry ha^{-1} and 46 kg N ha^{-1} produced the highest (14.4) number of rows ear^{-1}. On the other hand, the control treatment yielded the lowest value (Figure 4B). The combined application of N-sourced fertilizer increased the number of rows ear^{-1} by 51.5% compared to the control. The improvement in the number of rows ear^{-1} might be attributed to the availability of nutrients needed for plant growth and an increase in ear length and diameter due to the applied mineral N fertilizer and liquid bio-slurry. Consistent with this finding, Rasheed et al. (2004) found that maize had the highest number of rows ear^{-1} after applying the optimal N nutrient, which blends fertilizers made from liquid bio-slurry with mineral N. Thus, grain counts ear^{-1}, which are a function of row ear^{-1} and kernel number ear^{-1}, have a direct

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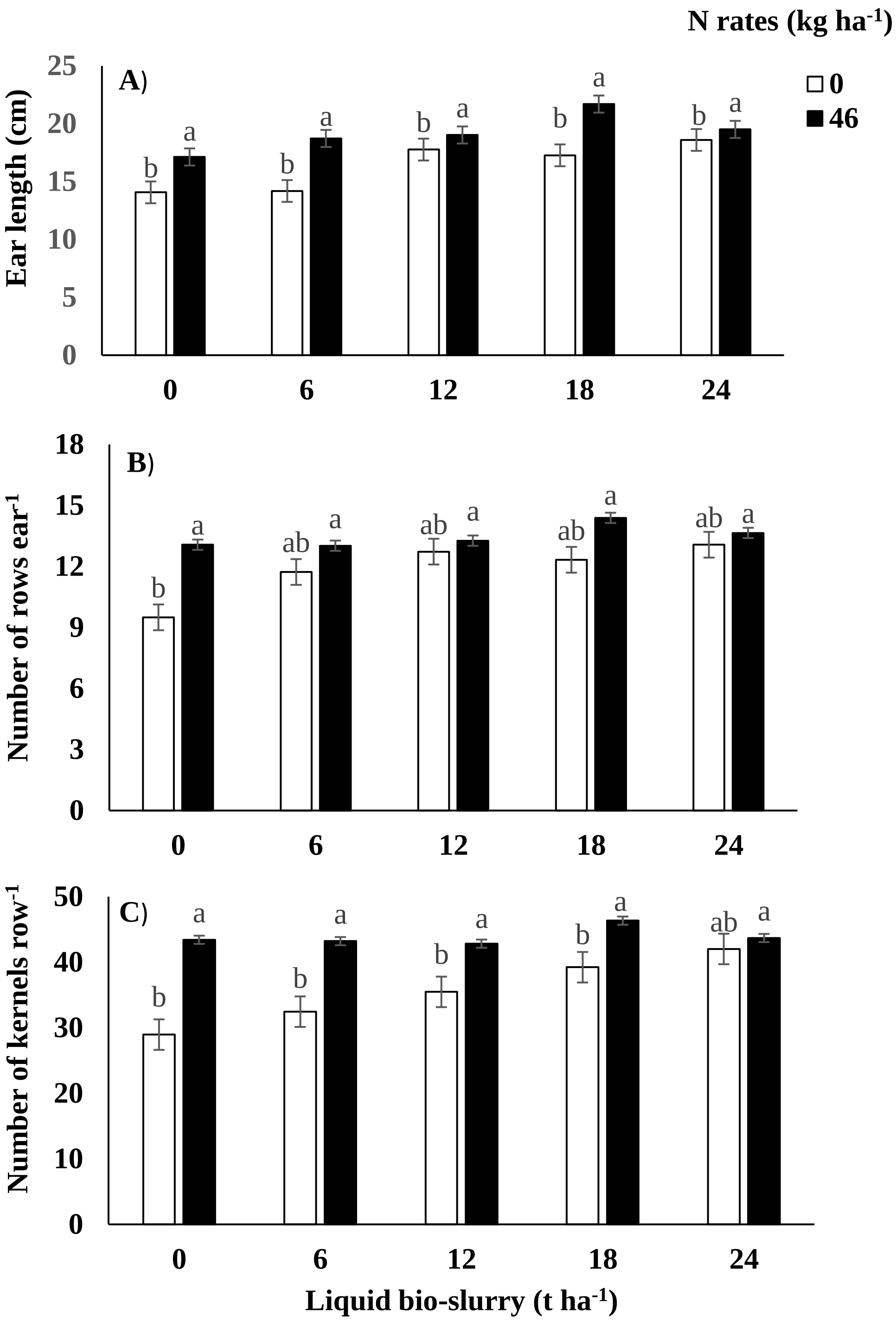

Figure 4. Interaction effects of mineral N and liquid bio-slurry rates on A) Ear length; B) Number of rows ear^{-1}; C) Number of kernels row^{-1}. Vertical S.E. bars followed by dissimilar letters significantly differ at *p*< 0.05.

influence on maize grain production unit area^{-1} (Inamullah et al., 2011).

Number of kernels row^{-1}

The number of kernels row^{-1} in maize significantly influences the final grain yield. The results from the present findings revealed that the interaction effects of mineral N and liquid bio-slurry had a highly significant ($p< 0.01$) effect on the number of kernels row^{-1}. When 46 kg of N and 18 t of liquid bio-slurry were applied together, the number of kernels row^{-1} increased by 60.0% compared to the control (Figure 4C). This might be because there is less competition for nutrients across maize crops, allowing the plant to store more biomass and convert more photosynthesis to a sink, increasing the number of kernels row^{-1}. This result is consistent with the findings of Hammad et al. (2011). Selassie (2015) also demonstrated a significant increase in the number of kernels row^{-1} of maize with an increase in the N fertilizer rate.

Number of kernels ear^{-1}

Based on the combined analysis results from the two experimental sites, the number of kernels ear^{-1} was significantly affected ($p< 0.01$) by the interaction effects of mineral N and liquid bio-slurry rates. The maximum number of kernels ear^{-1} (666.82) was obtained from the plants that received 46 kg ha^{-1} N with 18 t ha^{-1} liquid bio-slurry. However, the minimum number of kernels ear^{-1} (273.53) was recorded from the control plot (Figure 5A). The combined application of 46 kg N ha^{-1} with 18 t liquid bio-slurry ha^{-1} produced 393.3 (143.8%) more kernels ear^{-1} than the control. This is mainly due to the fact that at maturity, approximately two-thirds of the applied N is absorbed by the plant and ends up in the kernels. As a result, the number of kernels ear^{-1} was higher in treatments that received the optimal amount of organic and inorganic fertilizer sources. This, in turn, impacts the number of grains ear^{-1} and maximizes the potential yield (Belfield and Brown, 2008). It could also be attributed to the synergistic effects of mineral N and liquid bio-slurry fertilizers, which increased nutrient use efficiencies and maize growth. The result is also consistent with the findings of Demissie et al. (2017), who reported more kernels spike^{-1} of barley from the integrated application of 611 kg lime + 5 t compost + 150 kg NPSB [NPSB =nitrogen, phosphorus, sulfur, and boron] + 100 kg KCl + 72 kg N ha^{-1} compared with the control.

Above-ground biomass yield

Above-ground biomass production, which expresses relative growth rates as a net assimilation rate, is one measure of plant development (Khan et al., 2008). The interaction effects of mineral N and liquid bio-slurry had a highly significant ($p < 0.01$) effect on the above-ground biomass yield of maize. Its highest value (18330.0 kg ha^{-1}) was recorded from the application of 46 kg ha^{-1} N and 18 t ha^{-1} liquid bio-slurry. The lowest (6844.74 kg ha^{-1}) above-ground biomass was produced from the control plot (Figure 5B). Compared to the control plot, applying 18 t ha^{-1} of liquid bio-slurry and 46 kg ha^{-1} of N increased above-ground biomass yield by 11,485.3 kg ha^{-1} (167.8%). In line with the present finding, Demissie et al. (2017) also reported that plots treated with lime, compost, NPSB, and N fertilizer yielded the highest above-ground dry biomass compared with the control plots. Similarly, Bhatt et al. (2020) reported that the combined organic and inorganic fertilizer applications improved the above-ground dry biomass yield.

Straw yield

The combined results of the study from both locations showed that the rates of liquid bio-slurry and N had highly significant ($p < 0.01$) effects on maize straw yield. The highest straw yield (10308.6 kg ha^{-1}) was recorded from 46 kg ha^{-1} N with 24 t ha^{-1} liquid bio-slurry, which is 142.3% higher than the control.

The lowest straw yield (4254.92 kg ha^{-1}) was obtained from the control (Figure 5C). Such an improvement was achieved because N enhanced vegetative growth, leading to increased dry matter production and straw yield. In line with the current findings, Sanjivkumar (2014) and Khan et al. (2016) reported that the combined use of 50% organic and 50% inorganic fertilizers produced the highest straw yield and other yield components of maize compared with the sole application of organic or mineral fertilizers. Demissie et al. (2017) also reported the highest mean straw yield of barley using 611 kg lime ha^{-1}, 5 t compost, 150 kg NPSB, 100 kg KCl, and 72 kg N ha^{-1} compared to the control. Shilpashree et al. (2012) also indicated that the use of 50% N through inorganic fertilizer plus 50% N through organic fertilizer and 75% N through inorganic fertilizers plus 75% N through organic fertilizer resulted in significantly increased straw and grain yields.

Hundred-grain weight

The combined analysis results from two sites showed that the interaction of mineral N and liquid bio-slurry rates had a significant ($p < 0.01$) effect on the hundred-grain weight. The heaviest (36.93 g) weights of 100 seeds were achieved from the combined application of 46 kg N ha^{-1} with 18 t liquid bio-slurry ha^{-1}. The lowest weight of 100 seeds (27.1 g) was recorded from the control (Figure 6A). The improvement in grain weight due to the applied treatment was 9.83 g (36.3%). Such improvement in grain weight due to the applied treatments could be attributed to the synergistic effects of combining organic and mineral fertilizers for improved maize growth and grain filling. It may also be due to the applied N treatments responsible for grain filling, which improve grain thickness and integrate fragmentation with the seeds. In agreement with this result, Golla (2018) reported increased grain weight due to increased fertilizer rates from 92 kg ha^{-1} to 115 kg ha^{-1} at Bako, Western Ethiopia. Similarly, Gurmu and Mintesnot (2020) reported that the larger ear size provided enough area for the development of an individual grain, resulting in a greater hundred-grain weight with a sufficient supply of N fertilizer and farmyard manure. Moreover, Onasanya et al. (2009) reported a higher hundred-grain weight from the higher doses of NP from organic and inorganic fertilizers than the control. Woldesenbet and Tana (2014) also found a maximum hundred-grain weight of barely using 5 t ha^{-1} of farmyard manure combined with 75% inorganic NP compared with the 100% recommended rate of mineral NP.

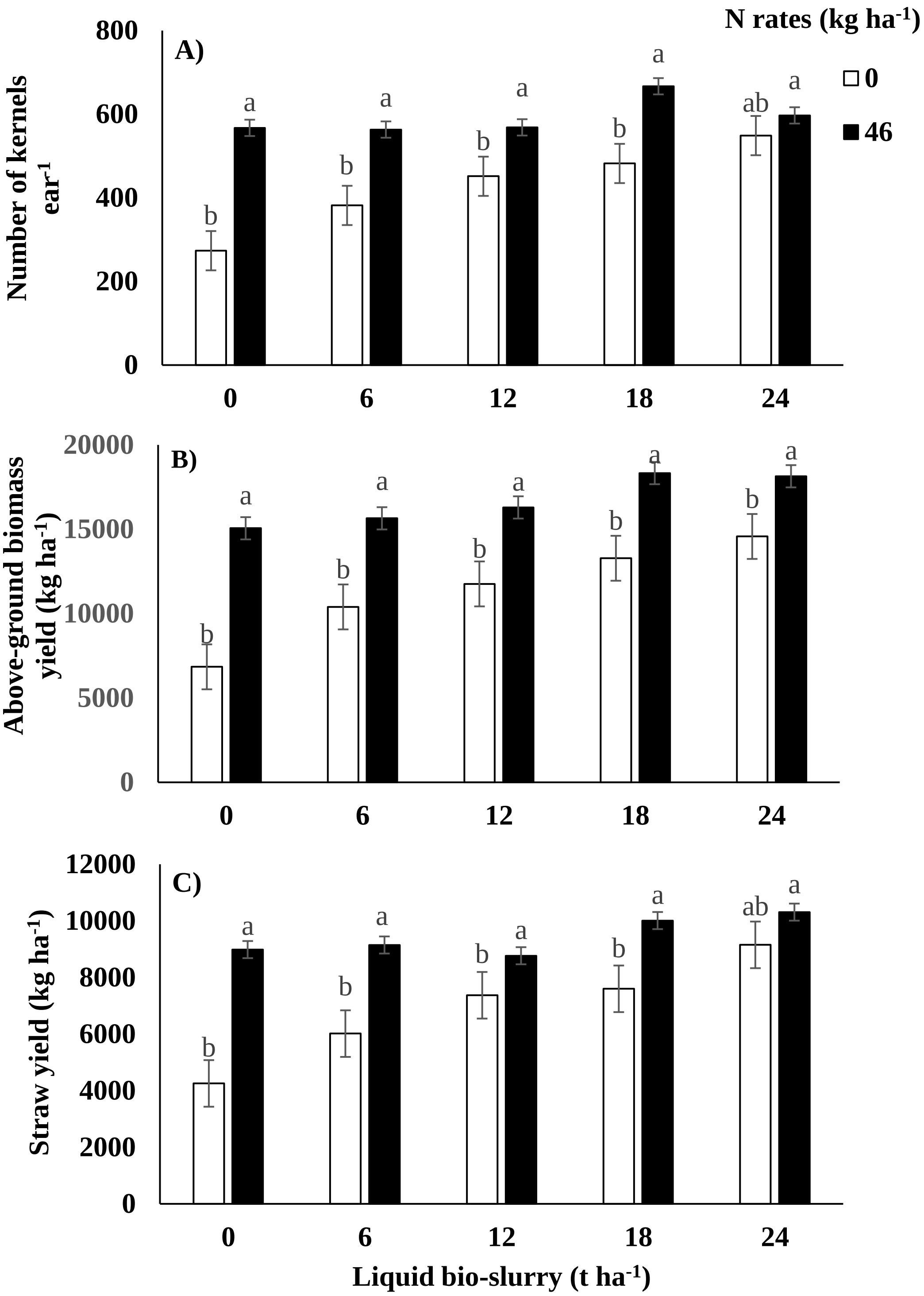

Figure 5. Interaction effects of mineral N and liquid bio-slurry rates on A) Number of kernels ear^{-1}; B) Above-ground biomass yield; C) Straw yield. Vertical S.E. bars followed by dissimilar letters significantly differ at *p*< 0.05.

Grain yield

The interaction of mineral N and liquid bio-slurry had significant ($p < 0.05$) effects on the grain yield of maize. The maximum grain yield of 8220 kg ha^{-1} was achieved by applying 46 kg ha^{-1} of N and 18 t ha^{-1} of liquid bio-slurry. The lowest grain yield (2590 kg ha^{-1}) was obtained from the control plot (Figure 6B). Such improvement could be attributed to the fact that the applied N nutrient might boost vegetative growth and influence grain production in maize (Zhengrui et al., 2008). The application of N increases the greenness of plants, CO_2 assimilation rate, and crop quality yield and improves resistance to environmental stresses such as limited water availability and saline soil conditions (Chen et al., 2010), which contributes to the improvement of grain yield. Wang et al. (2019) also found that N deficiency stress lowers crop photosynthesis by slowing leaf area development and photosynthesis rates, resulting in lower final grain production, which is consistent with

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the results reported in this study at the lowest rate of N. In agreement with the present findings, Dinka et al. (2018) and Naiji and Souri (2018) reported a better grain yield of maize from integrated nutrients compared to the recommended use of mineral or organic fertilizers alone. Similarly, Getnet and Dugasa (2019) reported the greatest grain yield when 120 kg N ha^{-1} and 60 kg P ha^{-1} were used together. In addition, other authors have also reported that when organic and inorganic fertilizers are used in an integrated form, crop improvement is usually larger (Fairhurst, 2013; Mugwe et al., 2019).

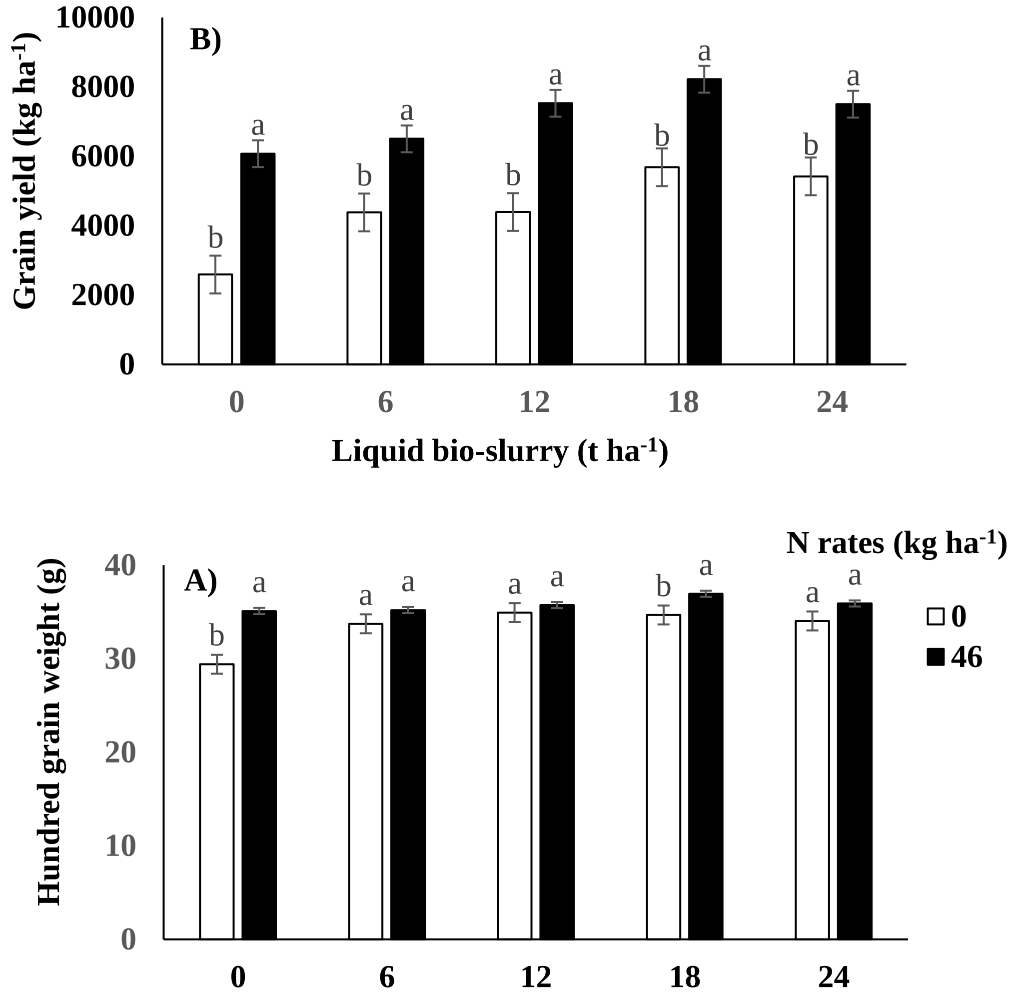

Figure 6. Interaction effects of mineral N and liquid bio-slurry rates on A) Hundred grain weight; B) Grain yield. Vertical S.E. bars followed by dissimilar letters significantly differ at *p*< 0.05.

Conclusion

Liquid bio-slurry alone or in combination with mineral N fertilization, increased grain yield and other yield components of the maize tested at the Wondo Genet and Hawassa University Research site during the 2021/22 cropping season. The significant increase in yield resulting from the recommended N application [46 kg N ha^{-1}], along with the supply of 18 t ha^{-1} of liquid bio-slurry, supports the recommendation of these agronomic inputs for use by resource-poor farmers in the country. The use of liquid bio-slurry can replace expensive chemical N fertilizers, which are inaccessible to smallholder farmers in the country and are also known to cause global warming. Therefore, maize producers can maximize their productivity through the integrated use of 46 kg N ha^{-1} with 18 t of liquid bio-slurry ha^{-1} around the study sites and areas with similar agroecologies. However, further research is needed to explore bio-slurry's application across various crop systems and agro-ecological zones.

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Conflict of Interest

The authors declare no conflict of interest.

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