Response of Maize (*Zea mays* L.) Varieties to Rates of Mineral Nitrogen Fertilizer Application in Haramaya District, Eastern Highlands of Ethiopia

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Abstract

Background: Maize is an important food security crop cultivated in Ethiopia. However, the productivity of the crop is markedly low due to low soil fertility and associated with low soil nutrient availability especially nitrogen and phosphorous deficiencies and the use of inappropriate fertilizer management practices.

Objective: A study was conducted in Haramaya District to investigate the effects of mineral nitrogen fertilizer application rates on yield components and yields of maize varieties during the 2019 and 2020 main cropping seasons.

Materials and Methods: The treatments consisted of two improved maize varieties (BHQPY 545 and MHQ 138), one composite open-pollinated variety (Raare-1), and six rates of nitrogen fertilizer (0, 23, 46, 69, 92, and 115 kg N ha^{-1}). The experiments were laid out as a randomized complete block design in a factorial arrangement and replicated three times per treatment. Data were collected on thousand kernel weight, stover yield, grain yield, and agronomic nitrogen efficiency. The data were subjected to analysis of variance.

Results: The main effect of nitrogen application significantly ($p \leq 0.05$) affected thousand kernel weight and harvest index. The highest thousand kernel weight (346.6 g) and harvest index (44.8%) were obtained in response to the application of 92 kg N ha^{-1}. The interaction effect of maize variety and nitrogen rate significantly ($p \leq 0.05$) influenced stover yield, grain yield, and agronomic nitrogen efficiency. The highest stover yield (9.62 t ha^{-1}) and grain yield (9.13 t ha^{-1}) were recorded for variety BHQPY 545 at 92 kg N ha^{-1}, which resulted in 55.6% and 67% more grain yield than MHQ 138 and Raare-1 varieties, respectively. The MHQ 138 and Raare-1 varieties produced only 5.9 t ha^{-1} and 5.5 t ha^{-1} grain yield at 92 kg N ha^{-1}, respectively. The highest net benefit (138222 Ethiopian Birr ha^{-1}) at 115 kg N ha^{-1} and marginal rate of return of 301% were obtained from variety BHQPY 545 at 69 kg N ha^{-1}.

Conclusion: It is concluded that the BHQPY 545 variety produced the optimal grain and stover yields, with the highest net benefit and marginal rate of return at 69 kg ha^{-1} as well as with the highest agronomic nitrogen efficiency that exceeded the agronomic nitrogen efficiency of MHQ 138 and Raare-1 by about 2.4-fold and three-fold, respectively. This implies that cultivating this variety at a relatively moderate rate of nitrogen fertilizers enhances the yield of the crop for improving food security and farmers' livelihood in the study area.

Keywords: Agronomic N use efficiency; Economic analysis; Grain yield; Stover yield

1. Introduction

Maize plays a significant role in ensuring food and nutrition security in countries like Ethiopia, where a rapidly increasing population is outstripping available food supplies (Ahmad *et al*., 2018). The crop has become a major staple food crop in Ethiopia especially given that the prices of other staple crops, such as teff and wheat, are rising constantly beyond the means of resource-poor consumers, and their yields generally fall short of household needs (Agrawal *et al*., 2018).

In Ethiopia, over the last six years (2012 to 2017), maize yield has generally increased from 0.73 to 2.89 t ha^{-1} (Tsedeke Abate *et al.,* 2015). Despite the increment in area coverage (2,526,212.36 ha), the number of smallholder farmers involved in producing the crop (10,189,355), and demand for maize, the national average yield of the crop has remained low (4.2 t ha^{-1}) (CSA, 2021), while the potential attainable yield under the research field is about 9.5 t ha^{-1} (Adefris Teklewold *et al*., 2015), and the global average yield of 5.97 t ha^{-1} (FAOSTAT, 2019; USDA, 2021). Similarly, Adefris Teklewold *et al.* (2015) found yields of 8.0 to 9.5 t ha^{-1}, 7.5 to 8 t ha^{-1} under demonstration plots for BHQPY 545 and MHQ 138 varieties, respectively, and 5.5 to 6.5 t ha^{-1} under farmers' fields in the same order. For the Raare-1 variety, the average yield from demonstration plots (research) is reported to be 6 to 8 t ha^{-1}, and 4 to 4.5 t ha^{-1} under farmers' fields (Mandefro Nigussie *et al*., 2002). Additionally, higher grain yields of maize (Melkassa I), which amounted to 3.87 and 5.07 t ha^{-1} in

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the Babile and Dire Dawa areas, respectively, were obtained with the application of 64 kg N ha^{-1} and 20 kg P ha^{-1}(Hassen Abdulahi *et al.*, 2006).

In Ethiopia, the current national average yield of maize indicated above is still much lower than the average yields obtained in other countries such as Turkey (11.45 t ha^{-1}), the United States (10.79 t ha^{-1}), Canada (9.63 t ha^{-1}), Argentina (7.7 t ha^{-1}), and Egypt (8 t ha^{-1}). The maize yield gaps observed in the country between the farmers' fields, research fields, and the world's average yield are mainly attributed to a lack of innovation and low adoption of improved agricultural technologies, use of low-yielding local varieties, poor nitrogen fertilizer management (inappropriate timing and dosing), rapid decline in soil fertility primarily due to continuous cropping without replenishing depleted nutrients, poor agronomic practices, erratic rainfall, disease, and others (Alemu Lelago *et al.,* 2016; Yemane Mebrahtu and Habtamu Tamiru, 2018; Banchayehu Tessema *et al.*, 2020).

Maize is a highly nitrogen-demanding crop and consistently responds to a high rate of N regardless of location and season of production (EIAR, 2015). Nitrogen fertilizer plays a prominent role in determining the overall physiological process contributing to the higher productivity and quality of the maize crop (Ariraman *et al.*, 2020). Nitrogen (N) is the most limiting nutrient in agricultural production for optimum yield and biomass (Asibi *et al.*, 2022). In the past four decades, global maize production has greatly increased (FAO, 2018) mainly due to the application of nitrogen (N) fertilizers. A high yield of maize can be obtained through the appropriate use of nitrogen, which can alone contribute to 40 to 60 % of the crop yield (Das *et al.,* 2010). Increasing N fertilizer input alone could close a large part of the yield gap (Mueller *et al.*, 2012).

A decade (2004–2013) study showed that the use of mineral fertilizers accelerated the growth of maize productivity in Ethiopia, though the used rate was insufficient and amounted to only 34–40 kg N ha^{-1} for maize (Tsedeke Abate *et al.,*2015). However, the national recommendation is about 110–130 N kg ha^{-1} (MoA, 2010), as cited by Dawit Alemu *et al.* (2014). In general, in Ethiopia, only 30% to 40% of smallholder farmers use chemical fertilizers (MoA, 2010), while those using nitrogen fertilizers apply on average only 37 to 40 kg N ha^{-1}, which is much lower than the national recommended rate (MoA, 2010), as cited by Dawit Alemu *et al.* (2014).

To date, the optimum recommended nitrogen and phosphorus fertilizer rates for the production of hybrid and open-pollinated maize varieties are 119 kg N ha^{-1} and 30 kg P ha^{-1} for the Bako area (central Ethiopia) with an average grain yield of 6.4 t ha^{-1}; 119 kg N ha^{-1} and 30 kg P ha^{-1} for the Jimma area (western Ethiopia), with an average grain of 6.1 t ha^{-1}; 110 kg N ha^{-1} and 20 kg P ha^{-1} for the Hawassa area (Southern Ethiopia) with an average grain yield of 7.9 t ha^{-1} (Wakene Negassa *et al.*, 2012); 87 kg N ha^{-1} and 20 kg P ha^{-1} for the Haramaya area (Eastern Ethiopia) (Wakene Negassa *et al.*, 2011), with an average yield of 4.29 t ha^{-1} (CSA, 2021). Moreover, farmers in the Hararghe area even do not apply such recommended fertilizer rates. This is because fertilizers prices have been rising steeply in the country and farmers have been unable to afford fertilizers. Furthermore, maize production in Hararghe Zones is constrained also by the shortage of farmland as well as the total removal of crop residues for some competing ends such as animal feed, fuelwood, construction, and sale to generate income. These practices exacerbate nutrient depletion in the soil because there is little or no addition of nutrients removed by crops from the soil as well as organic carbon removed with crop residues. Cultivating farmland repeatedly without crop rotation or fallowing practice causes depletion of nutrients and organic matter (Geremu Tadele *et al.*, 2021).

In addition, almost all maize varieties grown in the Hararghe Zones are local varieties that are devoid of essential amino acids such as lysine and tryptophan (Gemechu Nedi *et al.*, 2016) and cannot sustain an adequate supply of nutrients for human health. Although people have access to staple food, their knowledge of diversification of food remains limited, and very low consumption of valuable protein sources (animal proteins such as meats, eggs, and dairy products) implied the low nutritional value of the diet (ACF, 2014). Moreover, to adapt to climate change and improve the grain yield of maize, farmers are now being offered options to cultivate different maize varieties. However, no research has been done recently to determine the response of different maize varieties to the application of mineral nitrogen fertilizer in the eastern highlands of Ethiopia. Therefore, the use of higher nitrogen use efficiency nutritious quality maize (QPM) and local cultivars with an appropriate rate of nitrogen fertilizer would substantially improve maize yield and the protein supply. In this study, it was hypothesized that increasing the rate of mineral nitrogen fertilizer increases the grain yield of maize varieties and the maize varieties respond to the application of N fertilizer differently. Therefore, the objective of this research was to investigate the effect of applying different rates of nitrogen fertilizer on yields of maize varieties in Haramaya district, eastern Ethiopia.

2. Materials and Methods

2.1. Description of the Study Site

The field experiment was conducted at the Haramaya University's Rare Experimental Farm located at 9.63° N latitude and 42.051° E longitude and an altitude of 2022 meters above sea level during the 2019 and 2020 main cropping seasons. The selected physical and chemical properties of the soil of the study site were specified in Table 2. The site is characterized by a bimodal rainfall pattern with a short rainy season stretching from March to May, while the main rainy season extends from July to September, with the peak in August, having a mean annual rainfall of 500 to 800 mm in 1995–2017 (Ethiopian National Meteorology Agency). The mean maximum and minimum temperatures were 24.18 and 9.9 °C, respectively. In the 2019 and 2020 growing seasons, the rainfall amounted to 816 and 1137 mm, respectively (Figure 1).

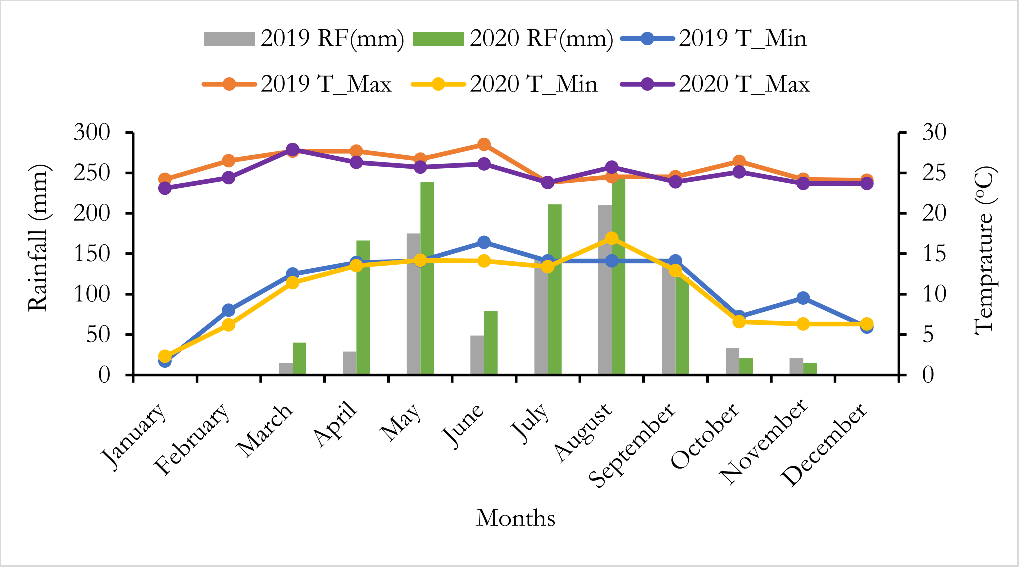

Figure 1. Monthly rainfall (mm) and monthly mean maximum and minimum temperatures (°C) of the experimental site during the 2019 and 2020 main growing seasons (Ethiopian National Meteorology Agency).

2.2. Planting and Fertilizer Materials

The planting material included seeds of maize varieties, namely, BHQPY 545, MHQ 138, and Raare-1, which are well adapted to the agroecological conditions of the area. Seeds of the BHQPY 545 and MHQ 138 varieties were obtained from Bako and Melkasa Research Centers whereas that of Raare-1 was obtained from the seed unit of Haramaya University. BHQPY 545 and MHQ 138 are hybrid varieties, whereas Raare-1 is an open-pollinated variety. A seed rate of 25 kg ha^{-1} (MoA, 2008) was used, and a detailed description of the varieties is presented in Table 1. Urea [$CO(NH_2)_2$] (46% N) and triple super phosphate (TSP) [$Ca(H_2PO_4)_2$] (20% P) were used for this experiment as sources of nitrogen and phosphorous, respectively.

Table 1. Description of maize varieties used in the experiment.

Variety	Year of release	Altitude (m)	Rainfall (mm)	Plant height (cm)	DM	yield (t ha^{-1})	
						RC	FF
BHQPY545*	2008	1000–1800	1000-1200	250–260	144	8.–9.5	5.5–6.5
MHQ138*	2012	1000–1600	600-1000	200–235	140	7.5–8	5.5–6.5
Raare-1	1997	1600–2300	900-1100	250–270	163	6–8	4–4.5.0

Note: ** QPM variety; DM = days to maturity; RC = Research center; FF = Farmers' fields.*

2.3. Treatments and Experimental Design

The treatments comprised six nitrogen fertilizer rates (0, 23, 46, 69, 92, and 115 kg N ha^{-1}), two maize varieties (BHQPY 545 and MHQ 138), and one local check Raare-1 with a total of 18 treatments. The experiment was laid out as a randomized complete block design in a factorial arrangement and replicated three times per treatment. The treatments were assigned to each plot randomly.

2.4. Experimental Procedures

2.4.1. Soil sampling, preparation and analysis

Before starting the experiment, surface soil samples were collected randomly in a W-shaped pattern from seven different spots of the entire experimental field at depths ranging from 0 to 20 cm using an auger. The samples were composited and replicated three times. The samples were air-dried and ground to pass through a 2 mm diameter sieve for determining most of the selected soil's physical and chemical properties. However, for determining organic carbon and total nitrogen contents, the soil sample was further crushed to pass through a 0.50 mm sieve diameter. The soil samples were analyzed in Haramaya University's soil laboratory. Soil textural class was determined by the Bouyoucous hydrometer method (Bouyoucos, 1951). Soil pH was determined at a soil: water ratio of 1:2.5 using a glass electrode pH meter (Black, 1986). Total nitrogen was analyzed using the Micro-Kjeldahl method (Bremner and Hauck, 1982). Soil organic carbon was determined by the chromatic acid oxidation method (Walkley and Black, 1934). Soil available phosphorus was analyzed using the Olsen method (Olsen *et al*., 1954). Exchangeable cations were measured by flame photometry after extracting Na^+ and K^+ from the soil with 1 N ammonium acetate (NH4OAc) at pH 7 using the procedures described by Black (1986).

2.4.2. Field preparation and planting

For proper seedbed preparation, the site was plowed by a tractor and left for three weeks. Then, the individual plots were prepared with a length of 3.0 m long and a width of 3.75 m (11.25 m^2) by keeping 1.0 m and 1.5 m wide paths between plots and blocks, respectively. The outer row from each side was considered a border row with edge effects, and plants in such rows were not considered for collecting data. In addition, one plant at the end of each row was excluded to remove edge effects. Hence, a net plot area spanned 2.25 m x 2.4 m (5.4 m^2), containing three rows with 24 plants. Maize was sown at the spacing of 30 cm between plants and 75 cm between rows (Adefris *et al*., 2015).

Two seeds were planted per hill on 25 May 2019 and 28 May 2020. At the three to the four-leaf stage, the maize seedlings were thinned to maintain the optimum plant population, by uprooting and discarding the weak, insect-damaged, and diseased plants and leaving the vigorously growing ones. According to the prescribed rates indicated in the experimental design above, urea was applied twice, half at sowing, and the other half at tillering (six to eight leaf stage). To reduce N loss, the fertilizer was applied late in the afternoon in rows and covered with soil. The recommended dose of phosphorus (20 kg ha^{-1} P) in the form of triple superphosphate (TSP) was applied at equal rates to all of the experimental plots in rows at the time of sowing and covered with soil. Controlling weeds and other cultural practices were performed as required throughout the growth period. For harvesting, maize ears were detached from the mother plant by hand at maturity, while stover was cut at the ground level using a hand sickle.

2.4.3. Data Collection and Measurements

2.4.3.1. Yield and yield components

Number of kernels per ear: After harvest, five ears were randomly taken from each experimental net plot area, sun-dried, and separately shelled. Then, the number of kernels of each ear was counted, and the average kernels per ear were computed from five ears.

Thousand kernels weight (g): From each experimental net plot, a total of 1000 kernels were counted using a Contador seed counter and weighed with an electric balance, and then the average weight was expressed as 1000-kernel weight at 12.5 moisture content.

Stover yield: After the mature ears were removed from each plant of the net plot area, all plants were cut at ground level, sun-dried until attaining a constant weight, and then weighed.

Converting stover yield to hectare

$$= \text{stover yield kg plot}^{-1} \times \frac{10000\ m^2}{\text{Net plot area } (m^2)}$$

Grain yield: After harvesting the crop from the net plot areas, the ears were dried, the seeds were manually shelled from all ears of each net plot area, and their moisture content was determined immediately using a kernel moisture meter. The values of the moisture content were adjusted to the standard moisture content of 12.5% and then multiplied by field weight to determine the adjusted yield of the plot on a hectare basis using the following formula:

$$\text{Adjusted Yield (AY)} = \frac{\text{Actual yield weight x 100-Measured moisture content}}{\text{100-12.5}}$$

$$\text{Converting kernel yield to hectare} = \text{kernel yield kg plot}^{-1} \times \frac{10000\ m^2}{\text{Net plot area } (m^2)}$$

Harvest Index (%): The harvest index was computed as the ratio of kernel yield to the kernel plus stover yield of each net plot and expressed as a percentage.

Nitrogen agronomic efficiency: The nitrogen agronomic efficiency (kg kernel per kg N applied) was also calculated using the following formula (Fageria *et al.*, 2014):

$$\text{NAE (kg kg}^{-1}) = \frac{\text{Kernel yield kg ha}^{-1}\text{ added N} - \text{kernel yield kg ha}^{-1}\text{ control}}{\text{Amount of N fertilizer applied}}$$

2.5. Partial Budget Analysis

Economic analysis was performed following the CIMMYT partial budget procedure (CIMMYT, 1988). The stover and grain yields were adjusted downward by 10% to reflect the difference between the experimental yield and the yield of farmers. Then, the gross yield benefit was obtained by multiplying the adjusted yield by the price of stover and grain. The total cost that varied comprised the sum of the costs of fertilizer and seeds of the three varieties, with the cost of labor for fertilizer application established by negotiation. The net benefit was calculated as the difference between the gross field benefit (Ethiopian-birr ha^{-1}) and the total costs (Ethiopian-birr ha^{-1}) that varied. The field price of maize was calculated as the sale price minus the harvesting, threshing, winnowing, bagging, and transportation. The marginal rate of return analysis of non-dominated grain yield responses for different N fertilizer rates was performed following the CIMMYT method.

2.6. Data Analysis

Statistical analysis software (SAS version 9.4) was used to perform an analysis of variance (ANOVA). To detect significant mean differences between treatments, Tukey honestly significant difference (HSD) test was used. Pairwise mean comparisons were made at $p \leq 0.05$ probability level. Each year's data was separately analyzed for agronomic parameters, and homogeneity of variances was tested using error mean square (EMS), considering years of growing as a random variable. Since the highest EMS was not three-fold larger than the smallest EMS, the error variances were considered homogeneous, and a combined analysis of variance was undertaken as described by Gomez and Gomez (1984).

3. Results and Discussion

3.1. Physical and Chemical Properties of Soil of the Experimental Site

The results of the physical and chemical properties of the soil of the study site are presented in Table 2. Accordingly, the soil is sandy clay loam in texture. According to Wibberley (2006), the suitable pH range for cereal crops ranges between 6.5 and 7.0, in which N availability is optimum. Maize can be cultivated on different types of soil, but the crop performs best on well-drained deep loams and silt loams containing adequate organic carbon and available nutrients and can grow well on soils with a pH value ranging between 5.9 and 7.0 (Wibberley, 2006). In soils where high pH can be a problem, maize can tolerate up to 8.5 (Wibberley, 2006).

According to the rating of Murphy (1968), the soil of the experimental site is mildly alkaline, considering that it is almost optimal for the production of maize without amending pH as indicated by Wibberley (2006). The available phosphorus content of the soil was found to be medium according to the rating of Cottenie (1980). Therefore, the soil has no limitation in P availability for producing the crop. The cation exchange capacity of the soil was found to be medium according to the rating of Landon (1991), indicating that there is adequate availability of cations for uptake by plant roots. However, the soil organic carbon content was found to be low according to the rating of Berhanu Debele (1980) as cited by Tekalign Tadese *et al.* (1991), indicating poor soil health and low activities of microorganisms which could enhance the mobilization of nutrients for uptake by plant roots. The total nitrogen content of the soil was found to be low according to the rating of Berhanu Debele (1980) as cited by Tekalign Tadese *et al.* (1991), indicating a low rate of mineralization of nitrogen contained in organic matter for release into the root zone for plant uptake in the form of nitrate and ammonium. Therefore, based on the results of the selected soil chemical properties, investigating the response of maize varieties to mineral nitrogen fertilizer was justified.

Table 2. Selected physical and chemical properties of soils of the experimental site in Haramaya district during the 2019 and 2020 main cropping season.

Soil property	Value	Rating	References
Sand (%)	61.0	–	
Silt (%)	16.8	–	
Clay (%)	22.2	–	
Textural class	Sandy clay loam		
pH (1: 2.5 H_2O)	7.54	Mildly alkaline	Murphy (1968)
Total N (%)	0.02	Low	Berhanu Debele (1980) as cited by Tekalign Tadese *et al.* (1991)
Organic carbon (%)	1.35	Low	Berhanu Debele (1980) as cited by Tekalign Tadese *et al.* (1991)
Available P mg kg soil^{-1}	14.60	Medium	Cottenie (1980)
CEC $cmol_c$ kg^{-1}	24.53	Moderate	Landon (1991)

3.2. Effect of Year, Nitrogen, and Variety on Yield Components and Yield of Maize

Analysis of variance revealed that the main effects of year, N rate, and variety significantly ($p \leq 0.01$) affected yield components (total number of kernels ear^{-1}, and 1000-kernel weight). Harvest index (HI) was influenced by the main effects of N rates, and variety, and stover yield, grain yield, and agronomic efficiency were influenced by the main effects of year, N rate, variety, and the interaction of variety with N rates. Year x rates of N, year x variety, and year x rates of N x variety, on the other hand, had no significant effect on these variables (Table 3).

Table 3. Mean squares of ANOVA for yield components, and yield of maize in Haramaya district during the 2019 and 2020 growing seasons.

Source of variation	df	Number kernels/ear	1000-kernel weight	Harvest Index	Stover yield	Grain yield	Agronomic efficiency
Year	1	142281**	17531.26**	10.8^{ns}	7064158**	6342394**	141.21**
Nitrogen rate (NR)	5	271103**	10369.09**	496.0**	7064132**	68130231**	1979.6*
Variety (VAR)	2	15410**	7324.53**	748.6**	9242821**	60079866**	1673.23**
Year x NR	5	1136^{ns}	153.24^{ns}	1.8^{ns}	432803^{ns}	131084^{ns}	12.08^{ns}
Year x VAR	2	1222^{ns}	22.62^{ns}	0.2^{ns}	222797^{ns}	9328^{ns}	16.47^{ns}
NR x VAR	10	370^{ns}	156.78^{ns}	18.7^{ns}	1304078**	3950664**	209.16**
Year x NR x VAR	10	406^{ns}	57.16^{ns}	1.9^{ns}	88814.1^{ns}	16671 ^{ns}	
Error	68	1941	687.62	17.08	328548	523475	5.22
Corrected total	107						
CV (%)		8.43	8.02	10.26	8.10	14.11	6.22

Note: *ns = not significant; *and ** = significant at 5% and 1% probability levels, respectively; df = degree of freedom; and CV= Coefficient of variation.*

Kernel number per ear

Statistical analysis of the data showed that kernel number per ear was significantly ($p \leq 0.01$) affected by the main effects of year, rate of nitrogen application, and maize variety (Table 3). However, it was not significantly influenced by the two-factor interaction effects of year and nitrogen rate, year and variety, and nitrogen rate and variety. Furthermore, the two-way or three-factor interactions of year, nitrogen rate, and variety did not significantly affect kernel number per ear (Table 3).

The analysis of variance also indicated that the number of kernels produced per ear was also influenced by the year of growing the crop. The total number of kernels ear^{-1} produced in 2019 exceeded that produced in 2020 by about 15.3%, which is probably attributable to the differences in the amount of rain that fell during the year 2019 (Figure 1), even though temperature changes over the growing seasons were comparable. This indicates that 2019 was more favorable for the growth and development of the maize crop than 2020. The optimum rainfall during the growing period of maize in the temperate region amounts to 460 to 600 mm whereas it is about 600 to 900 mm in the tropics (Fageria *et al*., 2010). Similarly, Albayrak (2021) indicated that maize performs optimally in regions that receive an annual rainfall of 700–750 mm. The total amount of rainfall received during the 2019 cropping season, most of which fell during the growing season amounted to 816 mm. This was within the range of rainfall required for the growth of maize in tropical regions (Fageria and Baligar, 2010). However, the amount of rain that fell during the 2020 growing year, most of which fell during the growing season of the crop amounted to 1137 mm, which was above the requirement of the crop. This excess rain may have led to the leaching of nitrate and other cations that could have suppressed kernel growth and development. Thus, the loss of nitrate from the root zone of the plant may have resulted in a deficiency of nitrogen, leading to lower growth and development of the variables listed above. Consistent with this postulation, Xia *et al.* (2021) suggested that heavy rain increases the risk of nitrate leaching into the deep soil.

Increasing the rate of nitrogen fertilizer from nil to 115 kg N ha^{-1} progressively increased the total number of maize kernels produced per ear (Table 4). The highest number of kernels per ear was produced at the highest rate of N fertilizer application (115 kg N ha^{-1}). The lowest number of kernels per ear was obtained at the nil rate of nitrogen fertilizer. Increasing the rate of the fertilizer further from nil to 23, 46, 69, 92, and 115 kg N ha^{-1} increased the number of kernels produced per ear by about 15%, 39%, 52%, 73%, and 89%, respectively (Table 4). The consistent increase in kernel number ear^{-1} in response to the increased application of N fertilizer could be attributed to the possible availability of nitrogen in the soil for growth and kernel formation by the plant and its sufficiency at the application rate of 115 kg N ha^{-1}. A similar result of the effect of nitrogen fertilizer rate on the number of kernels produced per ear of maize was reported by Gul *et al.* (2015), who obtained higher numbers of kernels per ear (334.94) in response to the application of 90 kg N ha^{-1}.

The number of kernels produced per ear varied amongst the maize varieties (Table 4). The maximum number of kernels per ear was produced by the BHQPY 545 variety. The minimum number of kernels produced per ear was produced by the Raare-1 variety, which was in statistical parity with the number of kernels produced per ear by the MHQ 138 variety. The variation in kernel number produced per ear might be attributable to genetic differences among the maize varieties. Supporting our postulation, Hejazi and Soleymani (2014) stated that a significant variation in the number of kernels per ear was observed due to varieties.

Table 4. The number of kernels ear^{-1}, thousand kernel weight, and harvest index as influenced by the main effects of year, rate of nitrogen fertilizer, and variety of maize in Haramaya district during the 2019 and 2020 main cropping seasons.

Year	Number of kernel ear^{-1}	1000-kernel weight (g)	Harvest index (%)
2019	555.2^{a}	339.5^{a}	40.5
2020	481.5^{b}	314.0^{b}	39.8
Tukey HSD ($P \leq 0.05$)	16.9	10.1	ns
Nitrogen rates (kg ha^{-1})			
0	361.4^{f}	299.7^{d}	32.4^{e}
23	416.6^{e}	304.9^{d}	36.6^{d}
46	503.7^{d}	316.7^{cd}	39.5^{cd}
69	547.7^{c}	332.1^{bc}	41.4^{bc}
92	623.6^{b}	346.6^{ab}	44.8^{ab}
115	684.1^{a}	360.7^{a}	46.1^{a}
Tukey HSD ($P \leq 0.05$)	43.0	25.61	4.1
Maize variety			
BHQPY545	538.2^{a}	340.5^{a}	44.4^{a}
MHQ 138	516.8^{b}	327.8^{a}	40.3^{b}
Raare-1	495.8^{b}	312.0^{b}	35.7^{c}
Tukey HSD ($P \leq 0.05$)	24.9	14.8	2.3
CV (%)	8.4	8.1	10.4

Note: *CV = Coefficient of variation and HSD = Tukey honestly significant difference. Means followed by the same letters within each column are not significantly different ($p \leq 0.05$).*

Thousand kernel weights (g)

Thousand kernel weight was ($p \leq 0.01$) affected by the main effects of year, nitrogen rates, and maize varieties. However, this variable was not affected by the two and three-factor interaction effects (Table 3). Thousand kernel weight is an important factor directly contributing to the final grain yield of the crop (Khan *et al.,* 2014). The 1000 kernel weight produced in the 2019 cropping season exceeded that produced in 2020 by about 8.1%, which may be attributed to the optimum rain that fell during the 2019 cropping year and did not predispose the applied N fertilizer to loss by leaching (Figure 1). In the 2020 cropping season, excess rainfall (1137mm) (Figure 1), may have resulted in the loss of nitrogen in the form of nitrate (NO_3^{-1}) from the soil because of leaching.

Increasing the rate of nitrogen fertilizer from nil to 23 kg N ha^{-1} and 46 kg N ha^{-1} did not affect 1000 kernel weight. An optimum 1000-kernel weight was observed at 92 kg ha^{-1} N, which was statistically comparable to the 1000-kernel weight produced at 115 kg ha^{-1} N. The 1000-kernel weight obtained at 92 and 115 kg ha^{-1} N exceeded the 1000-kernel weight produced from nil fertilizer by about 16%, and 20%, respectively. The minimum 1000-kernel weight was observed in the control treatment, which had a statistical similarity with the 1000-kernel weight obtained in response to applying 23 and 46 kg N ha^{-1} (Table 4). The lack of response in terms of the 1000 kernel weight when the rate of nitrogen was increased to only 23 kg N ha^{-1} and 46 kg N ha^{-1} may be because the added amounts of the nutrient were not sufficient for raising the status of soil nitrogen to a level optimum for uptake by roots of the maize crop. Conversely, the increase in this variable in response to raising the rate of fertilizer to higher rates indicates the added amounts of fertilizer raised the level of available nitrogen in the soil for high uptake by the plant.

The increased 1000-kernel weight with increased rates of N could be attributed to the positive effect on increasing leaf area index and duration, thereby extending the kernel-filling period that may have allowed enough time for high accumulation of more photosynthetic assimilates for producing healthy, well-filled, and larger kernels. These results are in accord with the findings of Anwar *et al.* (2017), who reported that increasing the rate of nitrogen application promoted healthy growth and properly filled kernels. Corroborating the results of this study, Ngosong *et al.* (2019) also reported increases in maize 1000–kernel weight in response to the application of 200 kg N ha^{-1}.

The maize varieties also differed significantly in 1000-kernel weight. However, 1000-kernel weights of BHQPY 545 and MHQ 138 varieties were in statistical parity, but significantly higher than the 1000-kernel weight of Raare-1 variety by about 9% and 5%, respectively. The differences in the 1000-kernel weight might be attributed to genetic differences between the hybrid varieties (BHQPY 545 and MHQ 138) on the one hand and the composite variety (Raare-1) on the other hand. These results are concordant with that of Kandil (2013), who found significant differences in 1000-kernel weights of maize varieties, which they attributed to genetic diversity.

Harvest Index (%)

The harvest index significantly ($p \leq 0.01$) responded to the main effects of the rate of N fertilizer and variety. However, the harvest index did not respond to a year of growth, and the interaction of the two and three factors (Table 3). The possible cause for the statistical similarity in the values of the harvest index during both years may be the proportional growth of both the harvestable (kernel) part of the plant and its stover (biomass) yield. Consistent with this postulation, Ion *et al.* (2015) also reported that proportional grain and biological yields were obtained in different growing seasons, leading to comparable harvest indices.

Increasing the rate of nitrogen fertilizer increased the harvest index of maize. The optimum harvest index was already obtained at 92 kg N ha^{-1} (Table 4). The increased HI in response to the increased rates of nitrogen fertilizer may be associated with the key role that nitrogen plays in promoting photosynthesis, plant growth, and partitioning of photoassimilates, thereby enabling the crop to partition a higher percentage of total dry matter into the final grain yield.

Crop yield is mostly caused by a low crop harvest index, which is inversely related to biomass yield. Harvest index is a novel trait that is directly associated to yield and a crop's capacity to convert total dry matter into economic yield (Gemechu Asefa, 2019). According to Ion *et al.* (2015), the maize HI varied between 20% and 56%, and HI values between 30% and 60% were prominent in cereal crops (Hay, 1995), which confirms the range of our observations. The present findings corroborate the findings of Keyro Assefa and Zenebe Mekonnen (2019), who reported a maximum maize harvest index of 42% with the application of 160 kg N ha^{-1}, 31.4% with the application of 120 kg N ha^{-1}, and 28.5% with the application of 69 kg N ha^{-1} in the order listed here.

Likewise, HI significantly differed among the varieties of maize, and the maximum HI was recorded for the variety BHQPY545, while the lowest HI was obtained for the variety Raare-1 (Table 3). The increase in HI recorded for variety BHQPY545 exceeded the HI values recorded from varieties MHQ 138 and Raare-1 by about 10.2% and 24.4%, respectively. Consistent with the results of this study, Mekuannet Belay and Kiya Adare (2020) also recorded different HI amounting to 35% and 40% for varieties BHQPY545 and MHQ 138, respectively. The authors also attributed the differences in HI among the maize varieties to genetic variations.

Stover yield

The analysis of variance revealed that stover yield was significantly ($p \leq 0.01$) influenced by the main effect of year, variety, N rate, and the interaction of rate of N and variety. However, this variable was not significantly affected by the two-factor interaction effects of year of cropping and nitrogen rate and year and variety as well as the three-factor interaction of year, nitrogen rate, and variety (Table 3).

Increasing the rate of N significantly increased the stover yields across the three maize varieties. However, a more vigorous response to the applied N in terms of stover production was observed for varieties BHQPY 545 and Raare-1. Thus, the stover yield produced by the BHQPY 545 variety continued to respond to N fertilizer application up 69 kg N ha^{-1}, where the optimum stover yield was already obtained, which was in statistical parity with the stover yield obtained in response to the application of 92 and 115 kg N ha^{-1}. The next vigorous response to the increasing rate of N in terms of stover yield was shown by Raare-1, the maximum yield of which was obtained at 115 kg N ha^{-1} (Table 5), which was statistically comparable with the stover yield produced by BHQPY 545 variety at 69, 92 and 115 kg N ha^{-1}. The variations in stover yield among the varieties in response to nitrogen fertilizer may be ascribed to genetic differences in the uptake of nutrients from the soil. Accordingly, an efficient variety may take up available nutrients from the soil more effectively, leading to increased growth parameters of individual plants, a higher leaf area index, and helps to capture more light, enabling plants to use photosynthesis more effectively and eventually leading to a large accumulation of dry matter (Peng *et al*., 2010; Shen *et al*., 2013). The lowest stover yields were reported for all maize varieties at nil and 23 kg N ha^{-1}, showing that applying just 23 kg N ha^{-1} is insufficient to improve the availability of nitrogen in the soil for uptake of the nutrient by the maize plants.

Variety BHQPY 545 produced about 63.6% higher stover yield at 69 kg N ha^{-1} (optimum rate) than at nil rate of N. Similarly, Raare-1 produced a 50% higher stover yield at 92 kg N ha^{-1}(optimum rate) than at the control (nil N rate) treatment. However, the MHQ 138 variety produced about 28.8% higher stover yield at 46 kg N ha^{-1} (optimum rate) than at zero. These differences among the maize varieties indicate differences among them in the ability to take up nitrogen from the soil and utilize it for biomass production. Thus, in terms of this ability, BHQPY > MHQ 138 > Raare-1. These results are consistent with the findings of Kandil (2013), who reported maximum biological yields from the highest rate (429 kg N ha^{-1}) for maize varieties.

The results of the study also indicated that the maize varieties produced significantly higher stover yields in 2019 than in 2020 by about 7% (Table 5). The higher value of the stover yield in 2019 than in 2020 may be attributed to the differences in the amount of rainfall received during the growing years (Figure 1). In the 2019 main growing season, the seasonal rainfall amounted to 816 mm, which was adequate for making available sufficient moisture in the soil for uptake by plants. Generally, maize performs optimally in regions that receive an annual rainfall of 700–750 mm (Albayrak, 2021). In contrast, the amount of rainfall received during the main growing season of 2020 was over the requirement and may have led to the loss of nitrogen through leaching and other nutrients held on soil particles loosely. This would result in a deficiency of nitrate (NO_3^{-1}) in the soil, whereby the plant may have suffered from nutrient deficiency, leading to stunted growth and lower stover yields (Gete Zelleke *et al*., 2010). Consistent with the results of this study, Zheng *et al.* (2021) also suggested that large amounts of nitrate nitrogen remain below the root zone under high rainfall and increase the risk of nitrate leaching to deep soil layers.

Grain yield

The analysis of variance revealed that the main effect of year, rate of N, maize variety, and the interaction effect of rates of N by variety significantly ($p \leq 0.01$) influenced grain yield (Table 3). However, grain yield was not significantly affected by the two-factor interaction effects of year and nitrogen rate and year and variety as well as by the three-factor interaction of year, nitrogen rate, and maize variety. Maize grain yields significantly increased across the three maize varieties in response to increasing N rates. Variety BHQPY 545 and MHQ 138, on the other hand, responded more vigorously to nitrogen treatment than variety Raare-1. Accordingly, the grain yields of varieties BHQPY 545 increased significantly starting from nil up to 69 kg N ha^{-1}, where the optimum grain yields were obtained. Increasing the nitrogen rate further to 92 and 115 kg N ha^{-1} did not increase the grain yield of the crop significantly. The lowest grain yields of all three varieties were obtained at nil and 23 kg N ha^{-1}. This shows that applying only 23 kg N ha^{-1} is not sufficient to raise the status of soil nitrogen for sufficient uptake of the nutrient by the roots of maize plants, resulting in nitrogen deficiency.

The grain yield of variety BHQPY 545 obtained at 69 kg N ha^{-1} exceeded the grain yield of variety MHQ 138 and Raare-1 obtained at 69 kg N ha^{-1} by about 75% and 108%, respectively. These results show that variety BHQPY 545 was more efficient in taking up nitrogen from the soil and utilizing it for grain production than the other two varieties. The grain yields of variety MHQ 138 and Raare-1 produced at 92 and 115 kg N ha^{-1} were statistically comparable. These comparable grain yields of the two varieties might be related to genetic similarity in nutrient use efficiency.

According to Adefris Teklewold *et al.* (2015), the grain yields of BHQPY 545 and MHQ 138 maize varieties amounted to 6 t ha^{-1}, and that of Raare-1 amounted to about 4 t ha^{-1} in farmers' fields (Mandefro

Nigussie, 2002). In research fields, the grain yields on average increased to about 9, 8, and 7 t ha^{-1} for the BHQPY 545, MHQ 138, and Raare-1 maize varieties, respectively. Based on this information, the grain yield of the BHQPY 545 variety obtained at 69 kg N ha^{-1} exceeded the average grain yield of the variety obtained from farmers' fields by about 40%. However, the average grain yield of MHQ 138 obtained at 92 kg N ha^{-1} exceeded the grain yield of the variety obtained from farmers' fields by about only 2.3%. This shows that the MHQ 138 variety markedly underperformed, possibly because this variety is perhaps more susceptible to excessive rainfall compared to the other varieties. On the other hand, the average grain yield of the Raare-1 variety obtained at 92 kg N ha^{-1} exceeded the average grain l yield of the variety obtained from farmers' fields by about 36.7%. These comparisons indicate that variety BHQPY 545 and variety Raare-1 have high yielding potential under Haramaya soil conditions and agroecology when fertilized with 69 kg N ha^{-1} and 92 kg N ha^{-1}, respectively. However, variety MHQ 138 was unable to realize its grain productive capacity under this condition although it was supplied with a nitrogen fertilizer rate as high as 115 kg N ha^{-1}. Therefore, the grain productivity followed the order BHQPY 545 variety > Raare-1> MHQ 138. The results also showed that variety BHQPY 545 required less nitrogen to attain its optimum yield than the other two varieties, indicating that it has higher agronomic nitrogen use efficiency.

Year of cropping significantly affected grain yields of the maize varieties (Table 3). Higher grain yields of all three maize varieties were obtained in 2019 than in 2020 (Table 5). The difference in grain yields between the two cropping years amounted to 10%. The most likely cause for the lower grain yield in 2020 than in 2019 is the excess rain that fell during the growing season, which was beyond the optimum rainfall requirement of maize, which ranges between 700 and 750 mm (Albayrak, 2021) and 600–900 mm in the tropics (Fageria and Baligar, 2010). The excess rainfall in 2020 may have led to the loss of soil nitrogen in the form of leaching of nitrate (NO_3^{-1}) from the root zone. Consistent with this suggestion, Varinderpal-Singh *et al.* (2021) also reported that high amounts of rainfall increased the risk of nitrate leaching to deep soil layers, resulting in low yields of maize. This means that variations in the amount of rainfall received during cropping seasons across the years lead to fluctuations in grain and stover yields of maize despite applying equal rates of fertilizers. This indicates that in the year of excess rainfall, the rate of nitrogen application should be higher than the amount recommended, and the timing of applying the fertilizer should also be more than two splits. This should be done to compensate for the nitrate lost due to leaching for adequate availability of the nutrient for uptake and growth by crop plants.

In the current study, variety BHQPY 545 at 69 kg N ha^{-1} produced the highest optimum grain yield with a 100% (two-fold) yield advantage over the national average maize yield in Ethiopia obtained from farmers' fields as reported by CSA (2021). Similarly, varieties MHQ 138 and Raare-1 treated with 92 kg N ha^{-1} at which optimal grain yields were already obtained, outperformed the national average maize yield by about 40% and 30%, respectively.

Table 5. Stover and grain yields of maize varieties as affected by the main effects of cropping year and the interaction of maize varieties by rates of nitrogen fertilizer in Haramaya district during the 2019 and 2020 main cropping seasons.

N rate	Stover yield (t ha^{-1})			Grain yield (t ha^{-1})		
(kg ha^{-1})	BHQPY 545	MHQ 138	Raare-1	BHQPY 545	MHQ 138	Raare-1
0	5.35^{g}	5.20^{g}	5.28^{g}	2.99^{fgh}	2.536^{gh}	2.130^{h}
23	5.82^{fg}	5.82^{fg}	5.91^{fg}	3.99^{d-g}	3.449^{e-h}	2.959^{fgh}
46	6.99^{c-f}	6.70^{def}	6.95^{c-f}	5.64^{bc}	4.461^{cdef}	3.658^{efg}
69	8.75^{ab}	7.02^{c-f}	7.53^{cd}	8.42^{a}	4.812^{cde}	4.037^{d-g}
92	9.62^{a}	7.15^{cde}	7.92^{bc}	9.13^{a}	5.866^{bc}	5.466^{bcd}
115	9.79^{a}	7.74^{bcd}	8.74^{ab}	9.34^{a}	6.856^{b}	6.531^{b}
Tukey HSD ($p \leq 0.05$)		1207.6			1511.4	
Year of cropping						
2019		7.38^{a}			5.37^{a}	
2020		6.89^{b}			4.887^{b}	
Tukey HSD ($p \leq 0.05$)		221.8			277.62	
CV (%)		8.1			14.1	

Note: *CV = Coefficient of variation and HSD = Tukey honestly significant difference. Means followed by the same letters within each column are not significantly different ($p \leq 0.05$).*

Agronomic nitrogen efficiency

The agronomic nitrogen efficiency significantly ($p \leq 0.05$) responded to year, rates of nitrogen fertilizer, variety of maize, and the interaction effects of rates of nitrogen and variety of maize (Table 3). However, agronomic efficiency was not significantly affected by the two-factor interaction effects of the year with nitrogen rate and year with variety as well as the three-factor interaction of year, nitrogen rate, and maize variety.

The agronomic nitrogen efficiency (NAE kg kg^{-1}) recorded in 2019 was significantly higher than the NAE recorded in 2020. However, the 2020 cropping year resulted in a lower grain yield possibly because most of the applied nitrogen was lost from the topsoil through leaching, and nitrogen was rendered unavailable due to this process. Consequently, the possible cause for the low NAE in 2020 may be the excess rain that fell during the cropping season of the year, which may have led to the loss of nitrogen through leaching in the form of nitrate ions. Supporting this postulation, Schlegel and Bond (2019) indicate that adequate uptake of N fertilizers is achieved if the fertilizer applied is not lost through leaching but is mainly taken up by the crop. Thus, the NAE registered in 2019 exceeded that recorded in 2020 by about 11.2% (Table 6).

Thus, increasing the rates of nitrogen fertilizer (though inconsistently) decreased or increased the agronomic nitrogen efficiency of the maize varieties. The agronomic efficiency values of the maize varieties ranged between 27.6 to 78.6 kg kg^{-1} (Table 6). Consistent with these results, Dobermann (2005) stated that the agronomic efficiency of applied nitrogen usually falls in the range of 10 to 30 kg grain kg^{-1} of applied nitrogen. However, the author further stated that NAE may be greater than 30 kg kg^{-1} under low soil nitrogen content as well as under a well-managed system. In line with this argument, Gondwe *et al.* (2014) reported that the nitrogen agronomic efficiency of maize ranged between 10-49 kg kg^{-1}.

The maximum NAE was produced by variety BHQPY 545 at 69 kg N ha^{-1}, at which already the optimal grain yield was obtained, which surpassed NAE values obtained from MHQ 138 and Raare-1 treated with 69 kg N ha^{-1} by about 138% and 185%, respectively. The lowest NAE value was obtained from variety Raare-1 at 69 kg N ha^{-1}, which was statistically comparable to the NAE value produced at 92 and 115 kg N ha^{-1} as well as the NAE value produced by variety MHQ 138 at 69 and 92 kg N ha^{-1} (Table 6). The lower NAE values of these varieties suggest that they yielded less kg grain kg^{-1} of applied N compared to the BHQPY 545 variety. The NAE value produced by variety MHQ 138 at 46 kg N ha^{-1} exceeded the NAE value produced by Raare-1 at 46 kg N ha^{-1} by about 51%. Therefore, in terms of NAE, the BHQPY 545 variety was found to be the most efficient, whereas the MHQ 138 variety was found to be moderately efficient. However, in terms of this characteristic, Raare-1 was the least efficient. Thus, in terms of NAE, the BHQPY 545 variety > MHQ 138 > Raare-1 variety, most likely due to increased grain yield kg^{-1} applied N and genetic variation among the varieties in the effective utilization of N. The results of this study confirm the findings of Davies *et al.* (2020) who reported that a high nitrogen rate interacted with varieties of maize and resulted in maximum NAE that produced higher grain yields.

Table 6. Agronomic nitrogen efficiency of maize varieties as affected by the interaction of maize variety with rates of nitrogen fertilizer in Haramaya district during the 2019 and 2020 main cropping seasons

Year of growing	Nitrogen agronomic efficiency (kg kg^{-1})					
2019	8.7^{a}					
2020	34.8^{b}					
Tukey HSD ($p \leq 0.05$)	1.7					
Maize variety	N rate (kg ha^{-1})					
	0	23	46	69	92	115
BHQPY 545	–	43.7^{d}	57.6^{bc}	78.6^{a}	66.7^{b}	55.2^{c}
MHQ 138	–	39.7^{de}	41.8^{de}	33.0^{ef}	36.2^{def}	37.6^{def}
Raare-1	–	36.0^{def}	33.2^{ef}	27.6^{f}	36.3^{def}	38.0^{de}
Tukey HSD ($p \leq 0.05$)	10.2					
CV (%)	6.2					

Note: *CV = Coefficient of variation and HSD = Tukey honestly significant difference. Means followed by the same letters within each column are not significantly different ($p \leq 0.05$).*

3.3. Partial budget analysis

The economic analysis revealed that optimum net returns of Birr 138222, 101482, and 101282 ha^{-1} were earned from the application rate of 115 kg N ha^{-1} for variety BHQPY545, MHQ138, and Raare-1, respectively (Tables 7). However, the highest marginal rate of return (MRR) of 301% was obtained for variety BHQPY 545 at 69 kg N ha^{-1}, 259% for Raare-1 at 92 kg N ha^{-1}, and 245% for variety MHQ138 at 46 kg N ha^{-1} (Table 8). This shows that the application of 69, 92 kg N ha^{-1}, and 46 kg N ha^{-1} yielded 3.0, 2.6, and 2.4 Ethiopian Birr (ETB) for every Birr invested in cultivating BHQPY 545, Raare-1, and MHQ138 varieties. In economic analysis, it is assumed that farmers require a minimum rate of return of 50–100% (CIMMYT, 1988), representing an increase in a net return of at least 0.5–1.0 Birr for every Birr invested to be sufficiently motivated to adopt new technology. On the other hand, the dominant treatment was further analyzed to distinguish treatments with an optimum return to farmers, and marginal analysis was performed on non-dominated treatments.

The interest of producers in fertilization is not only limited to increasing yields but also includes profiting from it. To maximize profits, the rate of fertilizer application and the cost of fertilizers are the key factors. In the study area, the demand for maize grain (for food) and stover (for animal feed, fuelwood, etc.), and the market price are very important. Accordingly, differences were apparent in maize varieties, and variety BHQPY 545 outperformed the rest of the varieties regarding MRR at 69 kg N ha^{-1}. Thus, variety BHQPY 545 with 69 kg N ha^{-1} is recommended for profitable maize yields, thereby enhancing food and nutrition security in the study area.

Table 7. Partial budget analysis of maize production as affected by N fertilizer application rates and varieties in Haramaya district during the 2019 and 2020 main growing season.

N rate (kg ha^{-1})	Variable input cost (seed, fertilizer + application (ETB)	Total variable cost (ETB)	Adjusted grain yield by 10% (kg ha^{-1})	Grain gross income at (17 ETB kg^{-1})	Adjusted Stover yield by 10% (kg ha^{-1})	Stover gross income at (5 ETB kg^{-1})	Total gross income (ETB ha^{-1})	Net benefit (ETB ha^{-1})
BHQPY545								
0	600	16134	2694	45795	4815	24075	69870	53736
23	1905	21478	3599	61183	5360	26802	87985	66507
46	3210	29429	5078	86329	6293	31464	117793	88364
69	4515	41988	7573	128743	7878	39389	168132	126144
92	5820	46060	8215	139652	8661	43304	182956	136896
115	7125	48767	8407	142911	8816	44078	186989	138222
MHQ138								
0	600	14420	2282	38794	4680	23401	62195	47775
23	1905	19461	3104	52763	5238	26190	78953	59492
46	3210	25098	4015	68260	6027	30137	98398	73299
69	4515	27918	4331	73625	6314	31570	105196	77278
92	5820	32963	5280	89752	6437	32185	121936	88974
115	7125	38232	6170	104897	6963	34817	139714	101482
Raare-1								
0	470	12978	1917	32586	4749	23747	56332	43354
23	1775	17747	2663	45273	5320	26602	71875	54127
46	3080	22474	3292	55969	6257	31286	87255	64781
69	4385	25649	3634	61773	6778	33890	95663	70014
92	5690	32228	4919	83628	7132	35658	119286	87058
115	6995	37987	5878	99931	7868	39338	139269	101282

Note: *Cost of Urea fertilizer 16.1 Birr per kg; Cost of hybrid seed 60 Birr per kg; Cost of OPV seed 47 Birr per kg; Cost of fertilizer application Birr 10 per kg; Sale price of grain maize Birr 17 per kg; Field price (harvesting 150-birr per100 kg; Cost of shelling Birr200 per 100 kg; Cost of transportation Birr 30 per 100 kg; Cost of Stover harvesting Birr 5 per 10 kg; Cost of Stover tying Birr 3 per 10 kg; transportation of stover Birr 30 per 100 kg. Based on variable input cost and total variable cost. Hint: During the harvesting period 1 USD = 46.49 ETB in the market.*

Table 8. Marginal rate of return of maize production as affected by N fertilizer application rates in Haramaya district during the 2019 and 2020 main growing seasons.

N rate (kg ha^{-1})	Total variable input cost (ETB ha^{-1})	Net benefit (ETB ha^{-1})	Marginal increase in net benefit (ETB ha^{-1})	Marginal increase in variable cost (ETB ha^{-1})	Marginal rate of return (MRR %)
BHQPY545					
0	16134	53736	–	–	–
23	21478	66507	12771	5344	239
46	29429	88364	21857	7951	275
69	41988	126144	37780	12559	301
92	46060	136896	10752	4072	264
115	48767	138222	1326	2707	49
MHQ138					
0	14420	47775	–	–	–
23	19461	59492	11717	5041	232
46	25098	73299	13807	5637	245
69	27918	77278	3979	2820	141
92	32963	88974	11696	5045	232
115	38232	101482	12508	5269	237
Raare-1					
0	12978	43354	–	–	–
23	17747	54127	10773	4769	226
46	22474	64781	10654	4727	225
69	25649	70014	5233	3175	165
92	32228	87058	17044	6579	259
115	37987	101282	14224	5759	247

3.4. Correlation analysis among rates of N, maize varieties, yield, and yield components

Correlation analysis revealed that nitrogen rate was significantly and positively correlated with all of the examined parameters (Table 9), implying that nitrogen fertilizer rates had significant and positive effects on all yield components and the yield of maize. The number of kernels produced per ear was highly and positively correlated with thousand kernels weight (TKW), stover yield, grain yield, harvest index (HI), and agronomic nitrogen efficiency (ANE) (Table 9). Grain yield was strongly correlated to all factors (Table 9), indicating that grain yield is the function of biological yield x harvest index, showing all of the parameters had a positive effect on the grain yield, which is the final result of many complicated morphological and physiological processes. Grain yield, HI, and ANE were strongly and negatively associated with variety. This negative association indicated that maize variety had a significant effect (that is, when diversifications of maize variety increased, the grain yield, HI, and ANE decreased among varieties). The number of kernels produced per ear, TKW, and stover yield were all non-significantly and negatively. Except for variety, all parameters were highly and positively correlated with stover yield. Similarly, ANE was significantly and positively correlated with all examined variables except for maize variety, which was negatively related. In general, HI and all yield components were strongly and positively linked with grain yield.

Table 9. The correlation coefficient among rates of N, maize varieties, yield components, and yield of maize in Haramaya district during the 2019 and 2020 main growing seasons.

	NR	VAR	NKE	TKW	S_yield	G_yield	HI	ANE
NR	1	0.23*	0.89**	0.58**	0.82**	0.78**	0.67**	0.43**
VAR		1	–0.13ns	–0.17ns	–0.17ns	–0.44**	–0.52**	–0.33**
NKE			1	0.61**	0.83**	0.79**	0.66**	0.48**
TSW				1	0.49**	0.56**	0.54**	0.25*
S_yield					1	0.85**	0.59**	0.61**
G_yield						1	0.90**	0.70**
HI							1	0.67**
ANE								1

Note: *NR= nitrogen rate; VAR= variety; NKE= number of kernels per ear; TSW= thousand kernel weight; S_yield =stover yield; HI= harvest index, and ANE= agronomic nitrogen efficiency.*

4. Conclusions

The results of this study have demonstrated that nitrogen application increased yield components and yield of the tested maize varieties. The optimum grain yield (8415 kg ha^{-1}) was obtained at the medium rate of 69 kg N ha^{-1} for variety BHQPY 545 and at 92 kg N ha^{-1} for variety Raare-1 and MHQ 138. The BHQPY 545 variety required 25% less nitrogen to attain its optimum grain yield than the other two varieties, indicating that it has higher agronomic N use efficiency, which was reflected by a superior agronomic efficiency value of 78 kg grain per kg applied nitrogen for BHQPY 545 variety to the values of 36.3 kg grain per kg applied nitrogen for Raare-1, and 36.2 kg grain per kg applied nitrogen for MHQ 138 varieties. The grain productivity of the BHQPY 545 variety was about 43.5%, and 53.9% higher than that of MHQ 138 and Raare-1 at 69 kg Nha^{-1}, respectively. The average yield of variety BHQPY 545 at 69, 92, and 115 kg N ha^{-1} was also found to be about 40%, 52%, and 56% higher than the yield obtained in farmers' fields, respectively. This implies that farmers should preferably cultivate the BHQPY 545 variety under conditions of seed availability since it can be grown profitably under lower nitrogen inputs. The grain yields of MHQ 138 and Raare-1 were found to be in statistical parity. The highest net benefit of 138221Birr ha^{-1} was obtained from variety BHQPY 545 at 115 kg N ha^{-1}, while the three varieties attained the lowest net benefit from the unfertilized plots. Therefore, cultivating the BHQPY 545 variety with the application of 69 kg N ha^{-1} is recommended for smallholder farmers in Haramaya district and other areas with the same soil and agroecological conditions. However, this recommended rate of nitrogen should not be taken for granted to increase the stover and grain yields of the crop since excess rainfall during certain years of the main cropping season as a result of climate change could result in loss of nitrate through leaching, which requires a compensatory additional rate of the N fertilizer. Therefore, the agricultural extension system of the East Hararghe Zone should demonstrate BHQPY 545 variety together with farmers' maize varieties in farmers' fields under this recommended rate of N fertilizers as well as farmers' fertilizer management practices as a control treatment. Furthermore, the tested maize hybrids and others should be evaluated at these and other varied rates of nitrogen as well as sulfur and phosphorus fertilizer at different locations to formulate judicious, profitable, and balanced fertilizer recommendations for enhancing the yield of maize and food security in the study area.

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