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Original Research

Plant Population Density and Nitrogen Fertilizer Rate on Productivity of Maize (*Zea mays* L.) in Sibu Sire District, Western Ethiopia

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Abstract

Maize yield is extremely reliant on nitrogen ratios and planting arrangement. Crop architecture provided additional space to increase yield per unit area. There was no adequate information on optimum nitrogen rates and spacing on maize hybrid (BH-546) variety in the study area. Thus, a field experiment was conducted in Sibu Sire District, in 2020 to evaluate the effect of different nitrogen rates and plant populations on the BH-546 variety. The experiment was arranged in the randomized complete block designed factorial arrangement with three replications. Four nitrogen rates (69, 92, 115, and 138 kg/ha) combined with four plant populations of 44,444, 53,333, 66,665, and 88,885 used for the experiment. The results showed that interaction effects of nitrogen rates and plant population were significantly affected leaf area index, harvest index, biomass yield, and grain yield. The highest plant population density of 88,885 plants/ha gave the maximum leaf area index at all rates of nitrogen applied. The maximum harvest index was achieved when nitrogen rates at 115 and 138 kg/ha were applied in combination with a plant population of 44,444 plants/ha. Similarly, the highest (26,725 kg/ha) biomass yield was obtained from 138 kg/ha nitrogen with 88,885 plant populations. The maximum (11,706 kg/ha) grain yield was obtained from a plant population of 88,885 plants/ha with a nitrogen rate of 115 kg/ha. The finding suggests that 88,885 population density combined with 115 kg/ha of nitrogen produced the highest (117.06 Qt/ha) with the highest net benefit of 91,845.8 ETB (Ethiopian Birr)/ha and cost-benefit ratio of 3.35.

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INTRODUCTION

Maize (*Zea mays* L.) is one of the leading cereal crops produced for human food, and animal feed in the tropical regions of the world (Zaidun *et al*., 2019). In Ethiopia, it is the most widely cultivated crop on more than two million hectares (CSA, 2021), and the most important major food crop ranks second in area coverage with an average grain production of 4.24 t/ha (FAO, 2020). Moreover, the Central Statistical Agency (2021) report indicated that maize is grown on an acreage of about 2.5 million hectares; accounting for approximately 23.97% of all cereal crop areas. Oromia state accounts for around 54.3% of the country's total agricultural land, with a current output of 3.31 t ha-1. However, maize harvest is mostly produced in western sub-humid regions, accounting for more than 60% of the region's total production, with an increased trend of production area (Derib *et al*., 2017). Even though maize is the second largest crop in area coverage and the highest productivity per unit area among cereal crops, there is a yield gap between the current actual grain yield (6 - 8.5 t ha-1) and the potential yield (9.5 - 12 t ha-1) (Tittonell and Gillerb, 2013). The major possible reasons for the low productivity of maize are inappropriate plant density (Sangoi *et al*., 2002 and Kebede, 2019), inappropriate nitrogen rate and inadequate improved varieties (Tolera *et al*., 2017 and Vandervelde *et al*., 2014), rapid reduction in soil fertility caused by intensive cultivation and mono-cropping, drought, pests, and diseases (Temteme *et al*., 2018). The importance of nitrogen for plant development and productivity is becoming more widely essential as nitrogen is the greatest growth and yield limiting essential plant nutrients and hence increasing nitrogen application rate per unit area and time increases grain and biological yields of maize to optimum levels (Arif *et al*., 2010). Nitrogen management is a major challenge in the maize production system since it is the most critical and primary nutrient for the crop's growth and development, and meets the nutritional requirements of maize, resulting in increased grain yield (Khan *et al*., 2017).

Today, the increasing global population has raised a great deal of interest in food security. Decreasing agricultural productivity due to the decrease in the area of cultivable land and climate change has resulted in millions of people living below the poverty line and becoming malnourished (Pradhan *et al*., 2017). Thus, maintaining optimal plant density is one of the important agronomic strategies in regulating maize yield components and grain yield (Abuzar *et al*., 2011). Altering the number of plants per unit area has an impact on plant growth, plant height, leaf area index, photosynthesis, and then yields (Gobeze *et al*., 2012 and Getahun *et al*., 2018). Al-Naggar *et al*. (2015) also revealed that maize yield of varies with varieties and its population density per unit area. Depending on the cultivar, a plant density of 44,444 plants per hectare (75 × 30) cm to 53,333 (75 × 25) cm is highly used in Ethiopia (Tesfa *et al*., 2012). Locally, most farmers and private sectors at and near the study area grew maize at 53333 plant density with the inter-and intra-row spacing of 75 cm × 30 cm. Some of the growers are also using narrower spacing for the same varieties, i.e., plant density of 62,500 plants/ha or spacing between inter-and intra-row space (80 × 20) cm. Even though nitrogen demand increases as the plant population increases, most of the farmers in the study area apply less than 92 kg/ha of nitrogen sources.

Increased plant population without increased nutrients, on the other hand, can affect maize during the growth season due to competition for nutrients, light, water, oxygen, and other plant growth resources. There is paucity of information on the interaction effects of plant population density and nitrogen rates on maize production. As a result, experiment has been conducted in the study area considering the rate of nitrogen and plant population. Thus, to attain a high yield from the BH-546 variety, plant population modification with an adequate nitrogen fertilizer rate should be considered. Therefore, this study aimed to identify plant population levels and nitrogen fertilizer rates on growth, yield components, and yields of maize in Sibu Sire District, Western Ethiopia.

MATERIALS AND METHODS

Description of Experimental Site

The experiment was conducted under rainfed conditions during the main cropping season of 2020/21 at Chari Jarso kebele in Sibu Sire District. The study site is located at 36°35’42.37’’ - 36°44’East and 8°57’- 9°22’North with an elevation of 1240 - 3140 meters above sea level in East Wollega Zone, Oromia Region. The experimental area gets unimodal rainfall receiving an average annual rainfall of 1348 mm with average minimum and maximum temperatures of 14.2ºC and 28.4ºC, respectively. The soil of the study area is Nitosols (red soil). The area is also characterized by a crop and livestock production mixed farming system. From the total cultivated land in the study area, maize accounted for (25.6%), teff (20.5%), sorghum (16.5%), 'nuog' (13%), and finger millet (12.3%). In addition, horticultural crops such as vegetables, roots, and tubers, as well as some perennial crops, cover the remaining percent of arable land (Sibu Sire agricultural office, 2021 unpublished data).

Experimental Materials

An improved variety of hybrid maize (BH-546) released in 2013 from Bako National Maize Research Institute was used for the study. The variety is characterized by a slender and erect leaf design and intermediate maturing time (140 days), yielding (8.5 - 11.5 t/ha) on the research stations and (6.0 - 7.5 t/ha) on the farm, adaptable to a wide range of agro ecology including low land area and resistant to diseases.

Treatments and Experimental Design

Factorial experiment containing sixteen treatments from four plant populations (44444, 53333, 66665, and 88885 plants/ha) with four plant spacing of 30, 25, 20, and 15 cm combined with four nitrogen rates (69, 92, 115 and 138 kg/ha) were used in a randomized complete block design three replications (Table 1). The treatment containing 53333 of the plant population treated with 92 kg/ha of nitrogen rate was used as a standard check as it has been used in the study area. Thus, a total of 48 plots with each gross plot of 3.75 m × 3 m (11.25 m2) with a row length of 3 m and a net plot of 2.25 m × 2 m (4.5 m2) were used. The treatments were assigned randomly to the experimental unit’s per block basis and each block and plot was separated with 1 m and 0.5 m space, respectively.

Table 1. Treatments used for the experiment

Treatment number	Factors Combination (4 levels of plant population + 4 rates of nitrogen fertilizer)
1	44444 plants/ha + 69 kg/ha of nitrogen
2	44444 plants/ha + 92 kg/ha of nitrogen
3	44444 plants/ha + 115 kg/ha of nitrogen
4	44444 plants/ha + 138 kg/ha of nitrogen
5	53333 plants/ha + 69 kg/ha of nitrogen
6	53333 plants/ha + 92 kg/ha of nitrogen
7	53333 plants/ha + 115 kg/ha of nitrogen
8	53333 plants/ha + 138 kg/ha of nitrogen
9	66665 plants/ha + 69 kg/ha of nitrogen
10	66665 plants/ha + 92 kg/ha of nitrogen
11	66665 plants/ha + 115 kg/ha of nitrogen
12	66665 plants/ha + 138 kg/ha of nitrogen
13	88885 plants/ha + 69 kg/ha of nitrogen
14	88885 plants/ha + 92 kg/ha of nitrogen
15	88885 plants/ha + 115 kg/ha of nitrogen
16	88885 plants/ha + 138 kg/ha of nitrogen

Experimental Procedure

The experimental field was plowed three times by oxen with a fine soil tilth and leveled manually before sowing/planting. Maize seed was planted at inter-row spacing of 0.75 m and intra-spacing of 0.30, 0.25, 0.20, and 0.15 m for plant populations of 44,444, 53333, 66665, and 88885, respectively. Two seeds per hill were planted and one week after emergence it was thinned out to one plant/hill to maintain the recommended population depending on the treatment. Urea (CO(NH2)2) fertilizer and chemically blended NPS fertilizer containing 19% nitrogen, 38% P2O5, and 7% sulfur were used as a source of nitrogen fertilizer. According to the recommendation in the study area, a full dose of NPS fertilizer (100 kg/ha) was uniformly applied during the sowing time to all experimental units. Nitrogen fertilizer was calculated for each treatment and applied by splitting, that its half at sowing time, and the remaining half was applied at the knee height stage as per the treatment. All other agronomic procedures, such as weeding and crop management, were applied similarly to all plots based on the farm's experience.

Data Collection and Measurements

Soil Sampling and Analysis

Soil samples were collected randomly at a depth of 0 - 30 cm in a zigzag pattern before planting. Composite samples were air-dried, prepared, and homogenized for analysis and to determine the soil physicochemical properties such as soil texture, soil pH, organic carbon, organic matter, total nitrogen, exchangeable calcium, magnesium, potassium, cation exchange capacity, and available phosphorus. The soil samples were grounded and sieved through a 2 mm sieve and analyzed for their chemical composition at Nekemte Soil Testing Laboratory. Soil particle size distribution was determined by hydrometer method (Gee and Or, 2002), and the pH of the soil was determined by using a pH meter at 1:2.5 soil to water ratio (Sertsu and Bekele, 2000). Soil organic carbon, total nitrogen, and available phosphorus were determined according to the methods developed by Walkley Black Oxidation (Schnitzer, 1982), Kjeldahl (Bremner and Mulvaney, 1982), and Bray-I (Spark, 1996), respectively.

Crop Phonology and Growth Parameters

Phenological parameters of maize such as a number of days to 50% tassel, silking, and numbers of days to 90% maturity were taken as the number of days from the day of planting to when 50% of each plot produced tassels, started producing pollen and formed a black layer at the point where the kernel attached to the corn cob, respectively. Plant height was measured at the physiological maturity stage from randomly sampled 10 plants of the net plot as the distance from ground level to the place where the tassel formed and started to branch. Leaf area index (LAI) was calculated by dividing the average total leaf area obtained from 10 plants (L × W × K) by the land area occupied by the plant (0.75 m × 0.30 m = 0.225 m^2), (0.75 m × 0.25 m = 0.1875 m^2), (0.75 m × 0.20 m = 0.150 m^2) and (0.75 m × 0.15 m = 0.1125 m^2) for 44444, 53333, 66665 and 88885 plant population, respectively; where L = leaf length, W = leaf width and K = correction factor (0.75) (Aikins *et al*., 2012).

Yield Components and Yield

Data for a number of ears/plants, ear weight (g), and a number of kernels/ears were taken from ten pre-tagged plants of the net plot area. Thousand-grain weight (g) was counted from the bulk of shelled grains and measured at standard moisture level (12.5%) by using an electronic grain counter and sensitive balance, respectively. In addition, biological yield (t/ha) and grain yield (t/ha) were calculated from the total biomass harvested from each experimental plot at the time of harvest and weighed the bulk of grain harvested from the net plot, respectively. Harvest index (%) was calculated by dividing grain yield (t/ha) by above-ground biomass yield (t/ha) and multiplied by 100.

Economic Analysis

Partial budget analysis of grain yields for selecting economically feasible and profitable levels of plant population and nitrogen rate applied was conducted according to CIYMMIT procedure (CIMMYT, 1998). The costs for fertilizer NPS 14.5 ETB/kg and urea 14 ETB/kg were used after the grain yield was deducted by 10% to estimate the real yield at farmers' conditions. The yield of maize was valued at an average open market price of 11 ETB/kg in January 2020 at the local market of the study area (Sibu Sire town).

Statistical Data Analysis

The data collected were subjected to SAS version 9.4 for analysis of variances and mean comparisons were done using least significant differences (LSD) test at 0.05 probability level.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Study Site Soil.

The textural class of the study site soil is clay loam. The soil pH in H_2O was 5.28, implying the soil reaction was found in the moderate acidic range (Landon, 1991). Total nitrogen and phosphorus were 0.17% and 7.08 ppm, respectively (Table 2), and were found in the low range (Bruce and Rayment, 1982). Organic carbon concentrations were 1.99% (Table 2) which was found in the medium range (Bruce and Rayment, 1982), whereas the cation exchange capacity concentration was 27.46 cmol+/kg and found in the high range (Bruce and Rayment, 1982, and Horneck, 2011). Generally, the soil analysis results indicated that the nitrogen content of the soils was found in a low range. As a result, low-to-medium soil total nitrogen levels indicate that external nitrogen-containing inputs are required to restore and sustain the fertility state of the experimental soil.

Table 2: Pre-planting soil physical and chemical properties of the experimental field

Physicochemical Properties	Value	Test methods	Rating
Chemical Properties			
pH (H_2O)	5.28	Potentiometer	Acidic
Organic Carbon (%)	1.99	Walkley-Black	Medium
Total Nitrogen (%)	0.17	Kjeldahl procedure	Low
Avail. P (ppm or mg kg^{-1})	7.08	Bray II	Low
Cation exchange capacity (meq $100g^{-1}$)	27.46	Ammonium acetate method	Moderate
Physical properties			
Particle size distribution			-
Clay %	40		
Silt %	26		-
Sand %	34		-
Soil textural class		Hydrometer method	Clay loam

Crop Phenology

The results of the analysis of variance showed a significant ($p < 0.05$) effect of nitrogen rate and plant population levels on days to 50% tasseling while their interaction effect was not significant (Table 3). The mean number of days to 50% tasseling showed an increased trend as the nitrogen rate increased. Application of 138 kg/ha nitrogen delayed number of days to 50% tasseling (85.93 days), silking (89.51 days), and number of days to 90% physiological maturity (141 days) which was on par with 115 kg/ha amount of nitrogen for number of days to tasseling and silking. Early tasseling (83.50 days), silking (86.67 days), and physiological maturity (138 .74 days) were recorded at 69 kg/ha (Table 3).

The raised in nitrogen level may have caused a delay in the phenology of maize due to the availability of sufficient nitrogen in the soil for uptake that enhanced vigorous vegetative growth, development, and increased effectiveness in light use. In line with these results various studies (Moosavi, 2012; Gudeta *et al*., 2021; Nure and Jara, 2021) also reported significant delayed in days to tasseling with increased nitrogen fertilizer application. Similarly, Khattack and Khalil (2009); Imran *et al*. (2015); Sharifi and Namvar (2016) stated that increased nitrogen application in maize took more time to silking. In addition, Shrestha (2013) found that increasing the nitrogen rate delays maturity because nitrogen promotes vegetative development. According to Gungula *et al.* (2003), an increase in nitrogen rates may have boosted photosynthetic rates, resulting in leaf longevity and delayed phonological features. On the contrary, Moges and Tana (2015) reported early tasseling and silking of maize with an increase in the rate of nitrogen application. Detebo *et al*. (2021) also reported the longest days to maturity at zero levels of nitrogen and vice versa.

The plant population results revealed that a greater plant population (88,885 plants/ha) required a greater days for tasseling (85.00 days), silking (89.25 days) and physiological maturity (140.75 days) respectively, whereas the minimum number of days was recorded at the lowest plant population (44444 plants/ha) for all maize phenology (Table 3). The delay in days for phonological parameters of maize with increased plant population might be due to high intra-specific competition that reduces the photosynthesis accumulation and delays the shift from vegetative growth to the reproductive stage of the crop. Competition between rows and within rows for growth resources such as solar radiation, soil, minerals, water, and the air was increased as the number of plants per unit area increased and resulted in reduced physiological process, growth, and delay in days to tasseling and silking of maize. In line with these results, Shafi *et al*. (2012) reported delays in days to tasseling under increased plant populations compared to the optimal and lower plant density. In addition, delayed days to silk were observed in maize planted densely (Bhatt, 2012). Furthermore, Imran *et al*. (2015) and Shrestha (2013) indicated that increased days to physiological maturity of maize in parallel with increased planting levels of plant population.

Table 3: Main effect of levels of plant population and nitrogen rate on days to 50% tasseling, days to 50% silking, and days to 90% physiological maturity of maize in Sibu Sire district during the 2020 cropping season

Treatment	**Number of 50% days to Tasseling**	**Number of days to 50% silking**	**Number of days to 90% physiological maturity**
Nitrogen rate (kg/ha)			
69	83.50[d]	86.67[c]	138.74[cd]
92	84.25[c]	87.75[b]	138.83[c]
115	85.84[ab]	89.42[a]	139.83[b]
138	85.93[a]	89.51[ab]	141.00[a]
LSD (5%)	0.64	0.55	0.52
Plant population (Plants/ha)			
44444	84.95[bc]	87.26[cd]	137.83[c]
53333	84.97[bc]	87.50[c]	139.00[b]
66665	85.42[b]	88.98[ab]	140.63[a]
88885	85.00[a]	89.25[a]	140.75[a]
LSD (5%)	0.48	0.45	0.53
CV (%)	3.68	4.61	3.46

Means within columns superscripted and shared the same letter(s) are not statistically different at 5% significance level

Growth Parameters

Analysis of variance revealed that the main effect of nitrogen rate and plant population levels as well as their interaction had significantly influenced plant height (cm) and leaf area index (Table 4). The maize grown in a plot treated with 138 kg/ha of nitrogen fertilizer and 88885 plants/ha produced the tallest plant height (284.00 cm) followed by 282.90 cm which was obtained from the interaction of 115 kg/ha with 88885 plants/ha; whereas the shortest plant height (254.4cm) was obtained from 69 kg/ha of nitrogen rate at all levels of plant population except 88885 plants/ha (Table 4). The increased plant height at a higher nitrogen rate and highest plant population might be due to the positive effect of mineral nitrogen fertilizer for vigorous vegetative growth of maize and increased plant population density which might increase the competition for solar radiation and other growth resources that decrease stem thickness and number of active green leaves. In line with the current study, Muhidin (2021) and Muhidin *et al*. (2019) reported increased plant height with an increased level of plant population. Plant population levels of 88,885 plants/ha with all rates of applied nitrogen resulted in a maximum leaf area index while the lower plant population density of 44,444 plants/ha treated with 69 kg/ha of nitrogen showed a minimum leaf area index of 4.61 (Table 4). The improvement in LAI may result in increased leaf development in plants as a result of optimal nitrogenous fertilizers and the green canopy of plants occupying more unit area. In line with this study, Abuzar *et al*. (2011) reported that LAI was strongly affected and increased linearly with an increase in plant population. According to Begizew *et al*. (2018), the increase in LAI with an increase in plant population density shows that the green canopy of the plants occupies more unit area. In contrast, Imran *et al.* (2015) reported increased LAI at lower levels of plant population and vice versa.

Table 4: Interaction effect of levels of plant population and nitrogen rates on plant height (cm) and leaf area index of maize in Sibu Sire district during the 2020 cropping season

Nitrogen rate (kg/ha)	Plant density	Plant height (cm)	Leaf area index (%)
69	44444	251.70[f]	4.61[f]
69	53333	251.68[f]	5.40[d]
69	66665	253.00[f]	5.87[c]
69	88885	266.70[c]	6.74[a]
92	44444	261.90[de]	4.97[e]
92	53333	265.60[cd]	5.47[d]
92	66665	267.80[c]	5.87[c]
92	88885	268.20[c]	6.76[a]
115	44444	264.50[cd]	5.43[d]
115	53333	265.00[cd]	5.90[c]
115	66665	265.60[cd]	6.24[b]
115	88885	279.90[ab]	7.08[a]
138	44444	265.50[cd]	5.46[d]
138	53333	267.00[c]	5.92[c]
138	66665	267.20[c]	5.94[c]
138	88885	281.00[a]	7.55[a]
LSD (5%)		3.926	0.30
CV (%)		0.9	9.71

Means within columns superscripted and shared the same letter(s) are not statistically different at 5% significance level

Yield Parameters

Number of ears per plant

Analysis of variance showed that the number of ears/plants was not significantly affected by the amount of nitrogen and levels of plant population as well as their interaction. However, numerically the highest number of ears/plant (1.58) was obtained from the application of nitrogen at 138 kg/ha, whereas reduced application of nitrogen (69 kg/ha) gave the least number of cobs/plant (1.20). In the case of plant population, a lower planting density of 44,444 plants/ha produced the highest number of ears/plant (1.55) while the lowest values of a number of ears/plant (1.28) were recorded at the plant density (88885) plants/ha (Table 5). This might be due to increased competition between and within plants for growth-limiting factors under a lower application rate of nitrogen and increased levels of plant population. In contrast, Abuzar *et al*. (2011); Begizew *et al*. (2020) and Karasu (2012) reported a significant reduced number of ears with an increased plant population and reduced nitrogen rate.

Number of kernels per ear

The main effect of nitrogen rate and plant population levels had a significant ($P < 0.05$) influence on the number of kernels/ears. However, their interaction effect showed a non-significant. The largest number of kernels/ear (386.75) was obtained when 138 kg/ha nitrogen was applied, while the lowest number of kernels/ear (318.17) was recorded with 69 kg/ha applied nitrogen (Table 5). Higher nitrogen rates may result in a higher number of kernels/ear because the crop has obtained more available nitrogen that allowed more above-ground biomass and transferring more photosynthesis into sinks which results in increased number of grains/ears. The finding of the present study is in consistent with Rizwan *et al*. (2003), who found that as nitrogen rates increased, the number of grains/cobs increased considerably. Regarding plant population, the highest number of kernels/ear (362.58) was recorded at 44,444 plant population which was on par with the value obtained from 53,333 plant population and 66,665 plant/ha, whereas the lowest number of kernels/ear (329.58) was recorded at the plant population of 88,885 plant/ha (Table 5). The highest number of kernels/ears observed at lower plant populations might be due to less competition for growth resources, and thus more available space for individual plants to produce the highest number of kernels/ears at low plant density. Similarly, Abuzar *et al*. (2011) found an increased number of kernels/ears with reduced levels of plant population/hectare and vice versa.

Thousand seed weight (g)

The main effect of nitrogen rates and plant population levels on maize thousand seed weight was significant ($p < 0.05$), while the interaction effect of both factors had no meaningful effect on maize thousand seed weight. The maximum thousand seed weight was obtained when nitrogen applied at rates of 138 and 115 kg/ha. However, the application of 69 kg/ha nitrogen was resulted in the lowest thousand seed weight (Table 5). Increased nitrogen application rate increases the vegetative parts of the crop, increases leaf area index, and hence improves the accumulation of more photosynthetic assimilates in the grain and increases the thousand grain weight. In line with this, Abduraman and Husen (2021); Hafez and Abdelaal (2015) and Anwar *et al*. (2017) reported increased thousand seed weight with the amount of nitrogen. Similarly, Moosavi (2012); Shafi *et al*. (2012) and Radma and Dagash (2013) found that as nitrogen levels rise, thousand-grain weight increases. Similarly, the levels of plant population at 44,444 plants/ha produced the highest thousand seed weight, whereas plant population levels at 88,885 plants/ha resulted in the lowest thousand seed weight (Table 5). The decrease in thousand seed weight might be connected to plant stands due to competition for plant growth-limiting resources. The lower plant population provides an opportunity for the crops to better utilize and assimilate available resources with reduced competition, which could explain why the lowest plant population produces higher thousand seed weight. This is consistent with the findings of Khan *et al*. (2017); Abduraman and Husen (2021); Zamir *et al*. (2011), and Azam *et al*. (2007).

Table 5: Main effect of levels of plant population and nitrogen rates on the number of ears/plant, number of kernels/ear, and thousand-grain weight of maize in Sibu Sire district during the 2020 cropping season

Treatment	Number of ears/plant	Number of kernels/ear	Thousand seed weight (g)
Nitrogen rate (kg/ha)			
69	1.20[a]	318.17[d]	233.33[c]
92	1.30[a]	337.58[c]	256.33[b]
115	1.55[a]	361.83[b]	283.50[a]
138	1.58[a]	386.75[a]	291.17[a]
LSD (5%)	0.40	11.27	7.77
Plant population (Plants/ha)			
44444	1.55[a]	362.58[a]	278.50[a]
53333	1.43[a]	359.67[a]	272.17[b]
66665	1.32[a]	352.5[a]	266.25[b]
88885	1.28[a]	329.58[b]	247.42[c]
LSD (5%)	0.30	16.96	7.93
CV (%)	8.50	5.79	3.58

Means within columns superscripted and shared the same letter (s) were not statistically different at 5% significance level.

Biomass yield (kg/ha)

The results of the analysis of variance revealed that the main effects of nitrogen rate and plant population, as well as their interaction effects significantly ($p < 0.05$) affected the above- ground biomass of maize. Maize grown at 88,885 plants/ha combined with 138 kg/ha application resulted in the maximum dry biomass yield (26,725 t/ha) followed by the same plant density with 115 kg/ha of nitrogen rate (23,999 t/ha) (Table 6). The lowest dry biomass yield (14667 t/ha and 14933 t/ha) was obtained from 44,444 plants/ha at 115 and 138 kg/ha of nitrogen rate, respectively. The dry biomass yield increased by 51.85% when 138 kg/ha of fertilizer was applied to maize grown at a plant population of 88,885 plants/ha (Table 6). The maximum dry biomass yield in response to the highest nitrogen application rate at high plant population density could be due to the high number of plants per unit area, which might have increased the photo interception through the crop canopy, and ultimately led to the accumulation of a high amount dry matter. This finding is consistent with those of Abduraman and Husen (2021), and Imran *et al*. (2015), who found the highest biological yield at higher plant populations with the highest nitrogen rate applied and the lowest biological yield under lower plant density in the absence of nitrogen application. In addition, Detebo *et al*. (2021) reported increased biomass weight in parallel with an increased amount of nitrogenous fertilizer.

Grain yield (kg/ha)

Grain yield was significant ($p < 0.05$) and influenced by the level of plant population and nitrogen rate, as well as their interaction. The highest maize grain yield (11,706 t/ha) was attained at plant population levels of 88,885 plants/ha combined with 115 kg/ha of nitrogen application (Table 6). In contrast, plant population levels of 44444 and 53333 plants/ha combined with 69 kg/ha of nitrogen fertilizer resulted in the minimum grain yield (4372 t/ha and 4606 t/ha), respectively. Maize sown at a plant population of 88,885 plants/ha with an application of nitrogen at 115 kg/ha maximizes grain yield by 79.69 % compared to the local cultivar of 53333 plants/ha with 92 kg/ha of nitrogen application. The possible reason might be due to reduced competition between and within the plant for nutrients, particularly nitrogen as the amount of nitrogen raised, and increasing solar radiation efficiency. Tolera *et al*. (2017); Shrestha (2013); Gozubenli and Konuskan (2010) reported similar findings to the current study. Similarly, Detebo *et al.* (2021), and Aziz *et al*. (2007) reported that increased grain yield of maize at optimum planting density is connected with increased availability of sufficient nitrogen nutrients leading to more growth and higher translocation of grains. In line with the study, Gudeta *et al*. (2021); Abduraman and Husen (2021); and Tekletsadik *et al*. (2017) also found increased grain yield of maize with increased levels of nitrogenous fertilizer and plant population to some extent.

Harvest index (%)

The main effect of nitrogen rate and plant population, as well as their interaction effect, significantly ($p < 0.05$) influenced the harvest index of maize. Plant population at a density of 44,444 plants/ha applied with 138 and 115 kg/ha resulted in a higher harvest index of maize. The lowest harvest index of maize was recorded from 69 kg/ha of nitrogen fertilizer applied to all plant population densities (Table 6). The high harvest index obtained from maize grown at a lower density supplied with either 138 kg/ha or 115 kg/ha might be due to adequate nitrogen and less intra-completion of sparsely grown maize crop for growth resources and associated with a pivotal role of nitrogen in many physiological and biochemical mechanisms that enable the crop to allocate a large amount of dry matter into grain during the growth and development period, which has a direct relationship to the harvesting index. Further, nitrogen additions, on the other hand, have promoted more vegetative growth, resulting in a lower harvest index. The decrease in harvest index in response to plant stand proximity could be attributed to significant competition for light, which may cause plants to rapidly rise in plant height and allocate more dry matter to the stalk, and result in reduced grain yield to total dry matter ratio. The findings of the present study agreed with the findings of Sharifi and Namvar (2016); Anwar *et al*. (2017); and Aghdam *et al*. (2014). Similar results were observed by Arif *et al*. (2010); Imran *et al*. (2015); Nik *et al*. (2011); and Akhtar *et al*. (2015).

Table 6: Interaction effect of nitrogen rate and plant population levels on maize biomass yield, grain yield, and harvest index during 2020 cropping season at Sibu Sire District.

Nitrogen rate (kg/ha)	Plant density (Plant/ha)	Biomass yield (kg/ha)	Grain yield (kg/ha)	Harvest index (%)
69	44444	15881[i]	4372[k]	31.65[h]
69	53333	16000[i]	4606[k]	32.30[h]
69	66665	18000[f]	5217[j]	32.33[h]
69	88885	21274[d]	5781[i]	31.39[h]
92	44444	15704[i]	5911[i]	34.92[g]
92	53333	17600[fg]	6514[h]	34.91[g]
92	66665	19955[e]	7123[g]	34.89[g]
92	88885	22399[c]	7922[f]	34.84[g]
115	44444	14667[j]	9102[e]	46.87[a]
115	53333	16747[h]	9813[d]	44.19[bc]
115	66665	20300[e]	10812[c]	40.14[d]
115	88885	23999[b]	11706[a]	37.52[e]
138	44444	14933[j]	9087[e]	45.49ab
138	53333	17280[g]	9696[d]	42.77c
138	66665	20844[d]	10615[c]	39.78de
138	88885	26725[a]	11215[b]	41.97[f]
LSD (0.05)		472.91	401.19	2.49
CV (%)		5.50	7.97	3.45

Means within columns superscripted and shared the same letter(s) are not statistically different at 5% significance level.

Economic Feasibility Analysis

A plant population of 88,885 plants/ha received 115 kg/ha of nitrogen fertilizer rate resulting in a maximum net return of 91,845.80 ETB/ha, while the lowest net return of 23152.20 ETB/ha was recorded from the interaction of nitrogen 69 kg/ha × 44444 plant population/ha (Table 7). The net benefit-cost ratio showed that promising treatments ranged from 104% - 335%. The highest net benefit of 91845.80 ETB/ha with a net benefit-cost ratio of 335% was obtained from maize planted at 88,885 plants/ha with the application of 115 kg/ha of nitrogen, followed by the net benefit of 82973.4 ETB with a net benefit-cost ratio of 309% and 73,016.9 ETB with a net benefit-cost ratio of 276%, and ETB 66016.75 with a net benefit-cost ratio of 253% were recorded when 115 kg/ha of nitrogen applied to a plant population of 66665, 53333 and 44444 plants/ha, respectively. Since the minimum marginal rate of return (MRR) assumed in the current study is 100%, all treatments promised are within an acceptable MRR range. Thus, the net benefits obtained from the promising treatments ranged from 104 to 335%, suggesting for each ETB invested, the producer would collect ETB 1.04 to 3.35 after recovering the cost. Generally, the application of nitrogen at 115 kg/ha to 88,885 plants/ha resulted in a 335% net benefit-cost ratio, implying that for each ETB invested, the maize growers of the study area would collect 3.35 after recovering the cost of production. Moges and Tana (2015) found similar results, indicating that higher planting density with a higher nitrogen rate resulted in higher yield and a larger net benefit.

Table 7: Partial budget analysis of levels of plant population and nitrogen rates of maize in the Sibu Sire district during the 2020 cropping season

Treatment combination		AGY (kg/ha)	ASY (kg/ha)	GYR (ETB/ha)	SYR (ETB/ha)	TR (ETB/ha)	TVC (ETB/ha)	NB (ETB/ha)	Value to cost ratio	MRR (%)
NR	PD									
69	44444	3934.53	8861.77	43279.85	2215.40	45495.25	22343.05	23152.2	1.04	-
69	53333	4145.13	8927.95	45596.45	2232.00	47828.45	22615	25213.5	1.11	758
69	66665	4695.66	10043.78	51652.25	2510.90	54163.15	22992.3	31170.9	1.36	1579
69	88885	5202.45	11870.95	57226.95	2967.70	60194.65	23446.5	36748.2	1.57	1228
92	44444	5319.81	8762.55	58517.90	2190.60	60708.50	24128.05	36580.5	1.52	D
92	53333	5862.96	9820.75	64492.55	2455.20	66947.75	24460	42487.8	1.74	566
92	66665	6410.88	11134.94	70519.70	2783.70	73303.40	24822.3	48481.1	1.95	1654
92	88885	7129.53	12498.64	78424.85	3124.70	81549.55	25306.5	56243.1	2.22	1603
115	44444	8191.71	8183.91	90108.80	2046.00	92154.80	26138.05	66016.8	2.53	1175
115	53333	8831.88	9344.6	97150.70	2336.20	99486.90	26470	73016.9	2.76	2109
115	66665	9730.35	11327.12	107033.90	2831.80	109865.70	26892.3	82973.4	3.09	2358
115	88885	10535.4	13391.44	115889.40	3347.90	119237.30	27391.5	91845.8	3.35	1777
138	44444	8178.21	8332.72	89960.30	2083.20	92043.50	27713.05	64330.5	2.32	D
138	53333	8726.31	9642.19	95989.40	2410.50	98399.90	28030	70369.9	2.51	D
138	66665	9553.5	11630.9	105088.50	2907.70	107996.20	28452.3	79543.9	2.80	D
138	88885	10093.5	14912.44	111028.50	3728.10	114756.60	28906.5	85850.1	2.97	D

Grain price = 11 Birr/kg, Stack price = 0.25 Birr/kg, NR = (nitrogen rate), PD = (Plant density), AGY = (adjusted grain yield), AS = (adjusted straw yield), GYR = (grain yield return), SYR = (straw yield return), TR = (Total Return), TVC = (Total variable cost), NB = (net benefit), ND = (Nominated), D = (Dominated), MRR = (Marginal rate of return

CONCLUSION

The interaction effects of nitrogen rate and plant population were found highly significant on leaf area index, harvest index, grain yield, and biomass yield of maize. The highest nitrogen rate and population density, significantly delayed the number of days to 50% tasseling, 50% silking, and 90% physiological maturity. Regardless of the rate of nitrogen treatment, the maximum leaf area index was obtained at a high plant population density (88885 plants/ha). The maximum yield attributes such as ear/plant, number of kernels/ears, and thousand seed weight were recorded at the highest rate of applied nitrogen and low plant population density (44444 plants/ha). Therefore, the highest net benefit of 91845.8 ETB/ha with a net benefit-cost ratio of 335%, which means that for each ETB invested, maize grower of the study area would collect ETB 3.35 after recovering the cost of production was obtained at the highest plant population density of 88885 plants/ha supplied with 115 kg/ha of nitrogen. Maize sown at a plant population of 88885 plants/ha in combination with nitrogen at 115 kg/ha, gave mean grain yield increment by 79.69% compared to the control of (53333) plants/ha with a nitrogen application rate of 92 kg/ha. Thus, maize production at a plant population density of 88885 plants/ha combined with rate of 115 kg/ha of nitrogen would be profitable.

Data Availability Statement

The corresponding author can provide the raw data that was gathered and used to support the study's conclusions upon reasonable request.

Conflict of Interest

The authors declare that there is no conflict of interest.

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