

Response of Malt Barley Varieties to Nitrogen Rate and Time of Application for Optimum Yield and Malting Quality in Highlands of Ethiopia

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Abstract

Background

Malt barley is an important crop cultivated for both home consumption and market purposes. However, its productivity and grain quality are mainly constrained by low-yielding varieties, a lack of appropriate time of N fertilizer application, and N fertilizer rate recommendations in the study area.

Result

Thus, this study was carried out under farmer's field at central Ethiopian highlands during the 2023–2024 main cropping season to assess the effect of varieties, time of nitrogen application, and nitrogen fertilizer rate on yield and quality of malt barley. The treatment consisted a combination of three malt barley varieties (Holker, Traveler and Henerike), three nitrogen fertilizer rates (0, 90 and 180 kg ha⁻¹), and three times of nitrogen application: (T1= ½ rate of N fertilizer ha⁻¹ at sowing, ½ at tillering, T2= ½ at tillering, and ½ at booting, T3 = 1/3 at sowing, 1/3 at tillering, and 1/3 at booting) which was laid out in randomized complete block design (RCBD) with three replications. Days to 50% heading, days to 50% physiological maturity, plant height, spike length, number of kernels per spike, thousand kernel weight, aboveground dry biomass, and grain yield data were collected. The main effects of variety, N rate, and time of N application had a significant effect on grain yield, above-ground dry biomass, and grain protein content. Similarly, the interaction of variety, nitrogen rate, and time of N application had a significant influence on dry biomass yield and protein content of malt barley.

Conclusions

Therefore, Holker, Traveler and Henerike varieties in priority order, with the application of nitrogen fertilizer rate that gave higher MRR (90 kg ha⁻¹) by three time application 1/3 at sowing, 1/3 at tillering and 1/3 at booting gave the highest grain yield, biomass yield with acceptable quality parameters requirements set by the maltsters to be recommended in the highland areas of north Shewa and similar agro ecological areas.

Introduction

Barley (*Hordeum vulgare* L.) is one of the world's most important cereal crops, has been grown as a food and malt source since the beginning of settled agriculture, and is widely adapted to a broader range of environments. In Ethiopia, it is one of the oldest domesticated crops, deeply embedded in traditional diets and farming systems, and is largely grown as a food crop in the central and northern parts of Ethiopia, with Oromia, Amhara, Tigray, and Southern Nations, Nationalities, and Peoples' Region (SNPPR) as the main areas of production. The demand for beer, whose consumption has also increased significantly, is directly tied to Ethiopia's malt barley market potential. After teff, wheat, sorghum, and maize, it is the fifth most important crop in terms of both area and quantity produced in the Amhara region [1]. In the North Shewa zone, it ranks fourth in terms of area coverage [1]. However, crop productivity and production remained very low in the region. Further, there is a gap between the regional and the world average yield of barley. The average yield of barley in the Amhara region is 2.25 tons per hectare, and the national average yield is 2.59 tons per hectare [1], and the world average is 3.3 tons per hectare [2].

Even though there is immense potential for producing malt barley in Ethiopia, only about 2% of the total barley produced goes into malt factories for the six local breweries in the country [3]. Only one-third can be supplied from locally produced barley. The remaining two-thirds are imported primarily from Belgium and France [4]. To satisfy the ever-increasing demand for raw materials by the beverage industry, and to ensure dependable and higher cash returns to the farmers, expansion of the malt barley production is very important. However, its production has not expanded, and productivity at the farm level has remained low. One reason for the low productivity of the crop is the poor soil fertility, mainly aggravated by continuous

cropping, high soil erosion, and removal of crop residues, without any soil amelioration. Soils in the highlands of Ethiopia usually have low levels of essential plant nutrients, especially low availability of nitrogen, which is the major constraint to cereal crop production [5].

Quality requirements for malt barley are strict and directly related to processing efficiency and product quality in the malting and brewing industries. Excessively higher protein content is undesirable because of the strong inverse correlation between protein and carbohydrate content; thus, high protein content leads to a low malt extract level [6]. Grain N content is thus a determining factor of malt quality; high grain N content not only means lower carbohydrate content and lower malt extract level, but also makes the barley more difficult to modify, causing problems for the maltster. As a result, the preferred grain N level is not greater than 1.6–1.8% [7]. Given the presence of a major malt factory in the research area, but the persistent shortage of quality malt barley, this study provides timely and locally relevant insights. By identifying the economic optimum nitrogen rate and highlighting the role of application timing on grain protein content, the trial offers practical recommendations that can improve both farmer profitability and the supply of quality barley to the malting industry.

Variety has also played an important role in the yield and quality of malt barley. The yield and quality specifications of a given malting barley variety are determined by its genetic makeup and the physical conditions during growth [8; 9]. Many studies have been conducted on the relationship between barley varieties and their yield and malting qualities. The yield and quality specifications of a given malting barley variety are determined by its genetic makeup and the physical conditions during growth, harvesting, and storage [8–10].

Nitrogen fertilizer amount and application time have a great impact on the grain quality of malt barley. Full nitrogen application at planting leads to nutrient losses through leaching and volatilization as the crop lacks a well-developed root system to efficiently absorb the applied nitrogen. Nevertheless, split application of nitrogen fertilizer at different growth stages of malt barley reduces loss of nitrogen and increases supply of N to the crop throughout its growth stage that improves grain quality and increases yield.

In addition to the lack of site-specific fertilizer recommendations, the varietal context remains underdeveloped. While malt barley varieties such as Holker, Traveler, and Henerike are cultivated in the region, their response to nitrogen rate and timing under local agro-ecological conditions has not been systematically studied. This gap limits both farmer decision-making and the ability of the malting industry to secure a consistent quality supply.

However, no studies have been carried out on the interaction between nitrogen fertilizer rate and application time for different malting barley varieties under the North Shewa highlands conditions. So, the present investigation was conducted with the aim of determining the optimum nitrogen rate and time of application that maximizes yield and quality of malt barley, to select the best malt barley varieties for maximizing yield and quality, and to investigate the interaction effects of the tested factors for yield and quality product for malt barley in the growing areas of the North Shewa highlands.

Materials and Methods

Description of the Study Area

The experiment was conducted at three districts (Bassona werena, H/mariyam and Angolelana tera on a farmer's field during the main cropping season for two consecutive years of 2023–2024 G.C. The geographical location of the experimental sites are located between 9° 15' 52" to 9° 46' 55" N latitude and 39° 26' 59" to 39° 39' 50" E, longitude, and altitude ranged from 2769–2905 m.a.s.l (Fig. 2). The areas have minimum and maximum average annual temperatures of 7.65 °C and 20.44 °C, respectively. The two-year average annual rainfall is 1083.35mm, with the highest precipitation occurring in July and August (Fig. 1). The Soil type of the experimental sites is clay – clay loam (Table 1). Major crops grown in the area are wheat, barley, faba bean, and field pea.

Table 1
Mean value of some physico-chemical properties of the soil of experimental locations

Soil characteristics	Rating	Level	Analysis method
Soil pH	5.38	Moderately acidic	1:2.5 soil to water ratio
Organic carbon (%)	1.82	Low	Walkley-Black
Total nitrogen (%)	0.17	Low	Kjeldahl
Organic matter (%)	3.14		
Available P (ppm)	16.61	low	Olsen
Soil texture			
Sand (%)	30		
Clay (%)	43		
Silt (%)	27		
Note: Rating range is according to Thiagalingam 2000 manual			
<i>Treatments and Experimental Design</i>			

Soil Sampling and Analysis

Soil samples were taken randomly in a zigzag pattern from the experimental site at a depth of 0–30 cm across the experimental field using an auger before planting and were composited. The composite sample taken before planting was submitted to the DBARC soil testing laboratory.

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Treatments and Experimental Design

Table 2
Description of the treatments

<i>Treatment #</i>	<i>Varieties</i>	<i>Nitrogen rate</i>	<i>Nitrogen application time</i>	<i>Treatment combination</i>
1	V1	N1		V1N1
2	V1	N2	T1	V1N2T1 (1.2.1)
3	V1	N2	T2	V1N2T2 (1.2.2)
4	V1	N2	T3	V1N2T3 (1.2.3)
5	V1	N3	T1	V1N3T1 (1.3.1)
6	V1	N3	T2	V1N3T2 (1.3.2)
7	V1	N3	T3	V1N3T3 (1.3.3)
8	V2	N1		V2N1
9	V2	N2	T1	V2N2T1 (2.2.1)
10	V2	N2	T2	V2N2T2 (2.2.2)
11	V2	N2	T3	V2N2T3 (2.2.3)
12	V2	N3	T1	V2N3T1 (2.3.1)
13	V2	N3	T2	V2N3T2 (2.3.2)
14	V2	N3	T3	V2N3T3 (2.3.3)
15	V3	N1		V3N1
16	V3	N2	T1	V3N2T1 (3.2.1)
17	V3	N2	T2	V3N2T2 (3.2.2)
18	V3	N2	T3	V3N2T3 (3.2.3)
19	V3	N3	T1	V3N3T1 (3.3.1)
20	V3	N3	T2	V3N3T2 (3.3.2)
21	V3	N3	T3	V3N3T3 (3.3.3)
<i>Where; - 1, V1 = (Holker), V2 = Traveler/, and V3 = Henerike</i>				
<i>2, N1 = 0 kg/ha, N2 = 90 kg/ha and N3 = 180 kg/ha nitrogen rate</i>				
<i>3, T1 = ½ at sowing, ½ at tillering and 0 at booting,</i>				
<i>T2 = 0 at sowing, ½ at tillering and ½ at booting,</i>				

T3 = 1/3 at sowing, 1/3 at tillering and 1/3 at booting.

The treatment consisted of a combination of three malt barley varieties (Holker, Traveler and Henerike), three nitrogen fertilizer rates (0, 90 and 180 kg ha⁻¹), and three nitrogen application times (T1=½ rate of N fertilizer at sowing, ½ at tillering, T2= ½ at tillering, and ½ at booting, T3 = 1/3 at sowing, 1/3 at tillering, and 1/3 at booting), laid out in a randomized complete block design (RCBD) with three replications. The gross size of each plot was 2.5 m × 2.4 m (6 m²). The outermost row on both sides of each plot and 20 cm of the two ends were considered as border plants. The distance between adjacent plots and blocks was 0.75 m and 2 m, respectively. The experimental field was ploughed with oxen to a fine tilth three times, and the land was leveled properly. P₂O₅ at 69 kg ha⁻¹ was applied as basal from the TSP source. Nitrogen fertilizer was applied

as per the treatment from urea. The seeds were manually hand-drilled in the first week of July for the 2023 and 2024 main rainy seasons. The plot was kept free of weeds before fertilizer application to reduce competition with the crop. Grain yield, biomass yield, and protein content were measured following standard procedures. Protein content was determined using near-infrared (NIR) spectroscopy.

Crop data collection

Phenology data

Days to heading were determined as the number of days taken from the date of sowing to the date of 50% heading of the plants from each plot by visual observation. Days to maturity were determined as the number of days from sowing to the date when 50% of the peduncles turned to yellow in straw color.

Agronomic data

Plant height was measured from the soil surface to the tip of the spike of ten randomly selected plants from the net plot area at physiological maturity, excluding the awns. Spike length was measured from the bottom of the spike to the tip of the spike, excluding the awns, from ten randomly selected spikes from the net plot. The number of kernels per spike was calculated as an average of ten randomly selected spikes from the net plot area. The thousand kernel weight was determined by counting 1000 kernels taken from the grain yield of each net plot by using an electronic seed counter and weighing them with a sensitive balance. Aboveground dry biomass was determined from plants harvested from the net plot area after sun-drying to a constant weight. Grain yield was taken by harvesting and threshing the seed yield from the net plot area. The yield was adjusted to 12.5% moisture content. Harvest index was calculated from the ratio of grain yield per plot to total aboveground dry biomass yield per plot multiplied by hundred.

Quality data

Grain samples were collected from each plot after harvest, cleaned, and dried to constant weight. Extract content was carried out at Holetta Agricultural Research Center, Food Science and Nutrition Research Laboratory, taking a grain sample of 300 g from each treatment using near infrared (NIR) spectroscopy as described in AACC (2000). Grain protein content was determined using near infrared (NIR) spectroscopy (NIR Grain analyzer model 1241) as described in AACC (2000) at the HARC Food Science and Nutrition Research Laboratory by taking a grain sample of 300 g from each treatment. Hectoliter weight, which represents grain bulk density, was determined using a hectoliter weight analyzer.

Statistical Data Analysis

Data collected were subjected to the analysis of variance (ANOVA) following the statistical procedures applied for three-factor experiments by using SAS Software version 9.0, Copyright (c) 2002 by SAS Institute Inc., and [11] for visualization. Mean comparison was performed by Least Significant Difference (LSD) at $P < 0.05$. Accordingly, a combined analysis of variance over years (2023 and 2024) and locations (hereafter termed Angolelanatera, Bassonawerena, and Hageremariyam) was performed for grain yield.

Economic analysis

The economic analysis was performed to investigate the economic feasibility of the average main effects of nitrogen rates and labor costs for nitrogen application following the [12] procedures. The field price was obtained by a simple assessment of farm gate prices near the experimental site after harvest (January to February), which was taken as the average of the two years, and the official prices of nitrogen fertilizers were used for economic analysis. Accordingly, the price of grain yield and straw yield was estimated at 65.00 and 8.00 Ethiopian Birr (ETB) per kg, respectively. The variable costs, including labor

for nitrogen application, were estimated to be 500.00 ETB per day per person, while the prices of nitrogen fertilizers were estimated at 173.91 ETB per kg. The average yield was adjusted downward by 10%, assuming a yield reduction of 10% under the farmer's field. To use the marginal rate of return (MRR) as a basis for plant density and fertilizer recommendations, the minimum acceptable rate of return was set at 100% [12]. A treatment having higher total costs that vary and a lower net benefit than the immediately preceding treatment with lower total costs that vary and a higher net benefit was considered to be dominated and was eliminated from further analysis.

Results and Discussion

Analysis of variance revealed that the main effects of variety, nitrogen fertilizer rate, and time of nitrogen application, as well as the interaction effect of nitrogen rate and time of nitrogen application, had a significant effect on days to 50% heading (Table 3). Traveler and Henerike were later maturing than the Holker variety (Table). Similarly, [13] reported that barley genotypes differ in days to heading. The difference in nitrogen fertilizer application time might be related to the extended vegetative growth stage that delays days to heading. [14] Also reported that N application significantly affected the days to heading in barley. The result indicates that as the amount of nitrogen fertilizer applied at tillering increases, days to heading also increase.

Table 3
ANOVA table of selected agronomic parameters

Mean square value of phenology, growth and yield parameters								
Source	DF	DH	DM	PHT	SPL	NSP	By	Gy
VR	2	284.5 ^{***}	1086.4 ^{***}	17153.9 ^{***}	22.57 ^{***}	72.13 ^{***}	177714400.4 ^{***}	7502002.8 ^{***}
NR	1	31.9	284.7 [*]	160.6 ^{NS}	3.55 ^{**}	41.13 ^{**}	96895817.4 ^{***}	7237172.4 ^{***}
NT	2	457.9 ^{***}	598.6 ^{***}	26.5 ^{NS}	1.26 [*]	5.81 ^{NS}	3809340.5 ^{NS}	497978.7 ^{NS}
VR*NR	2	21.6 ^{NS}	24.4 ^{NS}	38.6 ^{NS}	0.28 ^{NS}	1.99 ^{NS}	4222094.6 ^{NS}	78846.4 ^{NS}
VR*NT	4	16.2 ^{NS}	24.2 ^{NS}	74.6 ^{NS}	0.31 ^{NS}	0.78 ^{NS}	2224069.4 ^{NS}	379459.1 ^{NS}
NR*NT	2	46.5 ^{**}	119.2 ^{NS}	53.3 ^{NS}	0.34 ^{NS}	6.45 ^{NS}	583851.5 ^{NS}	272803.6 ^{NS}
VR*NR*NT	4	9.7 ^{NS}	26.6 ^{NS}	48.4 ^{NS}	0.34 ^{NS}	1.03 ^{NS}	5263385.2[*]	774098.1 ^{NS}
CV		3.46	3.61	8.93	7.49	7.91	8.80	7.04

Where DF = Degree of freedom; TKW=Thousand kernel weight; HLW = Hectoliter weight; HI = Harvest index; EC=Extract content; FB=Friability; PC = Protein content.

Table 4
ANOVA table of selected agronomic parameters

Source	Mean square value of quality parameters					
	TKW	HLW	HI	EC	FB	PC
VR	1121.50 ^{***}	623.80 ^{***}	839.2 ^{***}	60.5 ^{***}	4008.2 ^{***}	25.54 ^{***}
NR	6.17 ^{NS}	0.33 ^{NS}	58.0 [*]	77.3 ^{***}	2356.8 ^{***}	65.81 ^{***}
NT	57.30 ^{**}	6.19 ^{NS}	16.3 ^{NS}	16.2 ^{***}	1063.3 ^{***}	15.85 ^{***}
VR*NR	8.57 ^{NS}	10.06 ^{NS}	36.3 ^{NS}	0.8 ^{NS}	56.2 ^{NS}	0.001 ^{NS}
VR*NT	3.96 ^{NS}	15.40 [*]	33.7 [*]	4.2 [*]	30.1 ^{NS}	1.59 ^{NS}
NR*NT	0.82 ^{NS}	0.21 ^{NS}	18.6 ^{NS}	2.2 ^{NS}	59.8 ^{NS}	0.65 ^{NS}
VR*NR*NT	2.79 ^{NS}	0.71 ^{NS}	18.2 ^{NS}	2.2 ^{NS}	50.3 ^{NS}	1.87 [*]
CV	5.53	3.15	11.63	1.36	11.29	7.31

Where DF = Degree of freedom; TKW=Thousand kernel weight; HLW = Hectoliter weight; HI = Harvest index; EC=Extract content; FB=Friability; PC = Protein content.

Days to 50% physiological maturity were significantly ($p \leq 0.001$, $p \leq 0.05$) affected by the main effect of variety, nitrogen fertilizer rate, and time of nitrogen application, as well as by the interaction effect of nitrogen rate and time of nitrogen application (Table 3). Days to physiological maturity followed a similar trend to days to heading. Split N application time of $\frac{1}{2}$ at tillering and $\frac{1}{2}$ at booting in Traveler variety extended the days to 50% physiological maturity compared to Holker and Henerike varieties, as a larger proportion of N is allotted at the tillering stage than at sowing (Table). The effect of variety might be due to the genetic makeup of the variety, as Holker was an early-maturing variety, whereas Traveler and Henerike were late-maturing varieties [15]. Similarly, [13] and [16] reported that genotypes could differ in days to physiological maturity. The longer duration to physiological maturity might be due to nitrogen application at the tillering stage, when the crop has a well-developed root system, allowing efficient nitrogen uptake. This enhances vegetative growth and delays maturity. The highest nitrogen rate showed longer days to maturity. This result agrees with [17], who reported that high rates of nitrogen prolong days to physiological maturity.

Table 5
Main effects of varieties, nitrogen fertilizer rate, and time of application on growth parameters of malt barley

Varieties	Days to 50% heading	Days to 50% maturity	Plant height (cm)	Spike length (cm)
Holker	75.82 ^b	122.14 ^c	88.55 ^a	7.64 ^c
Traveler	79.61 ^a	129.88 ^a	61.74 ^b	7.96 ^b
Henerikie	78.75 ^a	126.63 ^b	61.90 ^b	8.73 ^a
LSD	0.891	1.502	2.081	0.200
N Rate				
90 kg ha ⁻¹	77.68 ^b	125.06 ^b	69.87 ^b	7.98 ^b
180 kg ha ⁻¹	78.44 ^a	127.36 ^a	71.59 ^a	8.24 ^a
LSD	0.727	1.226	1.699	0.163
N timing				
Timing 1	76.60 ^b	124.49 ^b	71.15	8.14 ^{ab}
Timing 2	80.97 ^a	129.54 ^a	70.04	8.22 ^a
Timing 3	76.61 ^b	124.61 ^b	71	7.96 ^b
LSD	0.891	1.502	2.081	0.200
Control/without fertilizer				
Holker	79.5	122.00 ^b	74.13 ^a	6.60 ^b
Traveler	81.92	127.75 ^a	48.04 ^c	6.40 ^b
Henerikie	82.25	124.17 ^b	54.98 ^b	7.20 ^a
LSD	3.238	3.176	4.380	0.552
CV	3.46	3.61	8.93	7.49

Where, N timing = Time of urea application; Timing 1= ½ at sowing and ½ at tillering; Timing 2= ½ at tillering and ½ at booting; Timing 3 = 1/3 at sowing, 1/3 at tillering and 1/3 at booting.

Plant height was significantly affected by the main effect of variety and nitrogen fertilizer rate (Table 3). A significant ($p \leq 0.001$) difference in plant height was observed in the Holker variety. The varietal difference could be attributed to genetic differences. From the nitrogen rate, the highest rate gave the longest plant height. This may be nitrogen rate helps the vegetative growth of the crop (Table). This result was similar to [18], who reported that varietal differences in plant height might be due to genetic behavior in combination with environmental conditions.

Spike length was significantly ($p \leq 0.001$, $p \leq 0.05$) affected by varieties and nitrogen fertilizer rates, respectively (Table 3). The longest spike length was recorded from the Henerike variety, followed by the Traveler variety (Table). The difference in the varieties in spike length could be due to genotypic difference of the varieties. Similarly, [18] also reported that spike length varied among barley varieties. Another study also revealed that differences were observed between varieties in terms of spike length in barley [19].

The number of kernels per spike was significantly ($p \leq 0.001$, $p \leq 0.05$) affected by the main effect of varieties and nitrogen fertilizer rate in malt barley, respectively (Table 3). The highest kernels per spike were recorded from the Henerike and Holker varieties, followed by the Traveler variety. The highest number of kernels per spike was obtained at a nitrogen fertilizer rate of 180 kg ha^{-1} (Table).

Table 6
Main effects of varieties, nitrogen fertilizer rate, and time of application on yield and yield-related parameters of malt barley

Varieties	Number of seeds per spike	Biomass yield kg ha^{-1}	Grain yield kg ha^{-1}	Harvest index
Holker	27.53 ^a	11922.20 ^a	4240.72 ^a	35.95 ^b
Traveler	26.08 ^b	10133.80 ^b	4095.69 ^b	42.16 ^a
Henerikie	28.00 ^a	8700.60 ^c	3592.99 ^c	42.63 ^a
LSD	0.710	297.210	92.221	1.543
N Rate				
90 kg ha^{-1}	26.77 ^b	9554.70 ^b	3783.28 ^b	40.42
180 kg ha^{-1}	27.64 ^a	10949.80 ^a	4169.65 ^a	40.07
LSD	0.579	242.670	75.298	1.260
N timing				
Timing 1	26.88	10269.00 ^{ab}	3956.57 ^b	39.67
Timing 2	27.41	10058.70 ^b	3903.25 ^b	39.88
Timing 3	27.32	10428.90 ^a	4069.57 ^a	41.19
LSD	0.710	297.210	92.221	1.543
Control/without fertilizer				
Holker	23.78	6490.9 ^a	2805.1 ^a	50.04 ^b
Traveler	23.2	5138.8 ^b	2548.6 ^{ab}	55.79 ^a
Henerikie	24.06	4855.4 ^b	2289.2 ^b	55.50 ^a
LSD	2.007	945.750	481.370	2.559
CV	7.91	8.80	7.04	11.63

Where, N timing = Time of urea application; Timing 1= $\frac{1}{2}$ at sowing and $\frac{1}{2}$ at tillering; Timing 2= $\frac{1}{2}$ at tillering and $\frac{1}{2}$ at booting; Timing 3 = $\frac{1}{3}$ at sowing, $\frac{1}{3}$ at tillering, and $\frac{1}{3}$ at booting.

Grain yield was affected significantly ($P \leq 0.001$) by the main effects of variety, N fertilizer rate, and time of application, as well as the interaction effect of variety by nitrogen fertilizer rate and application time (Table 3). The higher and the lower grain yields were obtained from the variety Holker and the Henerike variety, respectively. Variation in grain yield among varieties could be linked with the genetic differences among varieties or to the differences of the varieties in response to management practices and environment (Table 6, Figure). Accordingly, [13] reported that some varieties showed better performance in grain yield, which might be due to the highest response of varieties to nitrogen and nitrogen use efficiency. The highest grain yield was observed from the highest nitrogen rate, 180 kg ha^{-1} , while partial economic analysis revealed

that the highest marginal return was observed from a nitrogen rate of 90 kg ha⁻¹ (Table 9). So from the three-way interaction, the Holker variety interacted with a 90 kg ha⁻¹ nitrogen fertilizer rate by three-time application (1/3 at sowing, 1/3 at tillering, and 1/3 at booting) gave the highest MRR than that of other treatment combinations. Findings in splitting nitrogen fertilizer into many doses increase the efficiency of the fertilizers used by largely decreasing leaching and increasing both yield and quality of crops in favor of the highest number of splits, as indicated by [20]. Maximum efficiency should be obtained by the latest possible application compatible with the stage of development that still permits rapid N uptake [21]. Thus, unnecessary vegetative growth is avoided, which may result in lodged plants and subsequent reduction in grain yield. Furthermore, the opportunities for N losses by leaching, denitrification, volatilization, and runoff are reduced because an active root system is present for absorbing the fertilizer N when it is applied.

Aboveground dry biomass: the analysis of variance showed that above-ground dry biomass was significantly ($p \leq 0.001$) affected by variety and N rate, as well as Significant three-way interactions (Variety $\times$ Rate $\times$ Timing) were observed for biomass yield and protein content, indicating that these traits are strongly influenced by combined management practices. (Table 3). The higher and lower above-ground dry biomass were scored in the Holker and Henerike varieties, respectively. This variation was due to the genetic makeup of the varieties. The highest nitrogen rate gave the highest above-ground dry biomass (Table).

The significant three-way interaction (Variety $\times$ Nitrogen Rate $\times$ Nitrogen Timing) on above-ground biomass yield demonstrates that treatment responses were conditional on specific factor combinations. Biomass accumulation varied across varieties depending on both the rate and timing of nitrogen application (Table 8). Split applications enhanced biomass, particularly at moderate nitrogen levels in Holker, whereas other varieties required higher rates to achieve comparable yields (Fig. 4). These findings underscore that biomass yield cannot be explained by main effects alone, but rather by the synergistic influence of genotype, nutrient rate, and application timing. The three-way interaction revealed that Holker variety, when supplied with 90 kg N ha⁻¹ in three split applications, produced above-ground biomass yields statistically comparable to those obtained under 180 kg N ha⁻¹ treatments. This finding underscores the efficiency of Holker in utilizing nitrogen when applied in synchrony with crop demand, suggesting that moderate rates with optimized timing can achieve high biomass yields while reducing input costs and environmental burden.

Harvest index. The analysis of variance revealed that the main effect of variety significantly ($p \leq 0.001$) affected the harvest index of malt barley (Table 4). Statistically similar higher harvest index was recorded from Henerike and Traveler, while Holker variety gave a lower harvest index (Table). [13] Also reported that there was variation in the harvest index of different barley varieties due to barley's inherent variability. However, the harvest index was not affected by the time of N application and nitrogen fertilizer rates.

Thousand kernel weight: Analysis of variance indicated that the main effects of variety and time of N application had a significant influence on thousand-kernel weight of malt barley (Table 4). Holker variety gave the highest thousand-kernel weight. Whereas the Henerike variety gave the lowest thousand-kernel weight (Table). This could be associated with genetic differences of the varieties apart from management. [22] Also reported that variation in thousand kernel weight is a function of barley genotype. The time of N fertilizer application had an influence on thousand kernel weight. Higher thousand kernel weight was obtained when N was applied $\frac{1}{2}$ at tillering and $\frac{1}{2}$ at booting, and 1/3 at sowing, 1/3 at tillering, and 1/3 at booting. These could be a result of efficient uptake of applied N fertilizer by the plant, due to the application of nitrogen after emergence, which led to heavier thousand-kernel weight. The findings of [23] also indicated that a lower thousand-kernel weight was observed when half of the nitrogen was applied at sowing. This could be related to loss of applied N due to leaching, volatilization, or other means.

Extract content Analysis of variance indicated that the extract content of malt barley was significantly affected by the main effects of varieties, nitrogen fertilizer rate, and fertilizer application time (Table 4). Better extract content in Traveler is more advantageous than in Henerike and Holker, which might be due to the genetic differences among the varieties (Table). It is

an all-natural, nutritious, whole-grain sweetener with a minimum value of 76%, and the results of all the tested varieties were above the minimum requirement.

Grain protein content: Analysis of variance indicated that grain protein content of the varieties did not exceed the limit of grain protein content standards set by the Ethiopian Standards Authority and Asella Malt Factory (AMF), which should be within the range of 9–12% [24] in all treatments (Table).

Table 7
Main effects of varieties, nitrogen fertilizer rate, and time of application on quality parameters of malt barley

Varieties	Thousand kernel weight (gm)	Hectoliter weight (kg l ⁻¹)	Extract content (%)	Friability (%)	Dry grain protein (%)
Holker	47.50 ^a	65.95 ^a	80.72 ^c	58.26 ^c	11.27 ^a
Traveler	41.92 ^b	63.17 ^b	82.54 ^a	72.40 ^a	10.12 ^c
Henerikie	39.88 ^c	60.07 ^c	81.45 ^b	69.44 ^b	10.44 ^b
LSD	0.786	0.656	0.366	2.480	0.256
N Rate					
90 kg ha ⁻¹	42.93	63.02	82.17 ^a	70.00 ^a	10.06 ^b
180 kg ha ⁻¹	43.27	63.1	80.97 ^b	63.40 ^b	11.16 ^a
LSD	0.641	0.535	0.299	2.025	0.209
N timing					
Timing 1	42.07 ^b	62.82	82.05 ^a	71.08 ^a	10.10 ^c
Timing 2	43.61 ^a	62.98	81.10 ^c	63.90 ^b	11.03 ^a
Timing 3	43.62 ^a	63.39	81.56 ^b	65.11 ^b	10.70 ^b
LSD	0.786	0.656	0.366	2.480	0.256
Control/without fertilizer					
Holker	46.33 ^a	63.73 ^a	81.51 ^b	67.00 ^b	10.07 ^a
Traveler	39.80 ^b	61.92 ^a	83.84 ^a	87.08 ^a	8.32 ^b
Henerikie	39.08 ^b	59.41 ^b	82.90 ^a	84.96 ^a	8.75 ^b
LSD	2.423	2.036	0.995	6.619	0.746
CV	5.53	3.15	1.36	11.29	7.31

Where, N timing = Time of urea application; Timing 1= ½ at sowing and ½ at tillering; Timing 2= ½ at tillering and ½ at booting; Timing 3 = 1/3 at sowing, 1/3 at tillering, and 1/3 at booting.

Protein content is one of the important parameters in selecting malting barley. It is affected by genotype, cultural practices, and growing environments. Malt barley with high protein content results in lower extracts. It also slows down water uptake during steeping, potentially affecting final malt quality. A very low protein level, on the other hand, results in a lack of enzymes necessary to modify the barley kernel and to break down the starch during brewing. Low protein also impairs the

brewing performance due to poor yeast amino acid nutrition. The desirable range of protein is 9.0–11.0 per cent for 2-rowed and 9.0–11.5 per cent for six-rowed barley. Generally, maltsters can use barley with protein content in the range of 11–12.5% to meet brewers' requirements [25]. However, according to the Ethiopian Standards Authority, the acceptable protein content for raw barley predestined for malting purposes ranges between 9–12%. In this study, grain protein content was significantly influenced by the main effects of variety, nitrogen rate, and application time, as well as their interactions (Table 4). The highest grain protein content (11.27%) was recorded for the Holker variety, whereas the lowest (10.12%) was observed in the Traveler variety. Both values fall within the recommended range for beer production. The observed difference among varieties in grain protein content is probably attributable to their inherent genetic differences, which influence nitrogen uptake and assimilation efficiency. Variation in grain protein content of varieties agreed with the previous works of [26], who reported that grain protein content is influenced largely by both genotype and environment.

Protein content was also influenced by the time of nitrogen fertilizer application, in which maximum grain protein content (11.03%) was obtained when applying $\frac{1}{2}$ rate at tillering and $\frac{1}{2}$ rate at the booting stage. This might be due to the availability of N for crops during grain filling, as $\frac{1}{2}$ of the urea was applied at booting. The minimum grain protein content (10.10%) was recorded in response to applying $\frac{1}{2}$ rate urea at planting and $\frac{1}{2}$ rate at tillering (Table 7), which could be due to the basal application of N being used for vegetative growth rather than partitioning into grain. This result is similar to that of [27] who reported that applying all nitrogen at sowing consistently resulted in grain with the lowest protein levels; hence, grain protein tended to be maximized when some N is applied during tillering and again at stem elongation or flag leaf emergence.

The three-way interaction revealed that Holker variety, when supplied with 180 kg N ha⁻¹ in two split applications, produced significantly higher protein content compared to other treatments (Table 6 and Fig. 5). However, all protein values remained within the acceptable range defined by maltsters' grading standards. This finding highlights that while nitrogen management influences protein accumulation, the tested treatments maintained malting quality, underscoring the importance of synchronizing genotype, nutrient rate, and timing to balance yield and quality traits.

Hectoliter weight analysis of variance revealed that hectoliter weight was significantly influenced by the main effect of variety and the interaction of variety with time of N application (Table 4). A plump seed has better Hectoliter weight with efficient use of N. [28] also reported that the acceptable standard of Hectoliter weight for barley was in the range of 66.1–72.8 kg hl⁻¹. Though non-significant, Hectoliter weight was in the stated ranges in this study. When available nitrogen is deficient, hectoliter weight will be lower. However, once nitrogen requirements are met, additional nitrogen has the potential to result in reduced test weight. Managing nitrogen carefully to meet, but not exceed, yield goals maximizes the likelihood of a good hectoliter weight. Crop rotation and manure or other soil amendments, as well as commercial fertilizers, should be considered when estimating available nitrogen [7].

Table 8

Interaction effect on biomass yield, grain yield, and dry protein content of malt barley over location and over year data.

Varieties	N rate	N timing (sowing, tillering, and booting stage respectively)	Above-ground biomass t/ha	Grain yield t/ha	dry protein content %
Holker	90 kg ha ⁻¹	50%, 50%, 0	10.425 ^{d-f}	3.9261	10.080 ^{d-h}
		0, 50%, 50%	11.010 ^{c-e}	4.0037	11.115 ^{bc}
		33.3%, 33.3%, 33.3%	11.642 ^{a-d}	4.3183	10.967 ^{b-e}
Holker	180 kg ha ⁻¹	50%, 50%, 0	12.962 ^a	4.6460	10.894 ^{b-f}
		0, 50%, 50%	12.612 ^{ab}	4.1286	12.885 ^a
		33.3%, 33.3%, 33.3%	12.394 ^{a-c}	4.4260	11.705 ^b
Traveler	90 kg ha ⁻¹	50%, 50%, 0	10.439 ^{d-f}	4.1582	9.449 ^h
		0, 50%, 50%	9.324 ^{fg}	3.8956	9.855 ^{gh}
		33.3%, 33.3%, 33.3%	9.466 ^{fg}	3.7217	9.391 ^h
Traveler	180 kg ha ⁻¹	50%, 50%, 0	10.600 ^{d-f}	4.2222	9.982 ^{f-h}
		0, 50%, 50%	9.734 ^{e-g}	4.0380	10.926 ^{b-f}
		33.3%, 33.3%, 33.3%	11.236 ^{b-d}	4.5384	11.119 ^{bc}
Henerike	90 kg ha ⁻¹	50%, 50%, 0	7.652 ^h	3.3266	9.450 ^h
		0, 50%, 50%	7.602 ^h	3.4465	10.238 ^{c-h}
		33.3%, 33.3%, 33.3%	8.427 ^{gh}	3.4354	9.994 ^{e-h}
Henerike	180 kg ha ⁻¹	50%, 50%, 0	9.532 ^{e-g}	3.6472	10.777 ^{b-g}
		0, 50%, 50%	9.568 ^{e-g}	3.9071	11.174 ^{bc}
		33.3%, 33.3%, 33.3%	9.420 ^{fg}	3.9776	11.014 ^{b-d}
CV			8.80	NS	7.31
Note: T1 = 50%, 50%, 0; T2 = 0, 50%, 50%; T3 = 33.33%, 33.33%, 33.33% at sowing, at tillering, and at booting stage respectively.					

The correlation analysis showed that plant height was highly correlated (> 0.8) with above-ground biomass yield, grain yield, thousand kernel weight, and hectoliter weight. Similarly, grain has positively correlated (> 0.6) with biomass yield, number of seeds per spike, and thousand-kernel weight, while friability and extract content have negatively correlated with grain protein content (Figure).

Partial budget analysis

Partial budget analysis is a method of organizing experimental data and information about the costs and benefits of various alternative treatments. As indicated in Table 9, the highest net benefit of 288199 ETB ha⁻¹ with an MRR of 3274.9% was obtained in response to the application of 90 kg N ha⁻¹

combined with three-time application from the Holker variety. The other treatments were dominated by lower MRR values. Thus, applications of 90 kg N ha⁻¹ combined with three split applications are economically beneficial as compared to the other treatments because the marginal rate of return exceeded the minimum acceptable level (100%).

Table 9

Dominance and marginal rate of return analysis for the effect of varieties and nitrogen rate and time of application on grain yield (t ha⁻¹) of malt barley, combined over years.

Variety	N rate kg ha ⁻¹	Time of N application	Sy t ha ⁻¹	Gy t ha ⁻¹	adj Sy t ha ⁻¹	adj Gy t ha ⁻¹	GFB ETB ha ⁻¹	TVC ETB ha ⁻¹	NB ETB ha ⁻¹	MNB	MRR
Holker	90	1	6.499	3.926	5.849	3.533	276469	16652	259817		
Holker	90	2	7.006	4.004	6.306	3.603	284662	16652	268010	D	
Traveler	90	1	6.281	4.158	5.653	3.742	288476	16652	271825	D	
Traveler	90	2	5.428	3.896	4.886	3.506	266977	16652	250325	D	
Henerike	90	1	4.325	3.327	3.893	2.994	225749	16652	209097	D	
Henerike	90	2	4.156	3.447	3.740	3.102	231540	16652	214888	D	
Holker	90	3	7.324	4.318	6.591	3.886	305351	17152	288199	16374.7	3274.9
Traveler	90	3	5.744	3.722	5.170	3.350	259078	17152	241927	D	
Henerike	90	3	4.992	3.435	4.492	3.092	236910	17152	219759	D	
Holker	180	1	8.316	4.646	7.484	4.181	331666	32304	299362	11163.1	73.7
Holker	180	2	8.483	4.129	7.635	3.716	302604	32304	270300	D	
Traveler	180	1	6.378	4.222	5.740	3.800	292919	32304	260615	D	
Traveler	180	2	5.696	4.038	5.126	3.634	277234	32304	244930	D	
Henerike	180	1	5.885	3.647	5.296	3.282	255732	32304	223428	D	
Henerike	180	2	5.661	3.907	5.095	3.516	269324	32304	237020	D	
Holker	180	3	7.968	4.426	7.171	3.983	316291	32804	283487	D	
Traveler	180	3	6.698	4.538	6.028	4.085	313719	32804	280915	D	
Henerike	180	3	5.442	3.978	4.898	3.580	271875	32804	239071	D	

GFB= Gross field benefit; TVC= Total variable cost; NB = Net benefits; MC= Marginal cost; MNB= Marginal net benefit; MRR= Marginal rate of return; D= Dominated; ETB = Ethiopian birr; Adj. = adjusted; The treatments were arranged in ascending order by their TVC for the purpose of marginal analysis

Conclusions

Combined analysis of results showed that variety, nitrogen rate, and time of application had a significant effect on most of the studied parameters, both individually and through their interactions. Higher grain yield was obtained by Holker (4.6 t ha⁻¹), statistically similar to Traveler (4.5 t ha⁻¹), while the lower grain yield was obtained from the Henerike variety. Time of N application had a significant effect on grain yield and grain protein content. Applying 1/3 at sowing, 1/3 at tillering, and 1/3 at booting gave the highest grain yield with acceptable protein content, while applying ½ at tillering and ½ at booting gave out-of-range protein content. From the tested nitrogen rates, higher grain yield was observed from 180 kg ha⁻¹ in all varieties,

while 90 kg ha⁻¹ also gave statistically similar yield in Holker and Traveler varieties. Based on partial economic analysis, the highest net benefit of 288199 ETB ha⁻¹ with an MRR of 3274.9% was obtained in response to the application of 90 kg N ha⁻¹ combined with three-time application from the Holker variety. The other treatments were dominated by lower MRR values. Thus, applications of 90 kg N ha⁻¹ combined with three-time application are economically beneficial as compared to the other treatments because the highest marginal rates of return were above the minimum level (100%).

It is important to distinguish between official varietal recommendations and the site-specific experimental optima generated in this study. While the released malt barley varieties are recommended nationally, their performance under the highland areas of Amhara and under varying nitrogen rates has not been systematically validated. Our findings provide site-specific fertilizer rate optima (90 kg N ha⁻¹) and highlight timing effects on protein content, which complement but do not replace the official recommendations.

Therefore, by considering partial economic analysis and acceptable quality parameters, we recommend Holker, Traveler, and Henerike varieties in priority order, with 90 kg nitrogen ha⁻¹ by three-time application (1/3 at sowing, 1/3 at tillering, and 1/3 at booting) to produce malt barley in the highland areas of north Shewa and similar agro-ecological areas.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Note

T1 = 50%, 50%, 0; T2 = 0, 50%, 50%; T3 = 33.33%, 33.33%, 33.33% at sowing, at tillering, and at booting stage respectively.

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Author Contribution

Degu Temeche: Writing– original draft. Elias Getachew: Data curation. Getachew Hailu: Data curation. Adamu Molla: Data curation. Altaye Tiruneh: Data curation. Aemiro Bezabih: Data curation. Yeshitila Merene: Data curation.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Figures

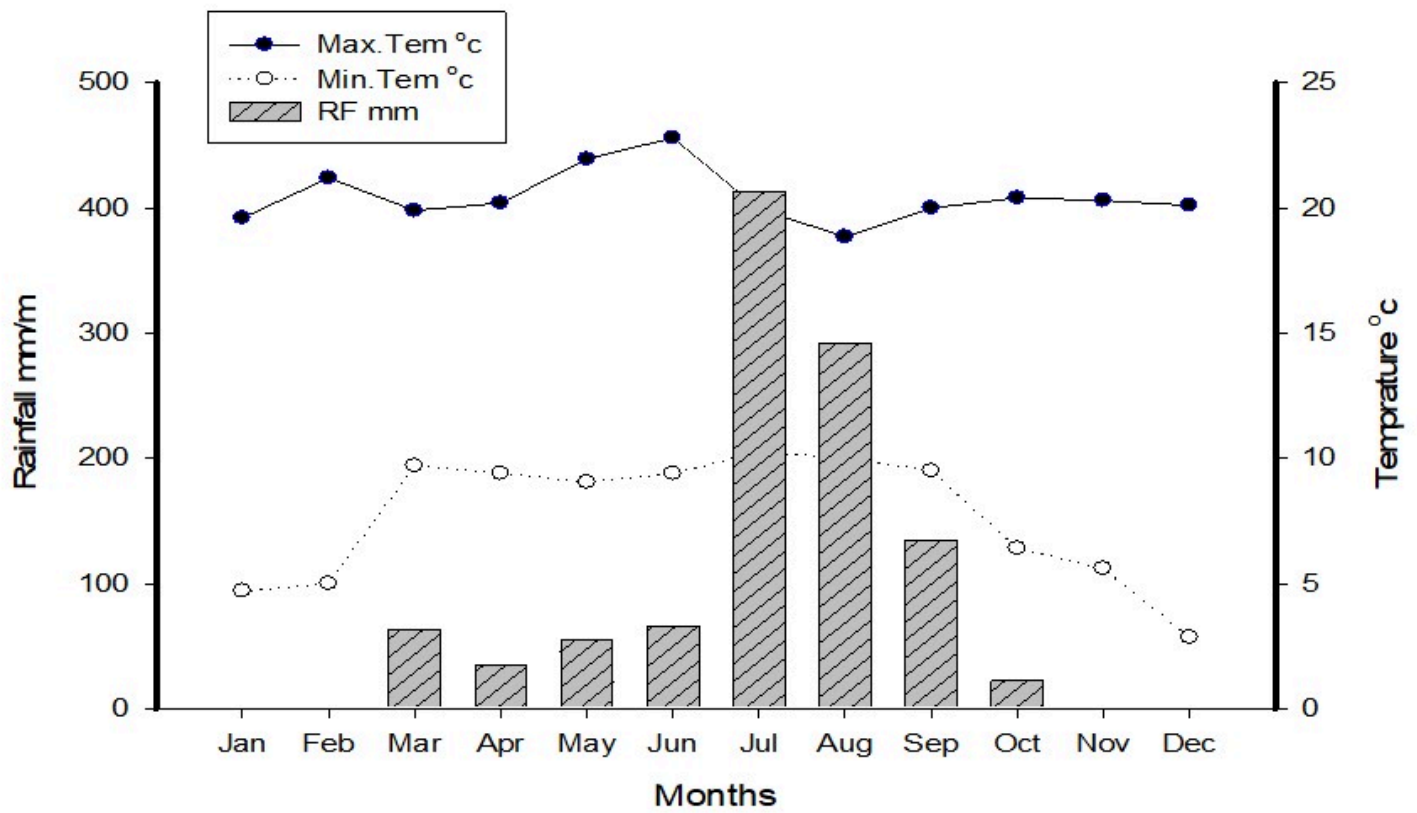


Figure 1

Mean monthly rainfall and the mean maximum and minimum temperatures during the experimental year

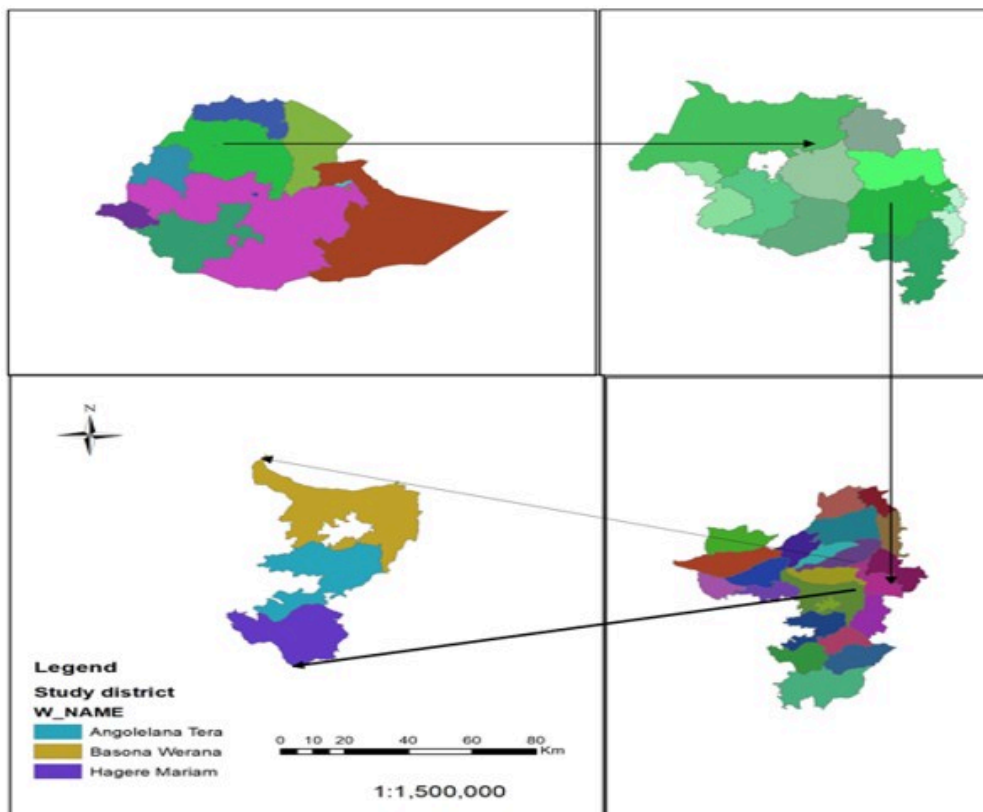


Figure 2

Location map of the study district

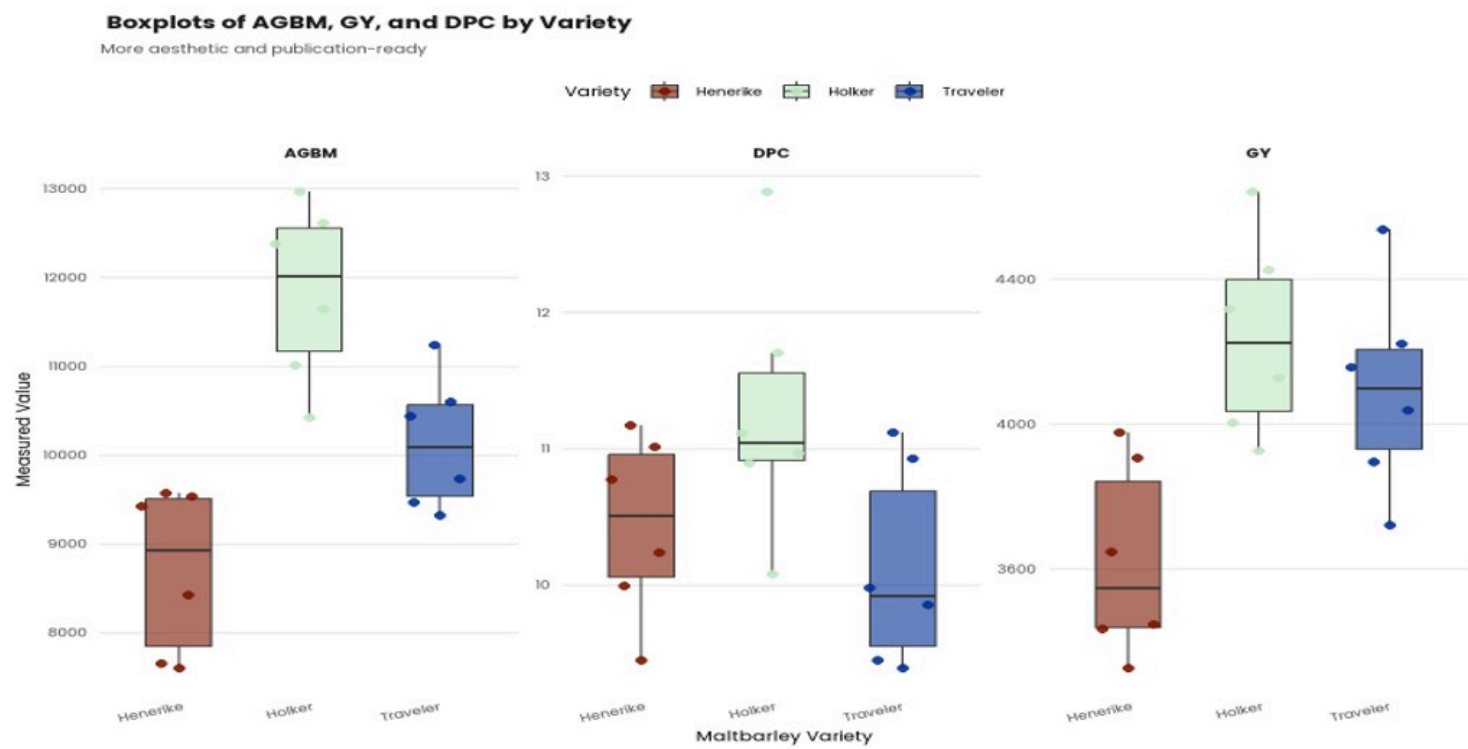


Figure 3

Boxplot presentation of varieties' response for different parameters

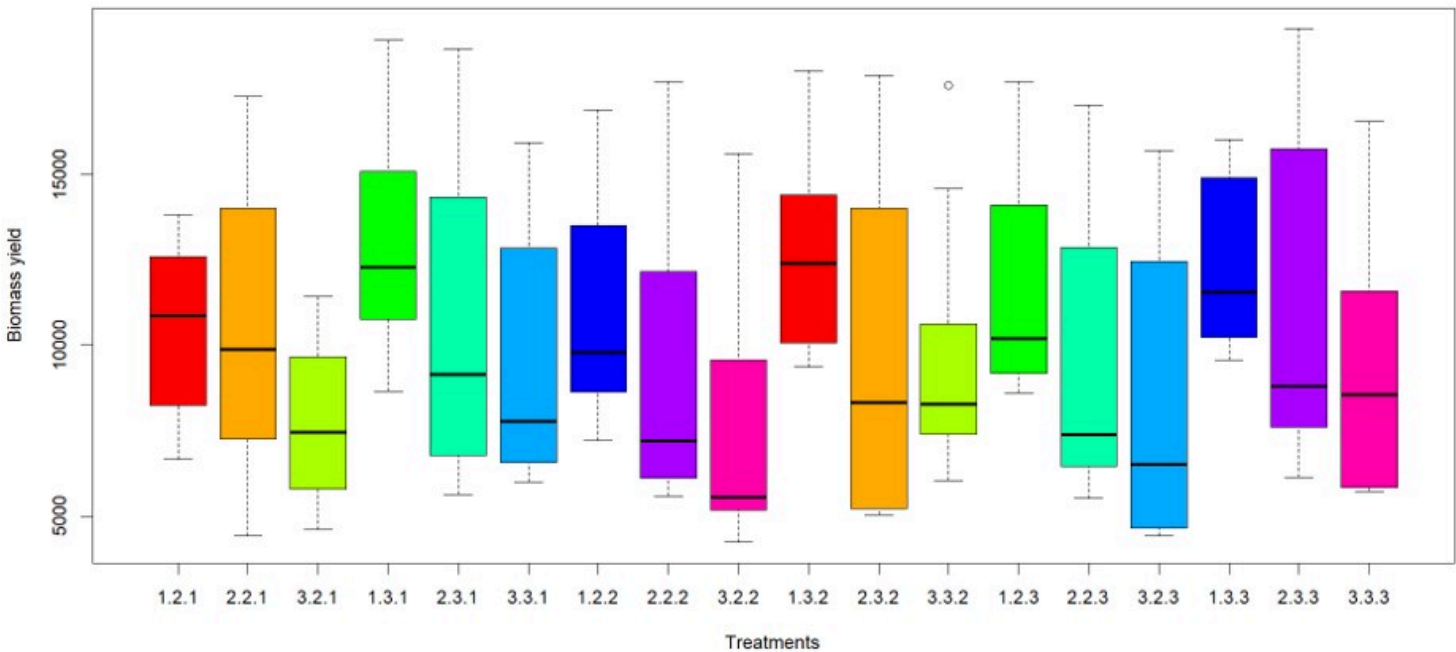


Figure 4

Boxplot presentation of three_way interaction response for biomass yield

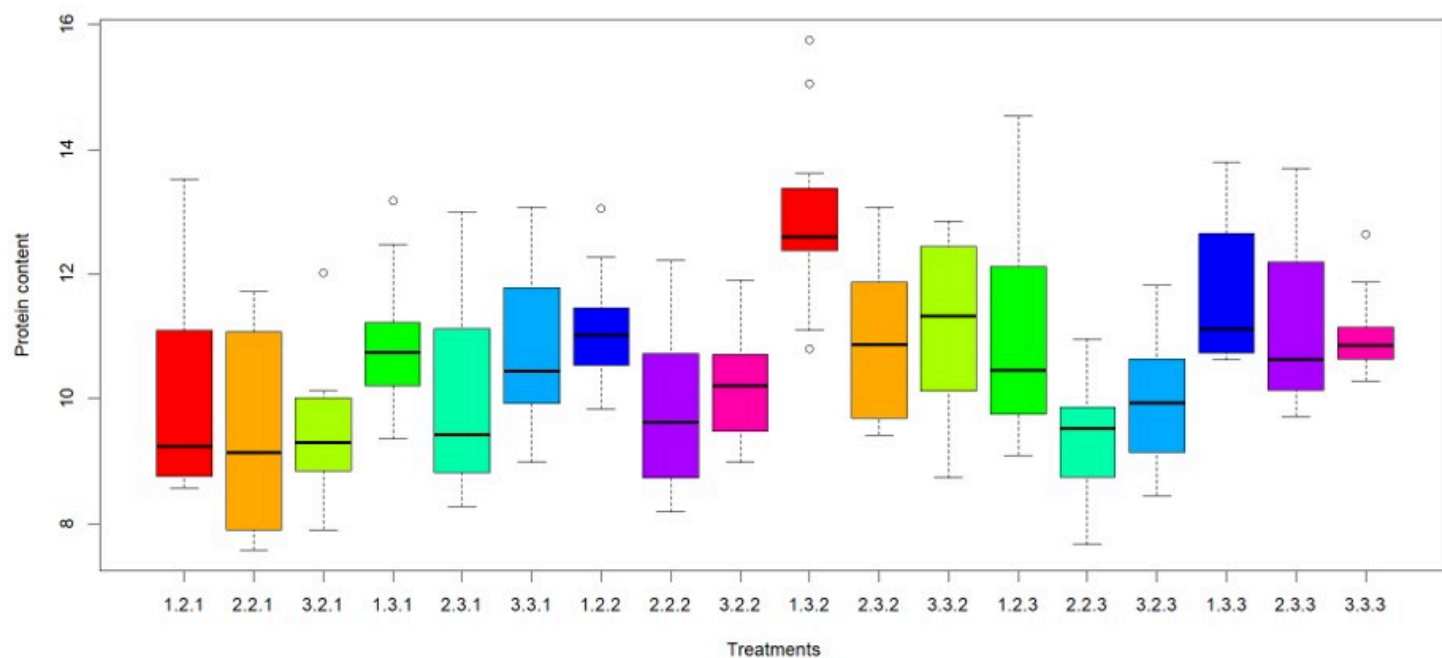


Figure 5

Boxplot presentation of three_way interaction response for protein content

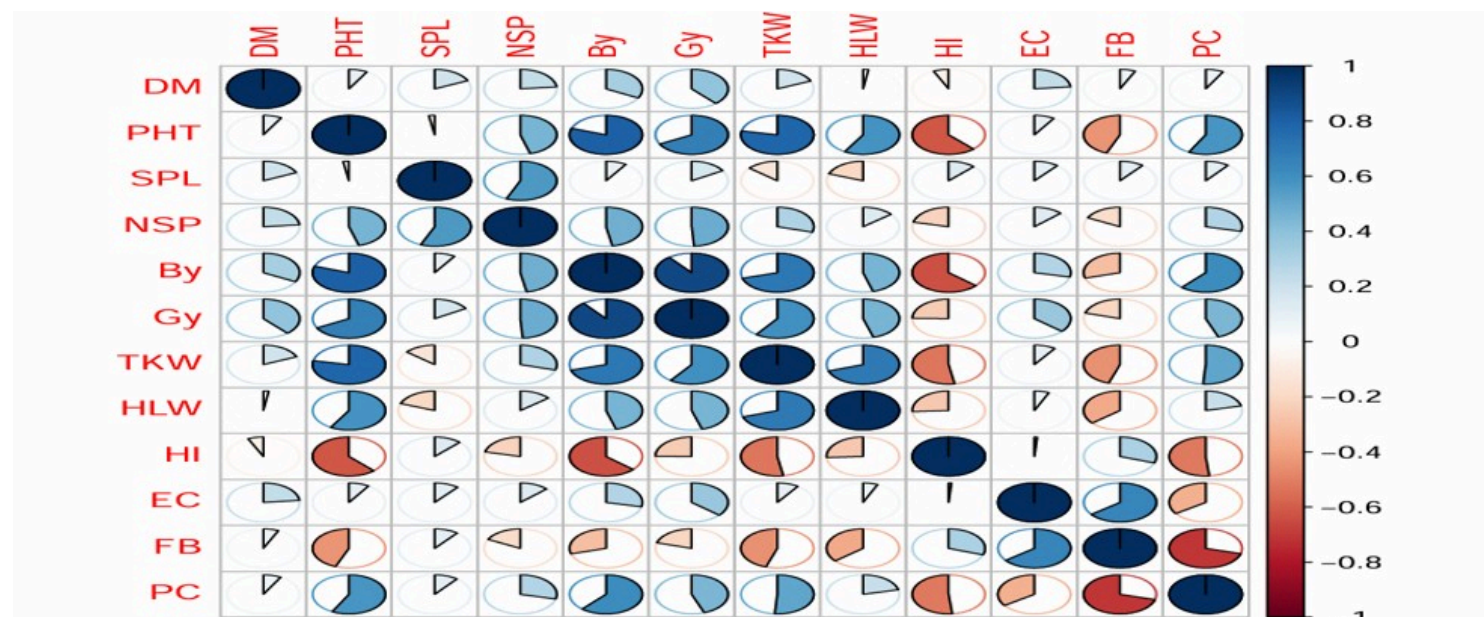


Figure 6

correlation analysis

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