



RESEARCH ARTICLE

Effect of nitrogen levels, plant growth regulators and cutting management on growth, yield and yield attributes of dual-purpose barley (*Hordeum vulgare* L.)

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Abstract

A field experiment was conducted during the rabi seasons of 2023–24 and 2024–25 at Mandawa, Jhunjhunu district, Rajasthan, India, to evaluate the combined effects of nitrogen (N) levels, plant growth regulators (PGRs) and cutting management on growth, yield and yield attributes of dual-purpose barley (*Hordeum vulgare* L.) variety RD 2715. The experiment was laid out in a factorial randomised block design (FRBD) with 18 treatment combinations comprising three cutting schedules (40, 50 and 60 days after sowing (DAS)), 3 N levels (100, 125 and 150 % of recommended dose of nitrogen (RDN)) and two PGRs (chlormequat chloride (CCC) at 1.25 L ha⁻¹ and ethephon (cerone) at 0.5 L ha⁻¹), replicated thrice. Results revealed that cutting management significantly ($p \leq 0.05$) influenced growth and yield parameters. Cutting at 60 DAS produced the highest green fodder yield, whereas cutting at 40 DAS recorded significantly higher grain yield, straw yield and yield-attributing traits, including effective tillers, spike length, grains per spike and test weight. Nitrogen application significantly improved growth parameters such as crop growth rate (CGR), relative growth rate (RGR), leaf area duration (LAD), chlorophyll content and flag leaf area. Application of 125 % RDN significantly enhanced most growth and yield attributes and remained statistically at par with 150 % RDN, indicating diminishing marginal returns beyond the optimum N level. Among PGRs, CCC at 1.25 L ha⁻¹ proved superior to ethephon by significantly improving vegetative growth, tiller density, chlorophyll content and yield attributes, resulting in higher grain, straw and biological yields. Overall, integration of early fodder cutting (40 DAS), optimum N application (125 % RDN) and CCC application emerged as an effective agronomic strategy for maximising grain yield while maintaining adequate fodder production in dual-purpose barley under semi-arid conditions.

Keywords: chlormequat chloride; chlorophyll content; nitrogen; plant growth regulators; productivity

Introduction

Barley (*Hordeum vulgare* L.) has been traditionally used as a grain crop for human consumption, animal feed and malting in India (1). It is the fourth most important cereal crop after wheat, maize and rice, contributing approximately 7 % of global cereal production (2). It belongs to the family Poaceae and genus *Hordeum*, with a diploid chromosome number of $2n = 14$. In India, barley is predominantly utilised for cattle and poultry feed (> 75 %), followed by malting and beverage industries (~ 20 %), while only about 5 % is used for direct human consumption (3). However, increasing health awareness and the presence of β -glucan, a functional dietary fibre known to reduce cardiovascular risks, have enhanced its potential as a nutritious food crop (4, 5).

Barley is an important rabi cereal crop in Rajasthan, occupying approximately 2.74 L ha, accounting for 8.23 % of the total rabi cereal area and contributing 7.46 % to production (6). Each 100 g of barley grain contains 10.6 g protein, 2.1 g fat, 64.0 g carbohydrates,

50.0 mg calcium, 6.0 mg iron, 31.0 mg vitamin B1, 0.1 mg vitamin B2 and 50.0 μ g folate (7). Globally, major barley-producing countries include China, Russia, Germany, USA, Canada, India, Turkey and Australia. In India, barley is cultivated over 0.62 M ha with a production of 1.91 M t and an average productivity of 3030 kg ha⁻¹ (8). In Rajasthan, it covers 0.27 M ha with a productivity of 3324 kg ha⁻¹ (9). Despite higher productivity than the national average, yields remain below the attainable potential (45–50 q ha⁻¹) due to water and nutrient limitations (10).

Nitrogen (N) is the most limiting nutrient in Indian soils, particularly in the loamy sandy soils of Rajasthan and plays a crucial role in enhancing cereal productivity. It is a primary constituent of proteins, chlorophyll, nucleotides, amino acids, enzymes and other cellular components (11). Nitrogen uptake and partitioning are governed by crop demand and supply during different growth stages, including tillering, stem elongation, heading and grain filling (12). However, N management becomes more complex in dual-purpose barley, where the crop is harvested both for fodder

and grain. Application of the entire N dose at sowing may not sustain nutrient availability throughout the crop growth period, leading to reduced yield and N accumulation in plant tissues.

In intensive agricultural systems, the use of plant growth regulators (PGRs) has become a common strategy to mitigate lodging and improve crop performance. Plant growth regulators influence plant physiology by regulating stem elongation, reducing internodal length and improving plant architecture (13). Their effects extend to tiller growth even when not directly applied, indicating systemic action (14). Chlormequat chloride (CCC), an anti-gibberellin compound, is widely used to reduce plant height by inhibiting gibberellin biosynthesis, thereby enhancing lodging resistance in cereals such as wheat and barley (15, 16). Similarly, ethylene-releasing compounds such as ethephon (cerone) regulate plant growth through hormonal modulation (17).

Cutting management is another critical factor influencing growth and productivity in dual-purpose barley. The timing of cutting significantly affects both fodder quality and subsequent grain yield. Early cutting may reduce biomass accumulation, whereas delayed cutting can adversely affect grain formation and yield (18). Therefore, optimising cutting stage is essential to achieve a balance between fodder and grain production.

Despite the individual importance of N management, PGRs and cutting practices, limited information is available on their interactive effects in dual-purpose barley under semi-arid conditions. Therefore, the present investigation was conducted during the rabi seasons of 2023–24 and 2024–25 at Mandawa, Jhunjhunu district, Rajasthan, to evaluate the combined effects of N levels, PGRs and cutting management on growth, yield and yield attributes of dual-purpose barley.

Materials and Methods

Experimental site

The experiment was conducted during the rabi seasons of 2023–24 and 2024–25 at the Research Farm, Mandawa, Jhunjhunu district, Rajasthan, India. The experimental site is located at 28°03' N latitude and 75°08' E longitude, falling under Agro-climatic Zone II A (Transitional Plains of Inland Drainage Zone) of Rajasthan.

Experimental details

The field experiment was conducted to evaluate the effect of N levels, PGRs and cutting management on growth, yield and yield

attributes of dual-purpose barley (*H. vulgare*) variety RD 2715. The experiment comprised 18 treatment combinations arranged in a factorial randomised block design (FRBD) with three replications, resulting in a total of 54 experimental plots. Each plot had a gross size of 3.6 × 5.0 m (18.0 m²) and a net plot size of 1.8 × 4.0 m (7.2 m²). The crop was sown at a row spacing of 22.5 cm using a seed rate of 100 kg ha⁻¹.

The treatments consisted of 3 cutting schedules at 40, 50 and 60 days after sowing (DAS) and 3 N levels, viz., recommended dose of N (RDN: 60 kg N ha⁻¹ + 20 kg P₂O₅ ha⁻¹), 125 % RDN and 150 % RDN. The additional N was applied after green fodder cutting.

Plant growth regulator treatments included CCC at 1.25 L ha⁻¹ applied at growth stages GS30–31, ethephon at 0.5 L ha⁻¹ applied at GS39–40 and their combined application (CCC at 1.25 L ha⁻¹ at GS30–31 followed by ethephon at 0.5 L ha⁻¹ at GS39–40). Fertilisers were applied as per treatment, with half of the N and the full dose of phosphorus (P) applied basally at sowing and the remaining N top-dressed at the first irrigation, except for additional N treatments, which were applied after fodder cutting. All other agronomic practices, including irrigation and weed management, were followed uniformly as per recommended package of practices. The treatment details along with their symbols are presented in Table 1.

Soil characteristics

Prior to sowing, composite soil samples were collected from the experimental field at a depth of 0–15 cm and analysed using standard laboratory procedures. The soil of the experimental site was loamy sand in texture, typical of the arid and semi-arid regions of Rajasthan. The soil was slightly alkaline in reaction (pH 7.7–8.1) with low electrical conductivity (< 0.5 dS m⁻¹), indicating non-saline conditions. The soil was low in available N (≈ 180–220 kg ha⁻¹), medium in available P (≈ 18–22 kg ha⁻¹) and medium in available potassium (K) (≈ 240–280 kg ha⁻¹). The organic carbon content was low (≈ 0.2–0.3 %), reflecting poor inherent fertility of the region.

Weather conditions

The experimental site at Mandawa falls under a semi-arid climate characterised by low and erratic rainfall, high evaporative demand and wide temperature fluctuations. During the rabi seasons of 2023–24 and 2024–25, the mean maximum temperature ranged 22–32 °C, while the minimum temperature varied between 4 and 12 °C during the crop growth period. The region receives most of its annual rainfall during the monsoon season (July–September) and

Table 1. Treatment with their symbols and details

		Treatments
		Cutting schedules
T ₁	40 DAS	Cutting at 40 days after sowing
T ₂	50 DAS	Cutting at 50 days after sowing
T ₃	60 DAS	Cutting at 60 days after sowing
		Nitrogen levels (N)
T ₄	100 % RDN	RDF (60 kg N + 20 kg P ₂ O ₅ /ha)
T ₅	125 % RDN	RDF + 25 % extra N
T ₆	150 % RDN	RDF + 50 % extra N
		Plant growth regulator (PGR)
T ₇	CCC (chlormequat chloride)	CCC at 1.25 L ha ⁻¹ at (growth stage) GS30 31; ethephon at 0.5 L ha ⁻¹ at GS39–40
T ₈	Ethephon (cerone)	CCC at 1.25 L ha ⁻¹ at GS30–31 + ethephon at 0.5 L ha ⁻¹ at GS39–40

DAS: days after sowing; RDN: recommended dose of nitrogen; RDF: recommended dose of fertiliser.

very limited rainfall (< 30–40 mm) occurred during the rabi season. The crop was therefore grown under irrigated conditions. Weather conditions during both years were generally favourable for barley cultivation, with no occurrence of severe frost or terminal heat stress during critical growth stages.

Chlorophyll content measurement

Chlorophyll content was recorded at the ear emergence stage using a soil plant analysis development (SPAD) chlorophyll meter. Observations were taken from the fully expanded flag leaf of five randomly selected plants in each plot and the average value was used for statistical analysis. The SPAD readings were used as an indirect estimate of leaf chlorophyll concentration and photosynthetic efficiency.

Characteristics of cultivar

The RD 2715 is a six-row barley variety developed by Sri Karan Narendra Agriculture University (SKNAU), Durgapura, Jaipur, Rajasthan for dual-purpose utilisation. It possesses a high degree of resistance to yellow and brown rust. The variety attains heading in about 80–85 days and matures in 120–125 days, with an average plant height of 70 cm and a 1000 grain weight of approximately 43 g. It has been identified as a suitable dual-purpose barley variety for timely sown irrigated conditions of the central zone.

Observations recorded

To evaluate the effect of different treatments, observations were recorded on growth parameters and yield attributes as follows:

Growth parameters

The growth parameters evaluated were plant population (m^{-2}), crop growth rate (CGR), relative growth rate (RGR), number of tillers (m^{-2}) and leaf area index (LAI).

Yield and its attributes

Yield and its attributes evaluated were effective tillers (m^{-2}), number of spikelets per spike, spike length (cm), number of grains per spike, 1000 grain weight (g), grain yield per spike, grain yield, straw yield,

biological yield, harvest index and fodder yield.

Statistical analysis

The experimental data recorded over two years were subjected to statistical analysis using standard procedures appropriate for a FRBD. Treatment means were compared using the critical difference (CD) at 5 % level of significance and the standard error of mean (SEM) was used to assess experimental precision. Pooled analysis across years was performed after testing the homogeneity of error variances to obtain reliable and valid conclusions.

Results

Growth parameters

Observations on growth parameters, viz., initial plant population, RGR, CGR, leaf area duration (LAD), flag leaf area, chlorophyll content and total tillers were recorded and are presented in Table 2–6.

Initial plant population (m^{-2})

The data presented in Table 2 indicated that initial plant population at 20 DAS and at harvest did not differ significantly due to N levels, cutting management, or PGR treatments, suggesting uniform crop establishment across treatments. The observed variations were non-significant and attributed to random experimental variation rather than treatment effects.

Relative growth rate

Cutting management

Data presented in Table 3 revealed that cutting at 60 DAS recorded significantly higher RGR during 0–30 DAS compared to cutting at 40 and 50 DAS. However, during 30–60 DAS, higher RGR was observed under early cutting (40 DAS), followed by a decline with delayed cutting, indicating a shift in growth dynamics with cutting stage.

Nitrogen levels

Application of 150 % RDN recorded the highest RGR, which was significantly superior to 100 % RDN but remained statistically at par with 125 % RDN, indicating marginal gains beyond the optimum N level.

Table 2. Effect of nitrogen and plant growth regulator, cutting on initial plant population (m^{-2}) of dual-purpose barley

Treatments	Plant population (per meter row length)							
	30 DAS		60 DAS		90 DAS		At harvest	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Cutting schedules								
40 DAS	12.35	12.79	71.59	73.97	138.23	142.84	203.59	207.25
50 DAS	12.17	12.61	44.08	49.90	108.43	111.34	167.39	167.39
60 DAS	11.93	12.41	193.84	196.90	89.33	74.71	142.96	146.74
S.Em. $\pm$	0.23	0.25	2.79	2.94	2.87	3.28	4.23	2.94
C.D. ($p = 0.05$)	NS	NS	7.94	8.40	8.21	9.39	11.44	12.06
Nitrogen levels (N)								
100 % RDN	11.11	11.55	110.90	113.20	121.40	123.62	170.72	174.63
125 % RDN	12.64	13.18	131.25	134.75	145.75	148.31	207.61	212.08
150 % RDN	12.94	13.32	134.85	138.80	149.91	152.82	214.01	218.64
S.Em. $\pm$	0.21	0.23	2.41	2.55	2.48	2.85	3.48	3.67
C.D. ($p = 0.05$)	0.62	0.66	6.88	7.28	7.11	8.13	9.92	10.45
Plant growth regulators (PGRs)								
CCC (chlormequat chloride)	12.11	12.60	122.87	125.97	140.41	142.30	197.90	201.82
Ethephon (cerone)	12.35	12.79	128.44	131.84	137.64	140.87	196.33	201.09
S.Em. $\pm$	0.17	0.18	1.96	2.08	2.03	2.33	2.84	3.01
C.D. at 5 %	NS	NS	5.51	5.94	NS	NS	NS	NS
C.V. (%)	8.14	8.41	9.36	6.65	8.75	9.81	8.62	8.91

DAS: days after sowing; RDN: recommended dose of nitrogen; NS: non-significant.

Table 3. Effect of nitrogen, plant growth regulators and cutting management on relative growth rate (RGR) of dual-purpose barley

Treatments	Relative growth rate (mg/g/day)					
	30–60 DAS		60–90 DAS		90 DAS at harvest	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Cutting schedules						
40 DAS	55.38	55.35	20.71	20.72	11.81	11.32
50 DAS	40.92	42.88	28.54	25.37	13.33	12.55
60 DAS	91.35	90.63	34.98	33.03	22.84	21.25
S.Em. ±	0.62	0.58	0.10	0.08	0.18	0.21
C.D. (p = 0.05)	1.77	1.68	0.29	0.24	0.53	0.61
Nitrogen levels (N)						
100 % RDN	66.98	67.11	5.78	5.47	12.40	12.10
125 % RDN	68.53	68.80	6.26	5.73	13.02	12.70
150 % RDN	68.76	69.45	6.29	5.74	14.10	13.72
S.Em. ±	0.53	0.50	0.08	0.07	0.16	0.18
C.D. (p = 0.05)	1.53	1.45	0.25	0.21	0.46	0.53
Plant growth regulator (PGR)						
CCC (chlormequat chloride)	67.68	67.94	7.17	6.57	12.64	12.41
Ethephon (cerone)	68.53	68.97	5.04	4.72	13.04	12.61
S.Em. ±	0.43	0.41	0.06	0.05	0.13	0.14
C.D. at 5 %	NS	NS	0.20	0.17	NS	NS
C.V. (%)	2.83	2.62	7.30	6.70	4.84	5.85

DAS: days after sowing; RDN: recommended dose of nitrogen; NS: non-significant.

Plant growth regulators

Application of CCC at 1.25 L ha⁻¹ significantly increased RGR during 30–60 DAS compared to ethephon, suggesting improved vegetative growth regulation under CCC treatment.

Crop growth rate

Cutting management

As shown in Table 4, cutting at 60 DAS recorded significantly higher CGR during 30–60 DAS, whereas during 60–90 DAS, maximum CGR was observed under early cutting (40 DAS), followed by a decline with delayed cutting. During 90 DAS to harvest, cutting at 60 DAS maintained significantly higher CGR compared to other treatments.

Nitrogen levels

Application of N significantly influenced CGR at all growth stages. Recommended dose of N (150 %) recorded the highest CGR; however, it remained statistically at par with 125 % RDN, indicating diminishing response beyond the optimum N level.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ significantly enhanced CGR during 30–60 DAS compared to ethephon, indicating its effectiveness in improving crop growth dynamics.

Leaf area duration

Cutting management

Table 5 indicated that cutting at 60 DAS recorded significantly higher

Table 4. Effect of nitrogen, plant growth regulators and cutting management on crop growth rate (CGR) of dual-purpose barley

Treatments	Crop growth rate (g/m ² /day)					
	30–60 DAS		60–90 DAS		90 DAS at harvest	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Cutting schedules						
40 DAS	1.874	2.038	2.121	2.195	2.178	2.146
50 DAS	1.063	1.142	1.152	2.047	1.865	1.784
60 DAS	6.063	6.149	4.15	4.072	2.354	2.301
S.Em. ±	0.071	0.074	0.014	0.011	0.036	0.029
C.D. (p = 0.05)	0.205	0.214	0.041	0.034	0.105	0.085
Nitrogen levels (N)						
100 % RDN	3.225	3.287	0.349	0.347	1.61	1.666
125 % RDN	3.852	4.151	0.483	0.451	2.06	2.125
150 % RDN	4.162	4.181	0.501	0.466	2.135	2.193
S.Em. ±	0.062	0.064	0.012	0.011	0.031	0.025
C.D. (p = 0.05)	0.177	0.185	0.036	0.03	0.091	0.074
Plant growth regulator (PGR)						
CCC (chlormequat chloride)	3.591	3.68	0.584	0.543	1.915	1.983
Ethephon (cerone)	3.769	3.869	0.306	0.3	1.955	2.006
S.Em. ±	0.05	0.052	0.01	0.008	0.025	0.02
C.D. at 5 %	0.145	0.151	0.031	0.024	NS	NS
C.V. (%)	8.11	8.25	14.11	11.44	8.15	6.42

DAS: days after sowing; RDN: recommended dose of nitrogen; NS: non-significant.

Table 5. Effect nitrogen, growth regulators and cutting management on leaf area duration (LAD) of dual-purpose barley

Treatments	Leaf area duration (days)					
	30 DAS		60 DAS		90 DAS	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Cutting schedules						
40 DAS	36.04	39.05	73.89	78.70	93.62	97.26
50 DAS	29.18	31.29	55.07	58.45	76.85	79.68
60 DAS	62.86	66.43	117.34	123.84	61.47	64.86
S.Em. ±	1.02	1.12	3.19	3.10	3.27	3.35
C.D. ($p = 0.05$)	2.89	3.16	7.23	6.99	7.47	7.69
Nitrogen levels (N)						
100 % RDN	41.51	43.31	81.26	84.11	77.66	80.51
125 % RDN	50.66	54.11	107.81	113.66	108.86	111.41
150 % RDN	51.86	55.46	110.51	117.11	111.11	115.46
S.Em. ±	0.87	0.97	1.90	1.83	1.98	2.05
C.D. ($p = 0.05$)	2.51	2.74	5.40	5.20	5.60	5.80
Plant growth regulator (PGR)						
CCC (chlormequat chloride)	47.92	50.80	104.14	109.07	108.88	112.10
Ethephon (cerone)	48.10	51.12	95.58	100.85	89.54	92.82
S.Em. ±	0.73	0.79	1.56	1.50	1.61	1.67
C.D. at 5 %	NS	NS	4.41	4.24	4.58	4.74
C.V. (%)	10.15	10.40	10.40	9.60	10.80	10.84

DAS: days after sowing; RDN: recommended dose of nitrogen; NS: non-significant.

LAD during 30–60 and 60–90 DAS. However, LAD decreased with advancement of crop stage, particularly during 90 DAS to harvest, except under 60 DAS cutting, which maintained relatively higher LAD.

Nitrogen levels

Application of 125 % RDN significantly increased LAD across growth stages compared to 100 % RDN and remained statistically at par with 150 % RDN.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ significantly improved LAD compared to ethephon, indicating enhanced leaf persistence and

photosynthetic duration.

Flag leaf area

Cutting management

Data (Table 6) indicated that maximum flag leaf area (27.41 cm²) was recorded under cutting at 60 DAS, which was significantly higher than other treatments.

Nitrogen levels

Flag leaf area increased significantly with N levels, with 150 % RDN recording the highest values, statistically at par with 125 % RDN, indicating optimum response at 125 % RDN.

Table 6. Effect of nitrogen, growth regulators and cutting management on flag leaf area and chlorophyll content at ear emergence of dual-purpose barley

Treatments	Flag leaf area (cm ²)		Chlorophyll content (mg/g)	
	2023–24	2024–25	2023–24	2024–25
	2023–24	2024–25	2023–24	2024–25
Cutting schedules				
40 DAS	29.95	31.09	3.55	3.57
50 DAS	28.55	28.72	3.38	3.41
60 DAS	25.15	26.33	3.19	3.22
S.Em. ±	0.48	0.53	0.06	0.07
C.D. ($p = 0.05$)	1.35	1.50	0.15	0.17
Nitrogen levels (N)				
100 % RDN	25.17	26.42	3.32	3.34
125 % RDN	30.46	31.16	3.49	3.52
150 % RDN	31.15	31.76	3.56	3.60
S.Em. ±	0.42	0.46	0.05	0.06
C.D. ($p = 0.05$)	1.17	1.30	0.13	0.15
Plant growth regulator (PGR)				
CCC (chlormequat chloride)	31.19	32.37	3.49	3.52
Ethephon (cerone)	26.66	27.19	3.43	3.45
S.Em. ±	0.34	0.38	0.04	0.05
C.D. at 5 %	1.17	1.30	0.13	0.15
C.V. (%)	8.13	8.72	9.56	10.74

DAS: days after sowing; RDN: recommended dose of nitrogen.

Plant growth regulators

Application of CCC at 1.25 L ha⁻¹ produced significantly higher flag leaf area (30.77 cm²) compared to ethephon, indicating improved canopy development.

Chlorophyll content

Cutting management

Chlorophyll content at ear emergence stage decreased with advancement in cutting stage, with cutting at 40 DAS recording the highest values, followed by 50 and 60 DAS.

Nitrogen levels

Application of 125 % RDN significantly increased chlorophyll content compared to 100 % RDN and remained at par with 150 % RDN, indicating improved photosynthetic efficiency.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ significantly increased chlorophyll content, whereas ethephon showed comparatively lower or non-significant effects, indicating differential hormonal regulation.

Total tillers (m⁻²)

Cutting management

The number of total tillers varied significantly among treatments. Cutting at 40 DAS recorded the highest number of tillers, followed by 50 and 60 DAS, indicating better tiller regeneration under early cutting.

Nitrogen levels

Total tillers increased with N application up to 125 % RDN, beyond which no significant increase was observed, indicating optimum N level.

Plant growth regulators

Application of CCC at 1.25 L ha⁻¹ produced significantly higher tiller density compared to ethephon, reflecting its role in enhancing tillering.

Yield parameters

Yield attributes and productivity parameters were significantly influenced by cutting management, N levels and PGRs (Table 7–9).

Effective tillers (m⁻²)

Cutting management

Data indicated that cutting stage significantly influenced the number of effective tillers, with early cutting (40 DAS) recording the highest effective tillers, followed by 50 and 60 DAS. A decline in effective tillers was observed with delayed cutting, indicating reduced tiller survival due to biomass removal at later stages.

Nitrogen levels

Application of N significantly increased effective tillers up to 125 % RDN, beyond which the increase was non-significant. Although 150 % RDN recorded numerically higher values, it remained statistically at par with 125 % RDN.

Plant growth regulators

Application of CCC at 1.25 L ha⁻¹ significantly increased effective tillers (274.82 m⁻²) compared to ethephon, reflecting enhanced tiller retention and growth.

Spike length (cm)

Cutting management

Spike length was significantly affected by cutting stage, with cutting at 40 DAS recording the highest spike length (9.03 cm), followed by 50 DAS and 60 DAS. Delayed cutting reduced spike length, likely due to reduced assimilate availability for reproductive growth.

Nitrogen levels

Increasing N levels up to 125 % RDN significantly improved spike length, while 150 % RDN remained statistically at par, indicating an optimum N level.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ significantly increased spike length compared to ethephon, suggesting improved reproductive

Table 7. Effect of nitrogen, plant growth regulators and cutting management on yield attributes of dual-purpose barley at harvest stage

Treatments	Total tillers/m ² (No.)		Effective tillers/m ² (No.)		Spike length (cm)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Cutting schedules						
40 DAS	345.97	354.72	274.42	283.76	8.82	9.03
50 DAS	325.42	332.87	217.06	225.09	7.57	7.79
60 DAS	291.43	297.13	167.91	175.64	6.42	6.64
S.Em. ±	7.01	7.26	4.96	5.58	0.16	0.17
C.D. (p = 0.05)	19.92	20.65	14.10	15.87	0.45	0.47
Nitrogen levels (N)						
100 % RDN	314.25	328.88	226.12	233.11	7.60	7.82
125 % RDN	339.75	342.99	254.59	261.59	8.06	8.27
150 % RDN	340.85	347.40	261.64	266.19	8.31	8.54
S.Em. ±	7.07	7.29	5.30	5.84	0.14	0.15
C.D. (p = 0.05)	18.25	18.88	13.21	14.74	0.39	0.41
Plant growth regulator (PGR)						
CCC (chlormequat chloride)	333.91	346.62	255.62	264.82	8.37	8.58
Ethephon (cerone)	329.33	332.89	239.28	242.54	7.61	7.84
S.Em. ±	5.96	6.14	4.51	4.95	0.12	0.12
C.D. at 5 %	15.09	15.60	10.97	12.22	0.32	0.33

DAS: days after sowing; RDN: recommended dose of nitrogen.

Table 8. Effect of nitrogen, plant growth regulators and cutting management on yield attributes of dual-purpose barley

Treatments	Spikelet's/spike (No.)		Number of grains per spike		Test weight (g)		Grain yield/spike (g)	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
Cutting schedules								
40 DAS	20.83	22.09	37.35	39.27	41.67	42.13	1.71	1.84
50 DAS	17.16	17.42	30.55	31.73	39.30	39.86	1.59	1.71
60 DAS	11.75	12.95	25.04	25.41	37.07	37.70	1.46	1.60
S.Em. ±	1.52	1.53	1.51	1.54	1.77	1.75	1.05	1.05
C.D. (p = 0.05)	1.45	1.51	1.44	1.51	2.16	2.12	1.11	1.12
Nitrogen levels (N)								
100 % RDN	17.32	18.64	32.32	32.40	38.12	38.97	1.56	1.69
125 % RDN	18.95	20.09	34.12	35.49	41.16	41.77	1.66	1.80
150 % RDN	19.12	20.34	34.89	35.98	42.22	42.78	1.72	1.84
S.Em. ±	1.45	1.47	1.45	1.47	1.67	1.65	1.04	1.04
C.D. (p = 0.05)	1.26	1.31	1.25	1.31	1.88	1.84	0.10	0.11
Plant growth regulator (PGR)								
CCC (chlormequat chloride)	19.84	21.11	35.49	36.36	41.74	41.92	1.72	1.85
Ethephon (cerone)	17.09	18.27	32.07	32.89	39.26	40.43	1.58	1.71
S.Em. ±	1.37	1.38	1.37	1.38	1.55	1.54	1.04	1.04
C.D. at 5 %	1.26	1.31	1.25	1.31	1.88	1.84	1.10	1.11
C.V. (%)	13.31	13.00	7.54	7.65	9.15	8.86	9.42	9.67

DAS: days after sowing; RDN: recommended dose of nitrogen.

Table 9. Effect of nitrogen, plant growth regulators and cutting management on yield and harvest index of dual-purpose barley

Treatments	Grain yield (t/ha)		Straw yield (t/ha)		Biological yield (t/ha)		Green fodder yield (t/ha)	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
Cutting schedules								
40 DAS	4.46	4.59	5.87	5.96	9.32	9.54	14.95	16.63
50 DAS	4.18	4.27	5.50	5.63	8.66	8.88	21.60	23.71
60 DAS	2.99	3.13	3.97	4.21	5.96	6.33	26.34	28.29
S.Em. ±	0.10	0.10	0.12	0.12	0.19	0.20	0.34	0.37
C.D. (p = 0.05)	0.25	0.26	0.32	0.34	0.51	0.55	0.96	1.04
Nitrogen levels (N)								
100 % RDN	3.99	4.19	5.07	5.19	8.06	8.38	15.22	16.09
125 % RDN	4.37	4.58	5.83	5.94	9.20	9.52	16.20	17.86
150 % RDN	4.51	4.70	6.04	6.06	9.55	9.76	16.50	18.28
S.Em. ±	0.08	0.09	0.10	0.11	0.16	0.17	0.30	0.32
C.D. (p = 0.05)	0.22	0.23	0.28	0.29	0.45	0.48	0.83	0.90
Plant growth regulator (PGR)								
CCC (chlormequat chloride)	4.47	4.66	5.99	6.07	9.46	9.72	15.25	16.09
Ethephon (cerone)	4.13	4.34	5.31	5.41	8.43	8.74	16.20	17.86
S.Em. ±	0.07	0.07	0.09	0.09	0.13	0.14	0.25	0.27
C.D. at 5 %	0.18	0.19	0.23	0.24	0.37	0.39	0.83	0.90
C.V. (%)	11.06	10.79	9.97	10.26	9.45	9.78	9.46	9.38

DAS: days after sowing; RDN: recommended dose of nitrogen.

development.

Number of spikelets per spike

Cutting management

Cutting at 40 DAS recorded significantly higher spikelets per spike, whereas delayed cutting resulted in a significant reduction, indicating adverse effects on reproductive development.

Nitrogen levels

Number of spikelets increased significantly up to 125 % RDN, with no significant increase beyond this level.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ produced significantly higher spikelets per spike compared to ethephon.

Number of grains per spike

Cutting management

Early cutting (40 DAS) resulted in significantly higher grains per spike, whereas delayed cutting reduced grain number.

Nitrogen levels

Application of N significantly increased grains per spike up to 125 % RDN, with 150 % RDN remaining statistically at par.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ recorded the highest number of grains per spike (36.36), significantly superior to ethephon (32.89).

Test weight (g)

Cutting management

Test weight was significantly influenced by cutting stage, with cutting at 40 DAS recording the highest test weight, while cutting at 60 DAS recorded the lowest.

Nitrogen levels

Application of 125 % RDN significantly improved test weight, with 150 % RDN showing numerical superiority but remaining statistically at par.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ significantly increased test weight compared to ethephon, indicating improved grain filling.

Grain yield per spike (g)

Cutting management

Cutting at 40 DAS recorded significantly higher grain yield per spike, while delayed cutting reduced yield.

Nitrogen levels

Grain yield per spike increased significantly with N application, with 150 % RDN remaining at par with 125 % RDN, indicating optimum response at 125 % RDN.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ produced higher grain yield per spike (1.85 g) compared to ethephon (1.71 g).

3.16 Grain yield (t ha⁻¹)

Cutting management

Grain yield decreased significantly with delayed cutting. Cutting at 40 DAS recorded the highest grain yield, which was significantly superior to 50 DAS and 60 DAS.

Nitrogen levels

Application of 125 % RDN significantly increased grain yield compared to 100 % RDN, while 150 % RDN remained statistically at par, indicating diminishing returns.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ recorded the highest grain yield (4.66 t ha⁻¹), significantly superior to ethephon, indicating improved yield performance.

Straw yield (t ha⁻¹)

Cutting management

Straw yield followed a trend like grain yield, with cutting at 40 DAS recording the highest straw yield (5.96 t ha⁻¹) and declining with delayed cutting.

Nitrogen levels

Straw yield increased with N application, with 150 % RDN recording the highest values, remaining at par with 125 % RDN.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ produced significantly higher straw yield compared to ethephon.

3.18 Biological yield (t ha⁻¹)

Cutting management

Biological yield decreased with delayed cutting, with early cutting treatments recording higher biomass accumulation.

Nitrogen levels

Biological yield increased with N application, with 150 % RDN showing the highest values, statistically at par with 125 % RDN.

Plant growth regulators

Chlormequat chloride at 1.25 L ha⁻¹ recorded higher biological yield compared to ethephon, indicating improved biomass production.

Green fodder yield (t ha⁻¹)

Cutting management

Green fodder yield increased significantly with delayed cutting, with cutting at 60 DAS recording the highest fodder yield, followed by 50 DAS and 40 DAS.

Nitrogen levels

Application of N increased fodder yield, with 150 % RDN recording the highest values, remaining statistically at par with 125 % RDN.

Plant growth regulators

Chlormequat chloride application improved fodder yield compared to ethephon, likely due to improved plant vigour and reduced lodging.

Discussion

Effect of cutting management

Growth attributes

The present study revealed that cutting at 60 DAS significantly enhanced green fodder yield (Table 9), primarily due to prolonged vegetative growth that promoted greater leaf area development, canopy expansion and cumulative photosynthetic activity. The extended retention of photosynthetically active tissues under delayed cutting improved radiation interception and biomass accumulation, thereby maximising pre-cut vegetative yield. This trend is consistent with earlier findings in dual-purpose cereals, where delayed cutting allows more efficient utilisation of growth resources such as light, nutrients and moisture, resulting in higher fodder production (19, 20).

However, early cutting at 40 DAS resulted in significantly higher dry matter accumulation at final harvest, as reflected in biological yield (Table 9), indicating superior post-cut recovery and regrowth potential. This response can be explained through compensatory growth mechanisms and source-sink dynamics, wherein early removal of above-ground biomass stimulates activation of basal meristems and enhances tiller regeneration (Table 7). The longer recovery period available after early cutting facilitates rapid restoration of leaf area and photosynthetic capacity (Table 4), enabling efficient assimilate production and partitioning during subsequent growth stages (21).

Delayed cutting reduces the effective regrowth window and limits the crop's ability to regenerate tillers and rebuild canopy structures before the onset of reproductive development. Consequently, assimilating availability during critical growth phases is restricted, leading to lower dry matter accumulation at final harvest despite higher initial biomass removal. Thus, the timing of cutting governs the balance between immediate fodder yield and subsequent regrowth efficiency, ultimately influencing total biomass production. These findings highlight a fundamental trade-off in dual-purpose barley systems, where delayed cutting (60 DAS) maximises fodder yield through extended vegetative growth, while early cutting (40 DAS) enhances regrowth dynamics, tiller survival

and final biomass accumulation. Similar trends have been reported in barley and other dual-purpose cereals, where cutting stage significantly influences tillering, assimilate partitioning and overall crop productivity (20,21).

Yield and yield attributes

Yield attributes such as effective tillers, grains per spike, spike length, test weight and grain yield were significantly influenced by cutting schedules (Table 7–9). Early cutting at 40 DAS resulted in superior reproductive development, as evidenced by higher effective tillers, spike length, grains per spike and test weight (Tables 7 and 8), ultimately leading to enhanced grain yield (Table 9). This improvement can be attributed to a longer post-cut recovery period, which facilitates restoration of leaf area, improved photosynthetic activity and efficient assimilate production during the critical reproductive phase.

From a physiological standpoint, early cutting promotes better source-sink balance, where regenerated foliage enhances source strength while developing spikes act as strong sinks for assimilates. The extended grain-filling duration under early cutting ensures adequate translocation of photosynthates towards reproductive organs, thereby improving grain formation and grain weight. In addition, enhanced tiller regeneration and survival increase the proportion of productive tillers, contributing to higher yield potential (Table 7).

Delayed cutting at 60 DAS significantly reduced yield attributes and grain yield (Table 7–9). This decline can be attributed to reduced effective leaf area and disruption of assimilate supply during the transition from vegetative to reproductive stages. Mechanical removal of biomass at a later stage limits the plant's capacity for tiller regeneration and reduces the conversion of vegetative tillers into productive tillers, thereby decreasing sink size and yield potential. Furthermore, delayed cutting shortens the effective grain-filling period, leading to reduced assimilation accumulation in grains and lower test weight (22, 23). Although cutting at 60 DAS maximised green fodder yield, it imposed a significant penalty on grain yield and quality (Table 9), likely due to forced or accelerated reproductive development under reduced assimilate availability. The shortened maturity duration and impaired source activity under late cutting restrict the supply of photosynthates to developing grains, thereby reducing grain number and weight (24, 25).

These results clearly demonstrate the inherent trade-off in dual-purpose barley systems, where early cutting favours grain production through improved regrowth and assimilate partitioning, whereas delayed cutting enhances fodder yield at the expense of reproductive efficiency. Similar findings have been reported in barley and other cereals, where cutting stage plays a critical role in determining the balance between vegetative biomass production and grain yield (23–25).

Effect of nitrogen

Growth attributes

Nitrogen application significantly improved growth parameters such as CGR, RGR, LAD, chlorophyll content, flag leaf area and tiller density (Table 3–6), with maximum response observed up to 125 % RDN, beyond which the response was non-significant. This improvement can be attributed to the role of N in chlorophyll synthesis, protein formation and enzymatic activity, which enhances photosynthetic efficiency and biomass accumulation (26–28). Higher N availability

promotes leaf expansion, tiller production and prolonged LAD (29), thereby increasing assimilate production (Table 5, 6). However, the non-significant difference between 125 % and 150 % RDN indicates diminishing returns and reduced N use efficiency (NUE) beyond the optimum level.

Yield and yield attributes

Nitrogen fertilisation significantly improved yield attributes, including effective tillers, spike length, grains per spike, test weight and grain yield (Table 7–9). Application of 125 % RDN was found optimal, as 150 % RDN did not produce significant additional yield benefits, indicating efficient utilisation of N at moderate levels. The improvement in yield attributes under higher N supply can be attributed to enhanced assimilate production, improved sink strength and better partitioning of photosynthates towards reproductive organs (30, 31). Post-cut N application maintained higher LAD and dry matter accumulation (Table 5), thereby supporting spike development and grain filling (Table 7, 8).

Effect of plant growth regulators

Growth attributes

Application of CCC at 1.25 L ha⁻¹ significantly improved growth parameters, including CGR, RGR, LAD, chlorophyll content and tiller density (Table 3, 6), compared to ethephon. This effect can be attributed to the anti-gibberellin action of CCC, which inhibits gibberellin biosynthesis, reduces stem elongation and promotes compact plant architecture, thereby improving assimilate distribution and reducing lodging risk. In contrast, ethephon releases ethylene, which may accelerate senescence and limit vegetative growth.

Yield and yield attributes

Chlormequat chloride application significantly enhanced yield attributes, including effective tillers, spike length, spikelets per spike, grains per spike, grain yield per spike and test weight (Table 7, 8), leading to higher grain and fodder yields compared to ethephon (Table 9). The superior performance of CCC can be attributed to improved source-sink relationships, enhanced nutrient uptake and efficient assimilate partitioning, resulting in better spike development and grain filling. Additionally, reduced lodging under CCC treatment likely contributed to improved light interception and photosynthetic efficiency, thereby enhancing overall productivity.

Conclusion

Productivity of dual-purpose barley can be effectively improved through integrated management of cutting schedule, nitrogen (N) fertilisation and plant growth regulators (PGRs). Cutting at 40 days after sowing (DAS) was optimal for maximising grain yield and yield attributes, whereas cutting at 60 DAS enhanced green fodder yield, indicating a clear trade-off between grain and fodder production. Application of 125 % recommended dose of nitrogen (RDN) significantly improved growth and yield and was comparable to 150 % RDN, suggesting that higher N levels are neither agronomically efficient nor economically justified. Among PGRs, chlormequat chloride (CCC) proved superior to ethephon by improving tillering, chlorophyll content and yield performance. Therefore, the combination of cutting at 40 DAS, 125 % RDN and CCC is recommended as an efficient and sustainable agronomic practice for dual-purpose barley under semi-arid conditions.

Authors' contributions

SCS carried out the studies, participated in the sequence alignment and drafted the manuscript. HS participated in the design of the study and performed the statistical analysis. SB, PS, N conceived the study and participated in editing and revising the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work the author used ChatGPT 5.2 to check grammar mistakes and scientific validation. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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