PLANT SCIENCE TODAY
Vol 13(sp1): 1-12
https://doi.org/10.14719/pst.10933

eISSN 2348-1900

RESEARCH ARTICLE

Modulating the nutritional composition of green onion (*Allium cepa* L.) through strategic sowing time management in tropical agroecosystems

Manasranjan Parida[1], Bibhuti Bhusan Sahoo[2]*, Pradyumna Tripathy[3], Barsha Rani Pradhan[3], Adyasha Dash[4], Mala Dasari Paban[3], Soumya Pragalva Mohanty[1], Nityamanjari Mishra[3], Tapas Panigrahi[2] & Bhabani Sankar Nayak[2]

[1]Department of Horticulture (Vegetable Science), Post Graduate College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa 848 125, Bihar, India

[2]Regional Research and Technology Transfer Station, Odisha University of Agriculture and Technology, Kalahandi 766 001, Odisha, India

[3]Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar 751 003, Odisha, India

[4]Department of Fruit Science & Horticulture Technology, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar 751 003, Odisha, India

*Correspondence email - bibhutihort@rediffmail.com

Received: 28 July 2025; Accepted: 09 December 2025; Available online: Version 1.0: 28 January 2026

Cite this article: Manasranjan P, Bibhuti BS, Pradyumna T, Barsha RP, Adyasha D, Mala DP, Soumya PM, Nityamanjari M, Tapas P, Bhabani SN. Modulating the nutritional composition of green onion (*Allium cepa* L.) through strategic sowing time management in tropical agroecosystems. Plant Science Today. 2026; 13(sp1): 1-12. https://doi.org/10.14719/pst.10933

Abstract

A field experiment was conducted at the Regional Research and Technology Transfer Station, Bhawanipatna, Odisha, India, to determine the best sowing time for green onion production and quality. The study used a Randomised Block Design with five sowing dates at 15-day intervals, from 15th June to 15th August, 2023 and replicated four times. The onion variety Bhima Dark Red performed best when sown on 15th August (D_5), during the late kharif season. This late-sown crop showed significant improvements in growth, including taller plants (57.57 cm), more leaves per plant (7.28), longer leaves (46.38 cm), thicker leaves (0.71 cm) and superior fresh (3.49 g) and dry weight (0.36 g) of leaves. Additionally, the late-sown green onion had better phytonutrients with higher chlorophyll content (62.24 SPAD units), reducing sugar (2.50 %) and total sugar (2.96 %). Onion leaves had the highest potash (2.38 %) and sulfur (0.58 %) content. However, non-reducing sugars, ascorbic acid, soluble protein, crude protein, nitrogen and phosphorus levels were lower in these leaves. Correlation studies on bioactive components at 90 days after planting showed positive relations between chlorophyll, sugars and potash, as well as between crude protein and nitrogen. Inverse relationships appeared between sugars and protein and between chlorophyll and ascorbic acid. Principal component analysis indicated strong positive associations among photothermal units, growing degree days and ascorbic acid, suggesting that 15th August was the best sowing date for maximising nutritious leaves. These results highlight the value of green onions planted on 15th August as a rich source of phytonutrients and the importance of choosing the right sowing dates for better yield and nutrition.

Keywords: ascorbic acid; chlorophyll; crude protein; green onions; total sugar

Introduction

Onion (*Allium cepa* L.), the principal *Allium,* is the earliest domesticated species of the monocotyledonous family *Alliaceae* and is one of the oldest cultivated genera, *Allium,* with chromosome number 2n = 16. The post-pandemic *era* has shifted global dietary preferences towards healthier, nutrient-rich foods. Vegetable crops, especially *alliums* like onions, play a crucial role towards nutritional security. Onions are a nutrient-dense food, serving not only as a flavourful addition to meals but also as an excellent source of both micro and macronutrients (1). The nutritional profile of onions makes them a valuable contributor to overall human health, providing numerous health benefits. It has the enzyme *Allinase,* which has antifungal action. When the modified leaves of onions are crushed, they release a volatile compound called allyl-propyl disulfide, which has hypoglycemic properties that can help lower blood sugar levels. Vitamin C and sulphur-containing chemicals found in onions have significant anti-bacterial and anti-viral properties that strengthen the immune system of the human body (2). Quercetin is one of the important flavonoids found in onions and helps to prevent high blood pressure. *Allicin* inhibits cholesterol production (3). A fresh onion contains almost 86.8 % moisture, 11.0 % carbohydrates, which include 6 to 9 % soluble sugars, 1.2 % protein, 0.6 % fibre, 0.05 % calcium, 0.05 % phosphorus and trace amounts of iron (Fe), alumininium (Al), copper (Cu), Zinc (Zn), Manganese (Mn) and Iodine (I). For centuries, this versatile crop has been integral to human health and wellness, serving as both a culinary staple and a valued component of traditional medicine and cosmetics.

The onion plant, including its bulbs, pseudostems, green leaves and young bulbs, is a culinary and medicinal treasure trove. These various components offer unique flavours, textures and a wealth of nutrients, boasting an impressive profile rich in ascorbic acid, dietary fibre, antioxidants and a diverse array of phytochemicals, such as phenolic acids, flavonoids, anthocyanins and organosulfur compounds. For centuries, onions have played a dual role in traditional medicine and cuisine, offering a potent immune-boosting effect that has been valued for its ability to enhance human health and resilience (4). These secondary metabolites have been demonstrated to possess antioxidant, anti-inflammatory and antimicrobial properties, offering numerous health benefits (5). As a result, incorporating *Allium* vegetables into a balanced diet can significantly enhance overall health and well-being, reduce the risk of chronic diseases and promote optimal health outcomes (2, 6).

Green onions are a nutrient-dense food, offering a wealth of essential vitamins and minerals while being low in calories and fat (7). They are rich in vitamins A, C and K, as well as various vitamins B complex and provide a range of vital minerals such as calcium, potassium and iron (8, 9). Beyond their fundamental nutrients, green onions contain potent bioactive compounds, including flavonoids, sulfur-containing compounds and phenolic compounds, which exhibit strong antioxidant properties (10, 11). These compounds help protect against chronic diseases by neutralising harmful free radicals and supporting cellular integrity. Green onions also offer anti-inflammatory benefits and have shown potential anti-cancer properties (12). In addition to their nutritional benefits, green onions are a versatile ingredient in many cuisines. Their mild, sweet flavour and crunchy texture make them a great addition to salads, soups, stir-fries and more. The white portion is more pungent and benefits from cooking, while the green tops are milder and ideal for raw applications (13). Green onions are also remarkably accessible, both through commercial cultivation and home growth. They can be easily cultivated at home, even from discarded root ends, making them an excellent entry point for sustainable home food production. Their widespread availability in grocery stores and markets ensures that their nutritional and culinary benefits are attainable for a vast global population. Overall, green onions are a valuable addition to diverse diets and cultures worldwide, providing a boost of nutrients, flavour and health benefits (13, 14). Their adaptability, nutritional value and culinary significance make them a fundamental ingredient in many cuisines. Consequently, this ancient crop continues to captivate researchers, driving ongoing investigations into its vast potential benefits and applications and solidifying its position as a crop of enduring significance.

Research on onions and green onions shows there are gaps in understanding how their various phytochemicals affect health. One important area that needs more research is how these phytochemicals vary across different parts of the plant and under different growing conditions. Specifically, it should be well known that the concentration of key nutrients like chlorophyll, Vitamin C, protein, sugar and organosulfur compounds in the green leaves of onions changes based on different sowing dates and growing environments. Knowing this variation is important for making the best use of the nutritious leaves in cooking and medicine.

Materials and Methods

Experimental site

The field experiment was conducted at the Regional Research and Technology Transfer Station, Bhawanipatna, Kalahandi, in the Western undulating zone of Odisha, operating under Odisha University of Agriculture & Technology. The study was carried out in a unique topographical and ecological diversity, situated at 19°92' N latitude and 83°15' E longitude and 245 m above mean sea level. The experimental site is marked by a harsh climate characterised by extreme heat and aridity, except for the monsoon season. Temperature fluctuations at the experimental site varied between 9.9 °C and 41.7 °C, while relative humidity ranged from 17.0 % to 93.5 %. The agroclimatic zone experiences a distinct rainy season, commencing mid-June and continuing up to mid-October. During this period, approximately 80.0 % of the annual mean rainfall occurs due to the movement of the southwest monsoon. The average annual rainfall during the experimentation year 2023 was 1364.2 mm, slightly more (2.5 %) than the normal rainfall for the zone (1330.5 mm). The soil at the experimental site was slightly alkaline (pH 7.85) and had a sandy clay loam texture. The experiment was conducted during the late Kharif season of 2023–24.

Meteorological observations

To understand the impact of weather on onion production during the 2023-24 growing season, weekly meteorological data were collected from the Gramina Krishi Mausam Seva (GKMS) operating at the RRTTS, Bhawanipatna. This data, encompassing parameters such as rainfall, temperature (°C), rainy days and bright sunshine hours, is graphically represented in Fig.1. The Growing Degree days (GDD), Photothermal units (PTU) and Heliothermal units (HTU) for various sowing dates were calculated using a base temperature (Tb) of 10 °C.

$$\mathbf{GDD} = \sum\left(\frac{T_{max} + T_{min}}{2}\right) - T_b \quad \text{(Eqn. 1)}$$

Since the crop was cultivated during the late Kharif season, the base temperature was set at 10 °C.

Growing degree days (GDD)

The cumulative growing degree days (GDD) units were determined by summing the daily mean temperatures that exceeded the base temperature as mentioned in Equation 1. These values are expressed in degree-days (°C Day) (15).

$$\mathbf{PTU} = \sum(GDD \times Day\ length) \quad \text{(Eqn. 2)}$$

Where T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature and T_b is the base temperature (10 °C).

The photothermal units

The Photothermal Units (PTU) for each day were calculated following equation 2, which multiplies the heat units by the h of maximum sunshine in a day, measured in °C Day h. The cumulative PTU for specific phenophases were then determined using the given equation, reflecting the combined effects of temperature and day length.

$$\mathbf{HTU} = \sum(GDD \times Sunshine\ Hours) \quad \text{(Eqn. 3)}$$

Heliothermal units (HTU)

The Heliothermal Units (HTU) for a day are obtained by taking the product of heat units and the bright sunshine hour for that day and are expressed in °C Day h. To calculate the total HTU for phenophases, the equation in Equation 3 was used, capturing the combined impact of temperature and sunshine duration.

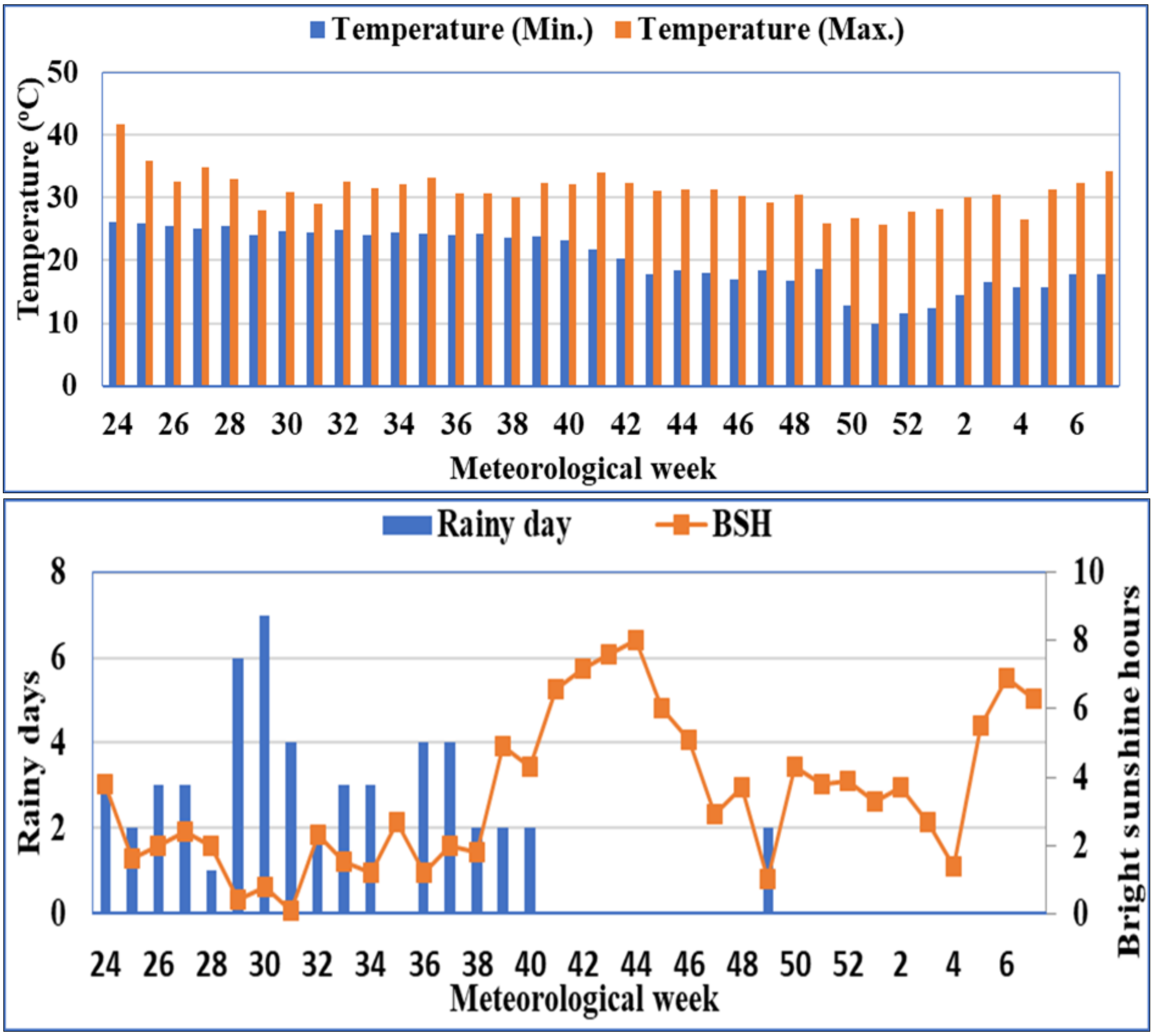

Fig. 1. Meteorological parameters recorded at the RRTTS, Bhawanipatna, throughout the experimentation period.

Treatment details and experimental design

The experiment was laid out in a randomised block design (RBD) with four replications and the treatment consists of five different sowing dates, viz. 15th June 2023 (D_1), 30th June 2023 (D_2), 15th July 2023 (D_3), 30th July 2023 (D_4) and 15th August 2023 (D_5). Raising seedlings and transplanting them during the Kharif and late Kharif seasons (during the above-mentioned months) are quite challenging due to heavy rainfall. This requires careful nursery management to ensure proper development of the seedlings, enabling them to withstand adverse climatic conditions. In this condition, it's better to transplant vigorous seedlings. Hence, eight-week-old vigorous seedlings were transplanted in a sizeable plot of 6 m^2. An ideal plant spacing of 15 cm between rows and 10 cm within rows was adopted to accommodate 400 plants in $plot^{-1}$. Furthermore, the ICAR-Directorate of Onion and Garlic Research recommends the onion variety Bhima dark Red for Kharif cultivation in Odisha and other similar states. Standardised cultivation practices were strictly adhered to promote healthy crop growth and development of the onion crop.

Crop husbandry

An overhead-protected nursery was established using green shed netting to shield onion seedlings from heavy rainfall. The soil was pulverised and sterilised with a 40 % formaldehyde solution, then covered with a polyethene sheet for seven days. Raised beds (1.0 m wide, 3.0 m long, 15 cm high) were prepared, incorporating 5 kg m^2 of well-decomposed farmyard manure (FYM) and marking lines for sowing. Seeds were treated with Carbendazim and Mancozeb, sown in lines, covered with sieved FYM and mulched with paddy straw to ensure moisture and protection, achieving 100 % germination. After germination, unwanted plants were removed and fungicides were applied to prevent damping-off. Seedlings were nourished with a water-soluble N:P:K fertiliser.

Meanwhile, the field was prepared using a cultivator and rotavator to achieve fine tilth and make the field free from weeds and residues. It was converted into 20 plots (6 m^2 each) using the Broad-bed & furrow (BBF) method for better drainage facilities. 15 t of FYM per hectare were added and a nutrient mix of NPKS (150:60:80:30) was applied, with the nitrogen split into three doses. Eight-week-old onion seedlings were treated with a fungicide slurry and transplanted with 15 cm spacing between rows and 10 cm between plants from 15th August to 15th October 2023. Light irrigation was applied immediately after planting to facilitate better plant establishment, followed by irrigation based on soil moisture. Regular intercultural practices like hoeing, weeding and top dressing were conducted. Insecticides like Thiamethoxam 25WG at 0.02 g L^{-1} and fungicides, i.e. Carbendazim 12 % + Mancozeb 63 % at 2 g L^{-1} were alternately sprayed to manage fungal infections as well as thrips infestation.

Morphological and biochemical parameters

Observations on morpho-physiological traits such as plant mortality (%), survivability (%), height (cm), leaves plant^{-1}, collar thickness (cm), leaf length (cm), diameter (cm), fresh weight (g) and dry weight (g) were recorded at 30, 60 and 90 days after transplanting (DAT). Quality metrics like chlorophyll content (SPAD), reducing sugar (%), non-reducing sugar (%), total sugar (%), ascorbic acid (%), protein (%), crude protein (%), N, P, K and S percentages were assessed at 90 DAT. Yield parameters included shoot fresh weight (q ha^{-1}). Survivability and mortality were calculated by dividing the number of harvested. To ensure accuracy, ten random plants from each plot were selected for measurements, excluding border plants. Data for biochemical analysis were collected from ten onion leaves in the experimental plots and analysed in the departmental laboratories of the Department of Fruit Science, the Department of Plant Physiology and the Department of Soil Science.

Statistical analysis

ANOVA for different vegetative growth, quality and yield parameters were analysed using Microsoft Excel (Windows 11). Treatment means were compared using the critical difference test at a 5 % significance level (16). The significance of treatment effects on onion plant growth, yield and quality was assessed via F-test (17), with degrees of freedom (df), mean square (MS) and F-values reported. Correlation studies of different biochemical components with green leaf and agrometeorological parameters were carried out using the software PAST 5.2.2 and principal component analysis was carried out using the online software, Grape.

Results

Effect of sowing dates on onion plant survivability

The ratio of plant mortality to survivability in open-field conditions significantly influences crop production outcomes. Table 1 revealed that sowing dates significantly influenced onion plant mortality and survivability. Mortality rates varied from 14.15 % to 38.81 %, while survivability rates ranged from 61.19 % to 85.50 %. Specifically, the early sown crop (15th June, D_1) resulted in the highest mortality (38.81 %) and lowest survivability (61.19 %), whereas the late sown crop (15th August, D_5) achieved the lowest mortality (14.15 %) and highest survivability (85.50 %). A higher percentage of plant survivability leads to increased biomass accumulation, greater crop yield and ultimately enhanced economic returns.

Effect of sowing dates on vegetative growth of onion plants

The present study revealed that onion plants consistently increased in height from 30 to 90 days after planting, irrespective of the variations in different sowing and planting times. The onion plants exhibited an optimum range of heights, varying from 24.0 cm to 24.1 cm at 30 days after planting, with no significant variations observed among different sowing dates. However, significant variations in plant height were evident at 60 and 90 days after planting, with a range of plant height of 46.3 cm to 51.7cm and 53.4 cm to 57.6 cm, respectively. The results showed a significant effect of sowing dates on leaf production. The maximum number of leaves plant^{-1} was recorded for the 15th August (D_5) sowing date, with means of 4.35, 6.18 and 7.28 leaves plant^{-1} at 30, 60 and 90 DAP, respectively. These values were statistically at par with those obtained for the 30th July (D_4) sowing date. In contrast, the minimum number of leaves plant^{-1} was observed for the 30th June (D_2) sowing date, with a mean of 3.90 leaves plant^{-1} at 30 DAP. Similarly, at 60 and 90 DAP, the minimum number of leaves plant^{-1} of 5.65 and 6.38 were recorded for the 15th July (D_3) and 15th June (D_1) sowing dates, respectively. The results revealed a significant impact of sowing dates on collar thickness. Interestingly, the early-sown crop (15th June, D_1) exhibited the highest collar thickness (1.79 cm), which was considered an undesirable trait. In contrast, the late-sown crop (30th July, D_4) produced a more desirable collar thickness (0.97 cm), which was statistically at par with (15th August, D^5), i.e. 1.01 cm.

Table 1. Effect of different sowing dates on percentage plant establishment and vegetative growth of green onion in the late Kharif season

Sowing dates	Plant mortality (%)	Plant survivability (%)	Plant height (cm)			Leaves plant^{-1}			Collar thickness (cm)		
			30DAP	60DAP	90DAP	30DAP	60DAP	90DAP	30DAP	60DAP	90DAP
D_1-15th June	38.81	61.19	24.00	46.35	53.41	4.05	6.13	6.38	0.43	1.08	1.79
D_2-30th June	34.63	65.38	23.22	47.75	54.21	3.90	5.68	6.55	0.44	0.98	1.06
D_3-15th July	31.19	68.81	24.56	47.06	54.46	4.33	5.65	6.83	0.42	1.01	1.05
D_4-30th July	24.63	75.38	24.52	50.22	55.72	4.33	6.15	6.93	0.39	0.95	0.97
D_5-15th August	14.15	85.50	24.11	51.72	57.57	4.35	6.18	7.28	0.38	0.92	1.01
Mean	**28.75**	**71.25**	**24.08**	**48.62**	**55.08**	**4.19**	**5.96**	**6.79**	**0.41**	**0.99**	**1.04**
SE(m)+	3.40	3.40	1.30	1.23	0.78	0.11	0.10	0.19	0.01	0.03	0.03
CD ($p = 0.05$)	10.48	10.48	NS	3.80	2.40	0.34	0.30	0.59	0.04	0.10	0.10
CV	23.65	9.54	10.77	5.08	2.83	5.22	3.26	5.63	5.86	6.87	6.14

Table 2. Effect of different sowing dates on leaf morphology of green onion in the late Kharif season

Sowing dates	Leaf length (cm)			Leaf diameter (cm)			Leaf fresh weight (g)			Leaf dry weight (g)		
	30DAP	60DAP	90DAP	30DAP	60DAP	90DAP	30DAP	60DAP	90DAP	30DAP	60DAP	90DAP
D_1-15th June	34.17	36.13	41.50	0.45	0.62	0.64	1.48	2.38	2.54	0.12	0.25	0.30
D_2-30th June	36.44	38.33	45.51	0.50	0.67	0.70	1.98	2.72	3.10	0.16	0.26	0.33
D_3-15th July	36.23	40.93	43.93	0.49	0.61	0.69	1.83	2.89	3.25	0.17	0.27	0.34
D_4-30th July	36.62	42.28	44.65	0.47	0.65	0.72	1.86	2.96	3.29	0.17	0.30	0.36
D_5-15th August	38.63	42.48	46.38	0.61	0.68	0.71	2.05	3.05	3.49	0.20	0.30	0.36
Mean	**36.42**	**40.03**	**44.39**	**0.50**	**0.67**	**0.68**	**1.84**	**2.80**	**3.13**	**0.16**	**0.27**	**0.34**
SE(m)+	0.83	1.45	0.88	0.03	0.02	0.01	0.12	0.09	0.13	0.01	0.01	0.01
CD($p = 0.05$)	2.55	4.47	2.70	0.11	0.05	0.03	0.36	0.29	0.41	0.04	0.04	0.03
CV	4.55	7.26	3.94	13.53	4.66	3.23	12.78	6.67	8.41	17.54	8.67	6.60

Effect of sowing dates on leaf morphology

The present study revealed (Table 2) significant variations in the leaf morphology of onion plants. Leaf length, a key morphological trait, exhibited substantial variations during the different plant growth stages. Onion plant growth showed a progressive increase with advancing growth stages. Leaf length increased from 34.77 cm-38.63 cm (avg. 36.42 cm) at 30 DAP to 36.13 cm-42.48 cm (avg. 40.03 cm) at 60 DAP and 41.50 cm-46.38 cm (avg. 44.39 cm) at 90 DAP. Leaf diameter also increased significantly, from 0.45 cm-0.61 cm (avg. 0.50 cm) at 30 DAP to 0.62 cm–0.68 cm (avg. 0.67 cm) at 60 DAP and 0.64 cm–0.71 cm (avg. 0.68 cm) at 90 DAP. Simultaneously, both the leaf fresh weight and dry weight of onion plants exhibited significant variations among plants grown from different sowing dates. Initially, leaf fresh weight ranged from 1.48 g to 2.05 g. As the plants matured, leaf fresh weights increased to 2.38–3.05 g at 60 days after planting (DAP) and further to 2.45–3.49 g at 90 DAP. Similarly, leaf dry weight varied significantly due to sowing date, initially ranging from 0.12–0.20 g and subsequently increasing to 0.25–0.30 g at both 60 and 90 DAP, respectively.

Effect of sowing dates on leaf quality

The present study revealed that sowing and planting dates significantly impacted leaf quality in onion plants (Table 3). The chlorophyll content of green onions was significantly affected by different sowing dates. Overall, the chlorophyll content ranged from 58.97 to 62.24 SPAD, with a mean SPAD value of 60.71. At 90 days after planting, the highest chlorophyll content was recorded in plants sown on 15th August (D_5), with a SPAD value of 62.24, which was statistically at par with those sown on 15th July (D_3) and 30th July (D_4), with SPAD values of 60.66 and 61.46, respectively. In contrast, the lowest chlorophyll content was observed in plants sown on 15th June (D_1), with a SPAD value of 58.97.

The sugar content of green onion plants varied significantly depending on the sowing date. Plants sown on 30th July (D_4) had the highest total sugar content (2.97 %). In contrast, plants sown on 15th August (D_5) had the highest Reducing Sugar content (2.50 %) and the lowest non-reducing sugar content (0.43 %). Conversely, the early-sown crop (15th June, D_1) had the lowest Total Sugar (2.56 %) and Reducing Sugar (1.85 %) content and the highest non-reducing sugar content (0.73 %).

The Ascorbic acid content of green onions varied from 20.82 to 25.19 mg 100 mL^{-1}, with an average ascorbic acid of 22.61 mg 100 mL^{-1}. Optimum ascorbic acid content of 25.19 mg 100 g^{-1} was significantly recorded on 15th June (D_1), however, a minimum of 20.82 mg100 g^{-1} was observed on 15th August (D_5) sown onion plants. Ascorbic acid, an essential antioxidant, remained relatively constant across sowing dates except for 15th June, where it was highest. While early planting generally had higher ascorbic acid levels, late-planted onions benefited from higher chlorophyll content, potentially enhancing photosynthesis and overall plant growth.

The onion plant grown from different sowing dates had a significant effect on protein (%) but a negligible impact on crude protein (%), nitrogen (%), phosphorus (%), potash (%) and sulphur (%) content of green onions at 90 DAP (Table 3). At 90 DAP, protein content ranged from 3.85 % to 5.40 %, with an average protein content of 4.33 %. Crude protein content ranged from 0.89 % to 1.09 %, with an average protein content of 0.98 %. Interestingly, the earliest sowing date (15th June, D_1) recorded the highest protein and crude protein content, while the (30th June, D_2) sowing date recorded the lowest values. Nitrogen content ranged from 0.14 % to 0.17 %, with an average of 0.16 %. Phosphorus content ranged from 0.47 % to 0.51 %, with a mean value of 0.49 %. Potassium content ranged from 1.99 % to 2.38 %, with an average of 2.15 %. Sulphur content ranged from 0.26 % to 0.41 %, averaging 0.41 %. These results indicated a negligible impact of sowing dates on the leaf nutrient contents of green onions.

Effect of GDD, HUT and PUT on plant growth

Table 4 presents a comparative analysis of varying sowing dates on the phenological development and thermal indices of the onion plants. The five sowing dates ranged from 15th June (D_1) to 15th August (D_5), resulting in crop growing periods terminating between early December and late January. Notably, the earliest sowing (D_1) exhibited the longest duration of the growth cycle, extending from 15th June to 5th December. A progressive delay in sowing led to a temporal shift in the maturity period towards January; however, it was accompanied by a concomitant reduction in the total number of effective growing days. The accumulated growing degree days (GDD), a critical metric for quantifying heat accumulation essential for plant development, demonstrated a declining trend with

Table 3. Effect of different sowing dates on bioactive components of green onion late Kharif season

Sowing dates	Chlorophyll content	Reducing sugar (%)	Non-reducing sugar (%)	Total sugar (%)	Ascorbic acid (mg 100 mL^{-1})	Soluble protein (%)	Crude protein (%)	N (%)	P_2O_5 (%)	K_2O (%)	S (%)	Shoot fresh weight (q ha^{-1})
D_1-15th June	58.97	1.85	0.73	2.56	25.19	5.40	1.09	0.17	0.49	1.99	0.40	23.61b
D_2-30th June	60.23	2.07	0.56	2.70	22.94	4.10	1.04	0.17	0.51	2.12	0.44	27.57b
D_3-15th July	60.66	2.15	0.65	2.85	22.08	3.90	0.96	0.15	0.51	2.11	0.26	36.17a
D_4-30th July	61.46	2.35	0.58	2.97	22.02	3.85	0.89	0.14	0.49	2.15	0.39	36.58a
D_5-15th August	62.24	2.50	0.43	2.96	20.82	4.40	0.91	0.15	0.47	2.38	0.58	39.42a
Mean	**60.71**	**2.18**	**0.59**	**2.81**	**22.61**	**4.33**	**0.98**	**0.16**	**0.49**	**2.15**	**0.41**	**32.67**
SE(m)+	0.64	0.07	0.05	0.08	0.49	0.12	0.07	0.01	0.06	0.11	0.07	3.72
CD (*p = 0.05*)	1.97	0.21	0.15	0.26	1.51	0.38	NS	NS	NS	NS	NS	11.46
CV	2.11	6.21	16.53	5.96	4.33	5.65	13.62	13.62	26.11	10.66	35.85	22.77

Table 4. Growing degree days (GDD), heliothermic units (HTU) and photothermal units (PTU) of green onions in the late Kharif season

Sowing dates	Crop growing period	GDD (°C days)	HTU (°C days)	PTU (°C days)
D_1-15th June	15th June to 5th Dec	2796	8715	36915
D_2-30th June	30th June to 18th Dec	2662	8630	34343
D_3-15th July	15th Jul to 25th Dec	2452	8093	31242
D_4-30th July	30th Jul to 6th Jan	2318	8344	28870
D_5-15th August	15th Aug to 29th Jan	2324	8812	27433

delayed sowing, ranging from a maximum of 2796 for D_1 to a minimum of 2318 to 2324 for the late sowing dates (D_4 and D_5).

This indicated a diminished thermal resource availability as the sowing period was postponed. Heliothermal units (HTU), which integrate GDD with actual sunshine h, peaked at 8812 for the D_5 sowing, suggesting a higher incidence of solar radiation during the later stages of crop growth despite the lower GDD accumulation. Conversely, the D_3 sowing recorded the lowest HTU value (8093), highlighting variability in the interplay between heat accumulation and sunshine duration across different sowing times. Photothermal Units (PTU), which account for both GDD and day length, exhibited a consistent decrease from 36915 for D_1 to 27433 for D_5. This decline underscores the reduced effectiveness of day length in contributing to crop development under progressively delayed sowing regimes.

While early sowing (D_1) benefits from higher cumulative Growing degree days (GDD) and Photothermal units (PTU), typically associated with enhanced developmental rates and yield potential in many crops, the presented data indicate a contrasting trend for onion in this specific agro-climatic zone. Despite lower accumulated thermal units in later sowing dates, the study demonstrably reveals superior vegetative growth in onions sown on 30^{th} July (D_4) and 15^{th} August (D_5). The green onion experiment under Odisha conditions revealed that sowing on 15^{th} August during the *late* Kharif season maximises yield components and phytonutrients. These findings can be applied to other tropical and subtropical regions by understanding the involved environmental factors. Key to the results is timing the crop growth stages with optimal weather conditions, particularly temperature and photoperiod, as indicated by correlations with PTU and GDD. The late-sown crop likely experienced cooler temperatures during its critical growth phase, promoting healthier leaf development. To translate these insights, growers in other tropical areas should find a sowing window that reflects the favourable combination of temperature, light and moisture, ideally 60 to 90 days before the coolest, driest period of the crop growth. This ensures that the vegetative phase benefits from residual soil moisture and moderate temperatures. As climate shifts may alter traditional sowing times, farmers should focus on maximising PTU and GDD rather than adhering to a strict schedule date, enhancing the adaptability of the Odisha findings.

Discussion

The observed superior performance of the late-sown onion crop, i.e. 15^{th} August, compared to the early-sown crop, i.e. 15^{th} June, was strongly supported by basic physiological and metabolic mechanisms that are activated by the more moderate environmental conditions prevalent during the later growth period.

Effect of sowing dates on onion plant survivability

The variation in onion plant mortality and survivability might be due to the prevailing weather conditions during the early vegetative growth stage. As an onion is a cool-season crop, it thrives in relatively low night temperatures. The temperatures recorded during the early sowing date of 15^{th} June (D_1), with a maximum of 41.70 °C and a minimum of 26.10 °C, likely created unfavourable conditions for plant survival. In contrast, delayed sowing time, i.e. 15^{th} August (D_5), allowed plants to avoid the most extreme temperatures, with a more moderate temperature range of 32.6 °C to 24.8 °C, thereby facilitating improved adaptation and reduced mortality. Researchers previously studied the survival and mortality rates of kharif onions in different agroecological conditions of Odisha. They found that onion seedlings in early-planted crops deceased due to harsh environmental conditions in open fields (18, 19).

Effect of sowing dates on vegetative growth of onion plants

During the early growth stage (30 DAP), onion seedlings exhibited non-significant variations in plant height across different sowing dates. This was attributed to the developing root system, which limited nutrient acquisition, resulting in suboptimal growth. The seedlings at the nascent stage restricted morphological differentiation, making them less responsive to planting time-induced variations. Consequently, growth disparities were not prominent and phenotypic variations were not significantly expressed during this phase. Nutrient uptake constraints hinder overall seedling development. In the later stage, i.e. 60 DAP and 90 DAP, significant variations in plant height across different sowing dates were observed. This might be attributed to the optimal availability of nutrients, air, water and photoperiodism and its efficient utilisation by the plants. The favourable climatic conditions allowed individual plants to exploit these environmental resources more effectively, resulting in superior growth and development as compared to other planting dates. Research has demonstrated similar results in onions (20–23).

The study indicated that late-sown onion crops, i.e. 15^{th} August, produced a higher number of leaves compared to early-sown crops. The increased leaf production in late-sown onion crops can be attributed to their rapid adaptation to favourable environmental conditions, including optimal temperature, humidity and rainfall, typically prevalent in open-field conditions. Additionally, delayed sowing dates allowed for enhanced physiological processes, including cell division and optimal photosynthesis, which collectively facilitated the production of additional leaves. Research has demonstrated similar results in onions (24–28).

Collar thickness is a crucial indicator of onion plant growth and bulb maturity. These findings suggested that late-sown onion crops may exhibit enhanced growth and development due to their greater adaptability to prevailing environmental conditions, viz. temperature, humidity and rainfall, which were often more favourable during later planting seasons, i.e. 15^{th} August in open field environments. In this study, it was observed that the temperature during the peak vegetative growth stages ranged from 9.9 °C to 32.4 °C. Relative humidity varied from a minimum of 17.00 % to a maximum of 79.30 %, with a maximum rainfall of 51.8 mm and a maximum of 8 hr of bright sunshine. The average temperature observed at various sowing dates exhibited a decline from 33.9 °C on 15^{th} June to 27.8 °C on 15^{th} August. Concurrently, the average relative humidity increased from 48.0 % to 82.7 %. This trend of decreasing temperature alongside increasing humidity persisted for an additional 30, 60 and 90 days following the earliest sowing date, i.e. 15^{th} June. For crops sown on 15^{th} July, a reduction in temperature was noted, accompanied by fluctuations in humidity observed at 90 days after sowing. In contrast, crops sown on 15^{th} August experienced declines in both temperature and humidity at 60 and 90 days after sowing. This data indicates a decrease in temperature from early-sown to late-sown crops, whereas relative humidity exhibited variability. Nonetheless, both temperature and humidity increased towards the end of the growing period, thereby creating favourable conditions for the cultivation of onion plants. These favourable environmental conditions may have contributed to the observed better vegetative growth in the late-sown onion plants, i.e.

15th August. Onion plants sown early (15th June) faced very high and low temperatures, between 41.7 °C and 26.1 °C. This extreme heat is harmful to a cool-season crop. It likely caused damage to cell membranes, altered proteins and blocked important enzyme functions. As a result, the plants experienced high death rates and poor early growth. In contrast, the later-sown plants (D_5) grew in more moderate temperatures of 32.6 °C to 24.8 °C and later 9.9 °C to 32.4 °C. These better conditions helped protect their cells and allowed enzymes to work properly, supporting better respiration and nutrient uptake. This was crucial for a strong root system and healthier growth. Research has demonstrated similar results in onions (20—23).

Effect of sowing dates on leaf morphology

The present study revealed that sowing dates significantly impacted leaf morphology in onion plants. This phenomenon can be attributed to the varying exposure to bright sunshine hour (BSH) during critical growth stages. Early-sown crops (15th June) were initially exposed to limited BSH (0.1 h—2.7 h), hindering photosynthesis. In contrast, late-sown and subsequently late-planted onion crops (15th August) received optimal BSH (5.1 h—8.0 h), enhancing photosynthate production, cell division and leaf expansion. The favourable environmental conditions during this period likely boosted photosynthesis rates, leading to improved leaf development with an optimum leaf length, leaf diameter, leaf fresh weight and leaf dry weight of 46.38 cm, 0.71 cm, 3.49 g and 0.36 g, respectively, resulting maximum of 7.28 leaves plant^{-1}. Research has demonstrated similar results in onions (29—32).

Effect of sowing dates on leaf quality

Chlorophyll content is crucial for plant growth and development, as it stimulates photosynthesis, enhances energy production and boosts stress tolerance and nutrient uptake. This, in turn, leads to increased crop yield and quality. Notably, late-sown crops benefit from increased Bright Sunshine Hour (BSH), which amplify photosynthesis, ultimately promoting healthier plant growth and higher yields (23). The harmonious interaction between chlorophyll, ascorbic acid and sugars plays a vital role in promoting plant growth, development and stress resilience. Chlorophyll's enhancement of photosynthesis boosts sugar production, while ascorbic acid safeguards cellular components against oxidative damage. Sugars, in turn, provide the necessary energy for repair and growth. Environmental factors, such as light intensity and nutrient availability, can influence the effects of these compounds. The synergistic relationship between chlorophyll, ascorbic acid and sugars in green onion may be a key contributor to the enhanced development and performance of onion plants (Table 5). Research has demonstrated similar results in onions (33—35).

Nutrient content of onion leaf findings suggested that while leaf protein content may be influenced by planting time, the overall nutrient composition of green onions remains relatively consistent across different sowing dates. The synergistic interaction of proteins, nitrogen, phosphorus, potassium and sulphur significantly influences onion leaf growth, development and vigour. Although the nutrient content in this experiment was not significantly affected by the sowing dates, these nutrients play a crucial role in plant metabolism. Proteins, essential for cellular structures and photosynthesis, might be the primary driver of this metabolic influence, supported by the synergistic effects of nitrogen, phosphorus, potassium and sulphur. Balanced levels of these nutrients remain essential for optimal onion growth and yield.

Effect of GDD, HUT and PUT on plant growth

This superficially counterintuitive finding underscores the critical influence of temperature during the early vegetative growth stage for this cool-season crop. The high temperatures prevalent during the early sowing period (15th June), characterised by a maximum of 41.70 °C and a minimum of 26.10 °C, likely induced significant stress, leading to higher mortality and compromised early development, as evidenced by the lower survivability rates (36, 37). Conversely, delayed sowing, i.e. 15th August, allowed the onion seedlings to establish during a period of more moderate temperatures, as seen with the 15th August sowing experiencing a range of 32.6 °C to 24.8 °C. This thermal regime proved more conducive to plant adaptation, resulting in reduced mortality and enhanced vegetative parameters such as plant height and leaf production. Therefore, in this specific environment, the avoidance of early-season heat stress through delayed sowing appears to compensate for the potential benefits of higher cumulative thermal units, ultimately encouraging better vegetative growth and development in onion plants (15).

Relationship between onion leaf bioactive components and environmental factors

Fig. 2 illustrates the Pearson correlation coefficients that quantify the linear relationships between various bioactive components in green onions at 90 days after planting and key environmental factors. These correlations highlight the influence of cumulative climatic conditions on the accumulation of these vital compounds and their potential impact on shoot fresh weight. The red ovals indicated a negative correlation between the bioactive components and the related environmental factors. In contrast, the blue ovals indicated a

Table 5. Contribution of various biochemical variables in green onion leaves to the major principal components and their relationship

Variables	PC1	PC2	PC3	PC4
Chlorophyll content	-0.994	0.09	0.065	-0.005
Reducing sugar	-0.991	0.128	0.01	-0.038
Non-reducing sugar	0.816	-0.442	-0.373	0.023
Total sugar	-0.98	-0.174	-0.071	-0.063
Ascorbic acid content (mg 100 mL^{-1})	0.962	0.057	-0.23	-0.135
Soluble protein	0.656	0.593	-0.434	0.171
Crude protein	0.963	0.193	0.158	0.103
Nitrogen	0.843	0.378	0.371	0.098
Phosphorus	0.468	-0.72	0.512	-0.002
Potash	-0.873	0.423	0.163	0.18
Sulphur	-0.36	0.917	0.124	-0.119
Shoot fresh weight (q ha^{-1})	-0.964	-0.173	-0.086	0.18
Growing degree days	0.976	0.175	0.124	0.03
Heliothermal units	0.132	0.985	0.064	-0.089
Photothermal units	0.996	0.027	0.086	-0.016

positive relationship between these bioactive components and environmental factors. The intensity of the colour and the size of the ellipse suggested the strength of the correlations. Values near ±1 indicated very strong correlations, while values close to 0 indicated weak or no relationship between the bioactive components and environmental factors. The data presented in Fig. 2 demonstrates significant positive linear correlations between leaf chlorophyll content and leaf reducing sugar (r = 1.00), leaf total sugar content (r = 0.95) and leaf potash content (r = 0.92) in green onions at 90 days after planting. These strong associations suggested a potential physiological interaction wherein enhanced photosynthetic pigment development is linked to increased accumulation of carbohydrates and potassium within the leaf tissue. Consistent with established nutritional principles, a strong positive correlation (r = 0.95) was observed between crude protein and nitrogen content in green onions, underscoring nitrogen's critical role as a primary constituent of plant crude proteins. As anticipated, a near-perfect positive correlation (r = 0.99) was noted between growing degree days (GDD) and Photothermal Units (PTU). This high degree of collinearity is attributable to the fact that both indices are fundamentally derived from the cumulative effects of temperature and solar radiation, respectively, throughout the plant's developmental period.

An inverse relationship (r = -1.00) was observed between the total sugar and crude protein content of the green onions, suggesting a potential trade-off or competitive allocation of resources between carbohydrate and protein synthesis. Furthermore, chlorophyll content exhibited a strong negative correlation (r = -0.97) with ascorbic acid content. Similarly, a negative association was found between total sugar content and photothermal units, indicating that increased cumulative heat accumulation during the growing period may be associated with reduced sugar levels in the green onions. Significant inverse metabolic relationships in plants indicate resource trade-offs. A strong negative correlation between total sugar and crude protein suggests competitive resource allocation, where protein synthesis may limit carbohydrate accumulation. Similarly, chlorophyll content negatively correlated with ascorbic acid, implying that higher chlorophyll might coincide with lower antioxidant levels, possibly due to a hermetic response under mild stress. Furthermore, increased photothermal units negatively correlated with sugar content, suggesting heat stress impairs carbohydrate synthesis or storage. Collectively, these findings support resource reallocation, where investment in one metabolic pathway (e.g. protein or chlorophyll synthesis) may occur at the expense of others, particularly under environmental stress (38).

The inverse relationship between total sugar and crude protein (r = -1.00) indicates a competitive resource allocation in onion plants. Under favourable conditions for growth and sugar accumulation, such as later sowing, the plant prioritises carbohydrate synthesis over protein synthesis, especially during stress. The strong negative correlation between chlorophyll and ascorbic acid (r = -0.97) suggests that fewer resources are allocated to antioxidant production under optimal conditions, reflecting a shift towards primary production over defence. Carbon (C) and nitrogen (N) are important elements that help microorganisms and plants grow and thrive. They play key roles in many biological processes necessary for life and in improving agricultural productivity. C and N are the main components of plant metabolism, affecting the health and yield of crops as well as individual growth and development (39). The better performance observed in the 15th August sowing highlights that avoiding early-season heat stress is more critical for plant efficiency than merely accumulating thermal units. This demonstrates how temperature-induced stress can severely limit onion physiological potential. The sugar-protein relationship is driven by the carbon–nitrogen balance; as sugars accumulate due to reduced nitrogen uptake or stress, protein synthesis declines. Conversely, with adequate nitrogen and active growth, protein levels

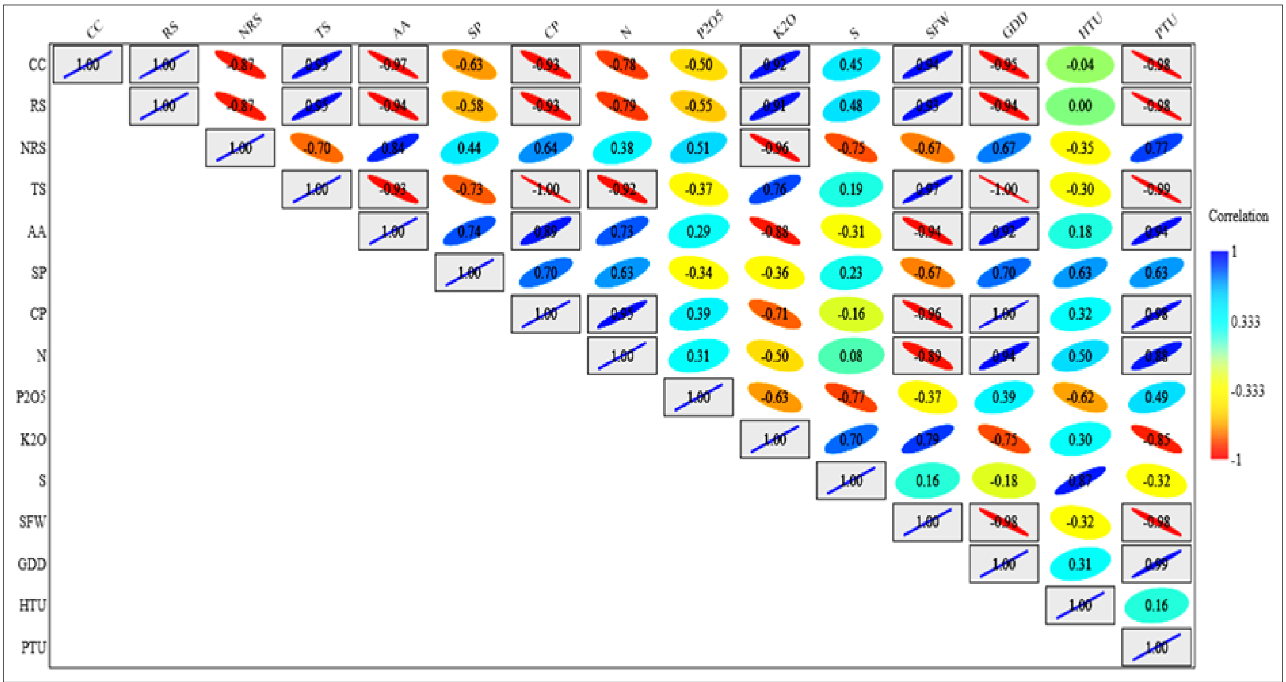

Fig. 2. Relationship between green onion bioactive components and environmental factors.

CC- Chlorophyll content, **RS** (%)- Reducing sugar, **NRS** (%)- Non-reducing sugar, **TS** (%)- Total Sugar, **AA** (mg 100 mL^{-1})- Ascorbic acid content, **SP** (%)- Soluble protein content, **CP** (%)- Crude protein content, **N** (%)- Nitrogen content, **P_2O_5** (%)- Phosphorus Content, **K_2O** (%)- Potash content and **S** (%)- Sulphur content of onion leaves at 90 days after planting, **SFW** (q ha^{-1})- Shoot Fresh Weight (q ha^{-1}), **GDD**- Growing degree days (°C days), **HTU**- Heliothermal Units (°C hr), **PTU**- Photothermal Units (°C hr). Boxed value represents the significance of traits at (p <0.05).

increase while sugars decrease, resulting in a negative correlation between sugar and protein concentration in onion leaves. Interestingly, the P_2O_5 exhibited predominantly weak to moderately negative correlations with shoot fresh weight and other nutrient concentrations within the green onions and sulfur (S) generally showed weak correlations across the measured parameters, suggesting that under this tropical agroecosystem, sulfur may not have been a primary limiting nutrient or involved in strong interactive effects within the onion leaf tissue.

Leaf chlorophyll, reducing sugars and total sugars are critical for onion plant health, growth and bulb quality. Chlorophyll, the primary photosynthetic pigment, absorbs light (blue/red spectrum), converting it to chemical energy (ATP, NADPH) to drive glucose synthesis from CO2 and water, forming biomass. Its concentration indicates plant health; declining levels often signal stress (drought, salinity, nutrient deficiency), impairing photosynthesis and growth (40, 41). Reducing sugars (glucose, fructose), direct products of photosynthesis, are the plant's immediate energy source, metabolising into ATP for growth. They also serve as fundamental building blocks for complex carbohydrates (e.g. disaccharides, polysaccharides). High reducing sugar levels contribute to osmotic pressure, aiding water uptake under drought and act as signalling molecules influencing growth, development and stress responses (41, 42).

Total sugar content, including reducing sugars and non-reducing sucrose, is crucial. Sucrose, as the main transport carbohydrate, efficiently distributes energy and carbon from leaves (source) to the developing bulb (sink), supporting growth and storage. While bulbs are primary storage organs, leaves hold temporary soluble sugar reserves vital for metabolism during low photosynthetic activity (43, 44). Leaf-derived sugars are essential for onion bulb size, sweetness and post-harvest storability; higher total sugar (especially fructans) correlates with better storage. Total sugar fluctuations also aid plant stress response, maintaining turgor and providing readily available energy.

In essence, chlorophyll drives photosynthetic energy production. Reducing sugars are immediate fuel and foundational building blocks. Total sugars, including transport forms like sucrose, ensure efficient energy distribution and storage, vital for the economically significant onion bulb and overall plant survival. Crops sown later in the season exhibited improved leaf growth and quality due to increased Bright Sunshine Hour (BSH), experiencing 5.1 h—8.0 h of sunlight compared to just 0.1 h—2.7 h for early-sown crops. The additional sunlight enhances chlorophyll's ability to absorb energy, leading to increased ATP and NADPH production during photosynthesis. This extra energy supports the Calvin cycle, resulting in more CO_2 fixation and sugar production. Higher chlorophyll content correlates strongly with increased sugar levels ($r = 1.00$ for reducing sugars, $r = 0.95$ for total sugars), providing the energy and resources necessary for plant growth.

Principal component analysis

PC1 includes traits like non-reducing sugar, ascorbic acid, soluble protein, crude protein, nitrogen, phosphorus, growing degree days and photothermal units. It accounts for 70.6 % of the variability in green onion leaf quality (Fig. 3). Key positive correlations are seen with photothermal units (0.996), growing degree days (0.976) and ascorbic acid (0.962), while negative correlations exist with chlorophyll content (-0.994), reducing sugar (-0.991), shoot fresh weight (-0.964) and potash (-0.873), all impacting green onion quality as presented in Table 5. Based on the individual principal component analysis of the five distinct sowing dates (Fig. 4), the sowing dates of 15th June, 30th June and 15th August emerged as favourable dates for quality traits, indicating the 15th August as exceptionally most suitable date.

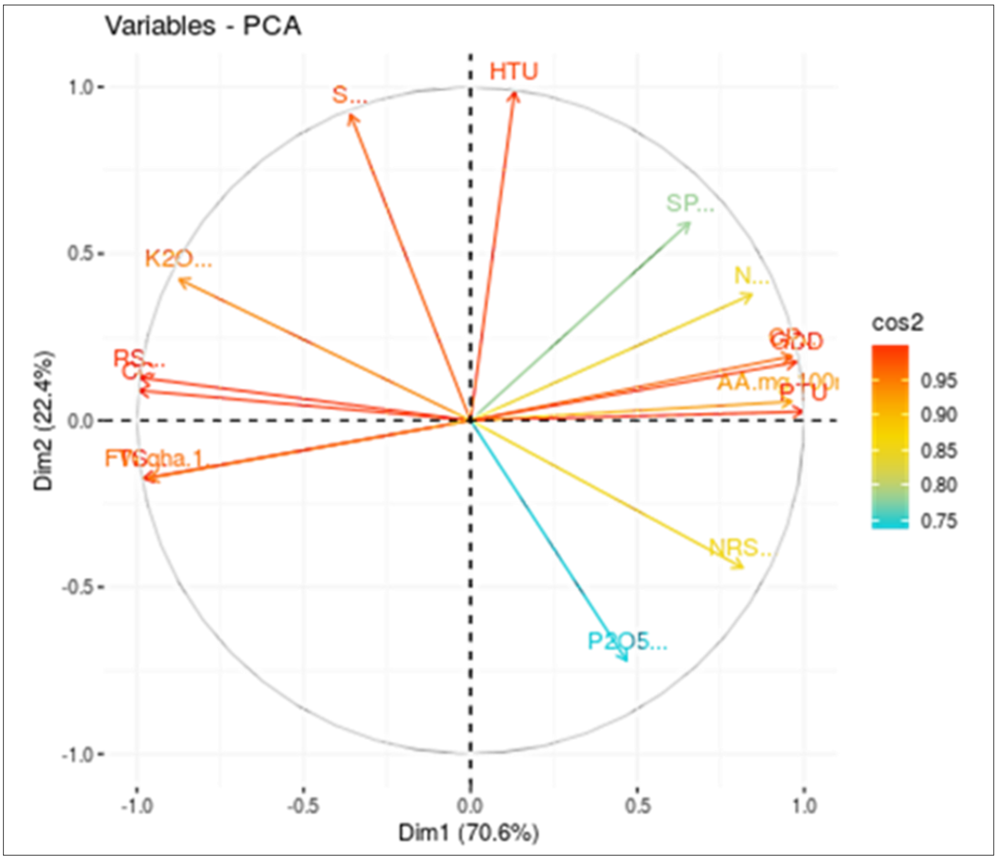

Fig. 3. Principal component analysis of ten biochemical traits and fresh weight of green leaves with GDD, HTU and PTU.

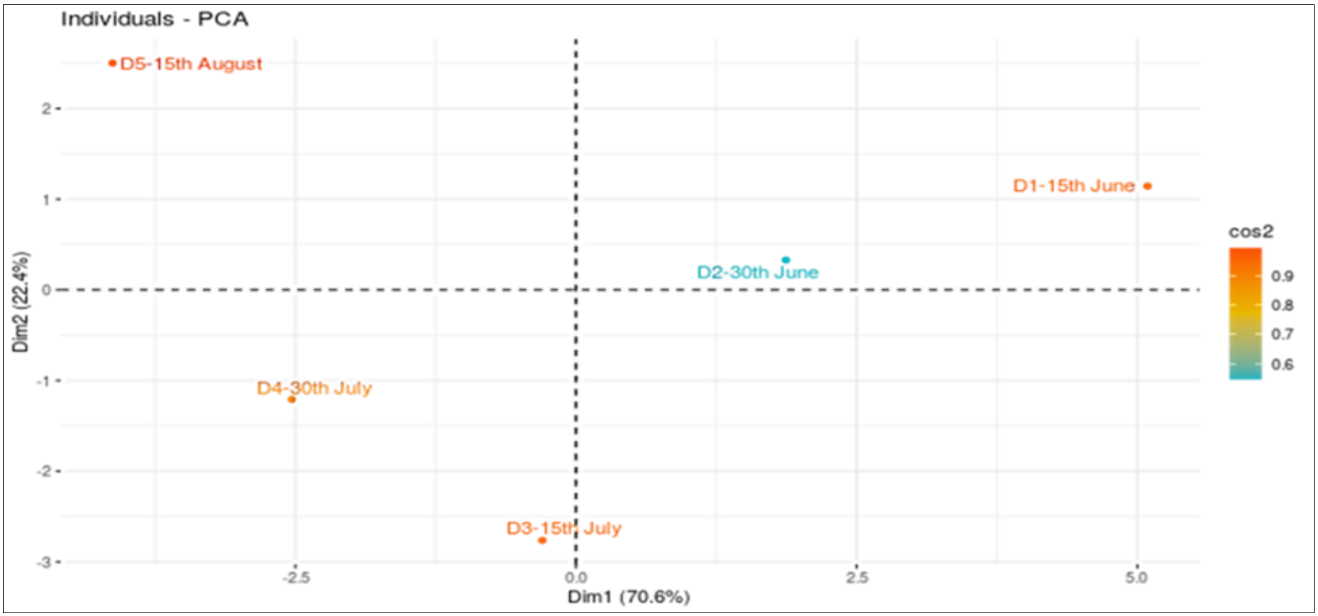

Fig. 4. Principal component analysis of five different sowing dates.

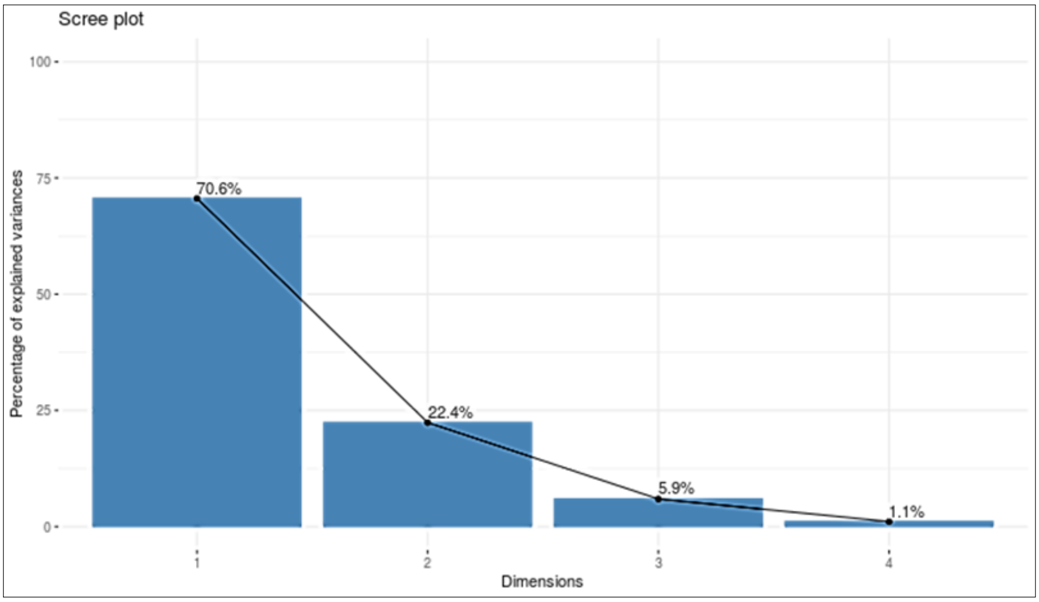

Fig. 5. Principal scree plot between component number and corresponding variance percentage.

Table 6. Eigenvalues and the contribution of the principal components to the total variance under investigation

Principal component	Eigenvalue	Variance (%)	Cumulative variance (%)
PC1	10.592	70.613	70.613
PC2	3.356	22.374	92.987
PC3	0.89	5.935	98.922
PC4	0.162	1.078	100

Fig. 5 illustrates the scree plot correlating component number with eigenvalues, complemented by the data presented in Table 6. The analysis reveals that the first three principal components account for approximately 98.92 % of the total variability observed across the five sowing dates under investigation. Among the four components identified, the first two exhibited eigenvalues exceeding 1, contributing to a cumulative variance of over 92.98 %. Specifically, the first principal component (PC1) demonstrated an eigenvalue of 10.59, which corresponds to 70.61 % of the total variability, while the second principal component (PC2) displayed an eigenvalue of 3.35, accounting for 22.37 % of the variability. As per Guttman's lower bound principle, principal components with eigenvalues less than 1 were overlooked. Principal component analysis is an important tool for understanding biochemical diversity and its relationships between crops. The various groupings of traits based on biochemical and physiological characteristics indicate that principal component analysis can effectively guide the selection of superior traits, putting them forward as viable candidates for further investigation. These findings demonstrate the effectiveness of principal component analysis in identifying key traits influencing green onion leaf quality. The 15th August sowing date stands out as the best option for maximising desirable quality attributes (45, 46).

Conclusion

It may be concluded that sowing in late July to mid-August in Odisha favours early vegetative growth in green onions by mitigating the detrimental effects of high temperatures experienced during early sowing. Despite lower cumulative thermal units, crops sown from late July to mid-August exhibited reduced mortality and enhanced vegetative growth with an optimum nutrient content in green onions. Correlation analysis of bioactive compounds revealed significant metabolic relationships. Positive correlations were observed between leaf chlorophyll and both leaf sugars and leaf potash, as well as between leaf crude protein and leaf nitrogen. Conversely, inverse relationships were found between leaf sugar and leaf protein and between leaf chlorophyll and leaf ascorbic acid. These findings underscore that for optimal early-stage development of this cool-season crop in this specific tropical agroecosystem, avoiding early-season heat stress through strategic sowing timing is more critical than maximising cumulative thermal unit accumulation.

Sowing green onions in late July to mid-August in Odisha promotes early vegetative growth by reducing heat stress associated with early sowing. Although thermal units are lower during this period, it leads to decreased mortality and improved nutrient content. Significant correlations were found between leaf chlorophyll, leaf sugars and leaf nitrogen, while inverse relationships existed between leaf sugar and protein. Thus, strategic sowing timing is critical for early-stage development in this tropical agroecosystem. It is recommended to avoid early to mid-July sowing to minimise heat stress and to maintain optimal nitrogen and potassium levels with split applications. Consistent moisture through light, frequent irrigation is essential. A phenology model integrating GDD and heat stress should be developed to predict optimal sowing dates and studies should identify resilient green onion cultivars. Further research into metabolic relationships can enhance breeding programs targeting specific pathways influenced by heat stress.

Acknowledgements

We gratefully acknowledge the Odisha University of Agriculture and Technology, Odisha, for providing financial support and other facilities to conduct this experiment at RRTTS, Bhawanipatna.

Authors' contributions

MP contributed to laboratory analysis, first drafting of the manuscript, material preparation, conduct of experiments, data collection, data analysis and manuscript preparation. BRP contributed to laboratory analysis and the first drafting of the manuscript. AD contributed to laboratory analysis and the first drafting of the manuscript. MDP contributed to laboratory analysis and the first drafting of the manuscript. SPM contributed to laboratory analysis and the first drafting of the manuscript. BBS contributed to material preparation, conduct of experiments, data collection, data analysis and manuscript preparation. PT and NM contributed to the overall supervision of the experiment and the review and editing of the manuscript. BSN contributed to the overall supervision of the experiment, reviewing and editing of the manuscript and collection and compilation of agrometeorological observations. TP contributed to the collection and compilation of agrometeorological observations. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1. Esakki A, Ramadoss R, Ananthapadmanabhan L, Sundar S, Panneerselvam S, Ramani P. Quantification of the anti-diabetic effect of *Allium cepa*. Cureus. 2024;16(4):e59174.
2. Gorrepati K, Khade YP. Onion and garlic keep us healthy. Indian Hortic. 2017;62(6):1–3.
3. Sharma D, Jarial K. Effect of different varieties and planting time on kharif onion production in lower Shivalik hills of Himachal Pradesh. Curr Agric Res J. 2017;5(1):74. https://doi.org/10.12944/CARJ.5.1.09
4. Liu X, Guo J, Chen Z, Xu K, Xu K. Detection of volatile compounds and their contribution to the nutritional quality of Chinese and Japanese welsh onions (*Allium fistulosum* L.). Horticulturae. 2024;10(5):446. https://doi.org/10.3390/horticulturae10050446
5. Zolfaghari B, Yazdiniapour Z, Sadeghi M, Troiano R, Lanzotti V. Furostanol saponins from the bulbs of Welsh onion, *Allium fistulosum* L. Planta Med. 2016;82(18):1584–90. https://doi.org/10.1055/s-0042-120122
6. Kandoliya UK, Bodar NP, Bajaniya VK, Bhadja NV, Golakiya BA. Determination of nutritional value and antioxidant activity from bulbs of different onion (*Allium cepa*) varieties. Int J Curr Microbiol Appl Sci. 2015;4(1):635–41.
7. Chaudhari VM, Singh OB, Gouthami NS, Thakur N, Singh R, Singh S, et al. Unlocking the nutritional power of vegetables: A guide to vibrant health. Eur J Nutr Food Saf. 2024;16:247–61. https://doi.org/10.9734/ejnfs/2024/v16i81512
8. Ebabhi A, Adebayo R. Nutritional values of vegetables. In: Vegetable crops - Health benefits and cultivation [Internet]. London: IntechOpen; 2022. https://doi.org/10.5772/intechopen.101090
9. Butnariu M, Butu A. Chemical composition of vegetables and their products. In: Cheung P, Mehta B, editors. Handbook of food chemistry. Berlin: Springer; 2015. p. 627–92.
10. Bhat R. Bioactive compounds of *Allium* species. In: Murthy HN, Paek KY, editors. Bioactive compounds in underutilized vegetables and legumes. Cham: Springer; 2020. p. 1–20.
11. Sagar NA, Pareek S, Benkeblia N, Xiao J. Onion (*Allium cepa* L.) bioactives: Chemistry, pharmacotherapeutic functions and industrial applications. Food Front. 2022;3(3):380–412. https://doi.org/10.1002/fft2.135
12. Iwar K, Ochar K, Seo YA, Ha BK, Kim SH. Alliums as potential antioxidants and anticancer agents. Int J Mol Sci. 2024;25(15):8079. https://doi.org/10.3390/ijms25158079
13. Kim SH, Yoon JB, Han J, Seo YA, Kang BH, Lee J, et al. Green onion (*Allium fistulosum*): An aromatic vegetable crop esteemed for food, nutritional and therapeutic significance. Foods. 2023;12(24):4503. https://doi.org/10.3390/foods12244503
14. Bahram-Parvar M, Lim LT. Fresh-cut onion: A review on processing, health benefits, and shelf-life. Compr Rev Food Sci Food Saf. 2018;17(2):290–308. https://doi.org/10.1111/1541-4337.12331
15. McMaster GS, Wilhelm WW. Growing degree-days: One equation, two interpretations. Agric For Meteorol. 1997;87(4):291–300. https://doi.org/10.1016/S0168-1923(97)00027-0
16. Gomez KA, Gomez AA. Statistical procedures for agricultural research. New York: John Wiley & Sons; 1984.
17. Panse VG, Sukhatme PV. Statistical methods for agricultural workers. 2nd ed. New Delhi: Indian Council of Agricultural Research; 1967.
18. Tripathy P, Sahoo BB, Priyadarshini A, Das SK, Dash DK. Standardization of kharif onion cultivars. Int J Bio-resour Stress Manag. 2014;5(2):269–74. https://doi.org/10.5958/0976-4038.2014.00566.1
19. Sahoo BB, Chinara N, Senapati N. *Alternaria porri*. Indian J Plant Prot. 2020;48(1–2):88–94.
20. Mohanta S, Mandal J, Dhakre DS. Growth of kharif onion (*Allium*

cepa L.) in response to planting dates and cultivars. HortFlora Res Spectr. 2017;6(4):262–7.

21. Aswani RC, Hada N, Singh YP, Jain DK, Tyagi SK, Gathiye GS. Assessment, estimation and economic performance of different kharif onion (*Allium cepa* L.) varieties under Malwa Plateau of Madhya Pradesh. J Agric Ecol. 2023;16:43–7. https://doi.org/10.58628/JAE-2316-209
22. Ojha MD, Kumar V, Pal M, Tiwari D, Kumar N, Singh PK. Effect of date of planting and varieties on growth, yield and storability of rabi onion (*Allium cepa* L.). J Pharmacogn Phytochem. 2019;8(4):1908–11.
23. Rugi M, Sharanya BR, Kushwah SS. Effect of varieties and transplanting dates on growth of kharif onion (*Allium cepa* L.). Pharma Innov J. 2022;11(4):2030–4.
24. Manna D, Santra P, Maity TK, Namw A, Basu A. Quality seed production of onion (*Allium cepa* L.) cv. Sukhsagar as influenced by bulb size and date of planting. Agric Res Technol Open Access J. 2016;2(3):01–7.
25. Santra P, Manna D, Sarkar HK, Maity TK. Genetic variability, heritability and genetic advance in kharif onion (*Allium cepa* L.). J Crop Weed. 2017;13(1):103–6.
26. Bal S, Maity TK, Maji A. Assessment of genetic variability, heritability and genetic gain for yield and quality traits in onion (*Allium cepa* L.). Int J Bio-resour Stress Manag. 2022;13(7):674–82. https://doi.org/10.23910/1.2022.2919
27. Gogoi S, Phookan DB, Kumar M, Jat RK, Patel R. Effect of different sowing dates and varieties on seedling growth of late kharif onion (*Allium cepa* L.) in Assam. Int J Plant Soil Sci. 2023;35(4):123–9.
28. Aswani RC, Hada N, Singh YP, Jain DK, Tyagi SK, Gathiye GS. Assessment, estimation and economic performance of different kharif onion (*Allium cepa* L.) varieties under Malwa Plateau of Madhya Pradesh. J Agric Ecol. 2023;16:43–7. https://doi.org/10.58628/JAE-2316-209
29. Das RA, Thapa UM, Chattopadhyay NA, Mandal AR. Performance of kharif onion genotypes under different dates of planting for productivity and economics in Gangetic Plains of West Bengal. Ann Plant Soil Res. 2015;17(1):19–23.
30. Behera TK, Mandal J, Mohanta S, Padhiary AK, Behera S, Behera D, et al. Assessment of growth, yield and quality of onion genotypes under red and laterite zone of West Bengal. J Pharmacogn Phytochem. 2017;6(6):493–7.
31. Kar I, Nayak BR, Bansude SN, Mandal D. Effect of different sulphur fertilization regimes on yield and quality of onion (*Allium cepa* L.). Pharma Innov J. 2022;11:2602–5.
32. Jana K, Thapa U, Kundu S, Hansda NN. Assessment of onion (*Allium cepa* L.) genotypes for horticultural traits during kharif season. Int J Multidiscip Res. 2023;5(5):1–13.
33. Sami R, Elhakem A, Alharbi M, Benajiba N, Almatrafi M, Helal M. Nutritional values of onion bulbs with essential structural parameters for packaging process. Appl Sci. 2021;11(5):2317. https://doi.org/10.3390/app11052317
34. Singh H, Verma P, Khar A. Screening of short-day onion cultivars of India for vitamin C content. Indian J Hortic. 2022;79(2):160–7. https://doi.org/10.5958/0974-0112.2022.00022.6
35. Jana K, Thapa U, Kundu S, Hansda NN, Ray K, Tamang D. Evaluation of different genotypes of late kharif onion (*Allium cepa* L.) under the Gangetic Plains of West Bengal, India. Int J Plant Soil Sci. 2023;35 (22):295–305.
36. Dar EA, Brar AS, Yousuf A. Growing degree days and heat use efficiency of wheat as influenced by thermal and moisture regimes. J Agrometeorol. 2018;20(2):168–70.
37. Nishad Y, Sastri AS, Durgam U. Evaluation and computing study of crop phenology and agrometeorological indices. J Pharmacogn Phytochem. 2018;7(6):268–73.
38. Agathokleous E, Feng Z, Peñuelas J. Chlorophyll hormesis: Are chlorophylls major components of stress biology in higher plants? Sci Total Environ. 2020;726:138637. https://doi.org/10.1016/j.scitotenv.2020.138637
39. Liu H, Gao X, Fan W, Fu X. Optimizing carbon and nitrogen metabolism in plants: From fundamental principles to practical applications. J Integr Plant Biol. 2025;67(6):1447–66. https://doi.org/10.1111/jipb.13919
40. Bibi N, Shah MH, Khan N, Al-Hashimi A, Elshikh MS, Iqbal A, et al. Variations in total phenolic and flavonoid contents and free radical scavenging potential of onion varieties under diverse environments. Plants. 2022;11(7):950. https://doi.org/10.3390/plants11070950
41. Kazimierczak R, Średnicka-Tober D, Barański M, Hallmann E, Góralska-Walczak R, Kopczyńska K, et al. Effect of fertilization regimes on yield, nutrients and bioactive compounds of onion. Agronomy. 2021;11 (5):883. https://doi.org/10.3390/agronomy11050883
42. Sagar NA, Pareek S, Benkeblia N, Xiao J. Onion (*Allium cepa* L.) bioactives: Chemistry, pharmacotherapeutic functions and industrial applications. Food Front. 2022;3(3):380–412. https://doi.org/10.1002/fft2.135
43. Perez-Gregorio MR, Regueiro J, Simal-Gándara J, Rodrigues AS, Almeida DP. Increasing the added-value of onions as a source of antioxidant flavonoids: A critical review. Crit Rev Food Sci Nutr. 2014;54(8):1050–62. https://doi.org/10.1080/10408398.2011.624283
44. Shukla S, Rawat M, Kumar N, Patel MK, Behera RK, Thakur MS, et al. Comparative analysis of physicochemical, nutritional and bioactive compounds of onion cultivated at different altitudes. Vegetos. 2024;1–2. https://doi.org/10.1007/s42535-024-00994-1
45. Sahoo BB, Panda D, Panda A, Gupta AJ, Tripathy P, Senapati N, et al. Morphological and biochemical characterization of kharif onion (*Allium cepa* L.). Vegetos. 2024;1–10. https://doi.org/10.1007/s42535-024-01005-z
46. Sahoo BB, Mohanty A, Nayak BS, Behera D, Dasgupta M, Sahoo MR, et al. Phenotypic and genotypic variations among tomato cultivars in the western undulating agroecosystem of India. Vegetos. 2025;1–10. https://doi.org/10.1007/s42535-025-01448-y

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.