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Pungency, sugar and antioxidant activity profiling of Indian garlic (*Allium sativum* L.) genotypes under short-day conditions

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Abstract

Garlic is valued for its culinary and therapeutic properties due to its sulfur-containing compounds, sugars and antioxidants. In the present study, 25 Indian garlic genotypes were profiled under short-day conditions during the two *rabi* seasons of 2020–21 and 2021–22 at ICAR-DOGR, Pune. Ten biochemical components were quantified and showed significant variation across genotypes, including total sugars (53.33–441.16 mg/g fw), reducing sugars (4.64–21.03 mg/g fw), non-reducing sugars (0.35–118.60 mg/g fw), pyruvic acid (25.49–47.42 μ mol PA/g fw), allicin (1.53–3.40 mg/g fw), total soluble solids (26.67–37.60%), moisture (58.98–68.88%), total phenols (4.21–6.34 mg/g GAE fw), total flavonoids (0.46–1.80 mg/g QE fw) and antioxidant activities estimated through FRAP (0.24–0.56 μ mol/g TE fw), DPPH (0.29–0.41 μ mol/g TE fw) and ABTS (0.58–1.30 μ mol/g TE fw). Clove colour based evaluation revealed significant effects on biochemical trait partitioning, particularly antioxidant capacity as determined by FRAP, ABTS and DPPH assays, with notable variation among white, purple and pink cloved genotypes. Purple-cloved types exhibited higher reducing sugars and allicin content, white-cloved genotypes showed greater accumulation of non-reducing sugars, phenolics and ABTS activity, while pink-cloved types recorded elevated pyruvic acid levels. Correlation analysis indicated strong associations between pyruvic acid and allicin and between phenolics and ABTS activity. Principal component analysis coupled with k-means clustering grouped the genotypes into three distinct clusters. Overall, the study elucidates clove colour associated metabolic differentiation in garlic and provides a useful biochemical framework for breeding and food-industry applications targeting quality, pungency and health-promoting attributes.

Keywords Garlic, Clove colour, Pungency, Sugars, Antioxidant activity, Biochemical profiling



1 Introduction

Garlic (*Allium sativum* L.) has been esteemed since antiquity, valued not only as a culinary spice but also as a potent medicinal resource across diverse civilizations. Its therapeutic use is well documented in Ayurvedic and Unani systems of medicine, as well as in ancient Egyptian, Greek and Chinese traditions, where it was employed to combat infections, enhance physical strength and promote longevity [1–4]. The sustained importance of garlic is largely attributable to its diverse array of bioactive constituents that impart both nutritional and health-promoting properties. Garlic is believed to have originated in Central Asia, evolving from its wild progenitor *Allium longicuspis* Regel [5, 6]. Over time, it has transcended its primary role as a flavoring agent to emerge as a functional food with recognized therapeutic potential. Garlic can be consumed in multiple forms, including fresh leaves and cloves, dried cloves, or processed products such as oils, extracts and powders. Each form differs in chemical composition and bioactive profile, influencing its functional attributes [7]. Global garlic cultivation has expanded markedly over recent decades. Presently, garlic is grown across approximately 1.66 million hectares worldwide, yielding about 29.15 million tonnes annually. India ranks as the second-largest producer, contributing nearly 3.21 million tonnes per year, which accounts roughly about 5% of the global production [8].

Fresh garlic bulbs consist of about 66% moisture and are rich in carbohydrates (28%), organosulphur compounds (2.4%), proteins (2.5%), free amino acids (1.3%) and dietary fibre (1.5%). They also provide essential vitamins, including vitamin C and B-complex, along with minerals such as sodium, potassium and magnesium [9–11]. Sulphur-containing phytochemicals represent nearly 82% of the total secondary metabolites in garlic, underscoring their central role in its biological activity [12, 13]. In intact garlic tissue, the principal sulphur compound is alliin (S-allyl-L-cysteine sulfoxide), which is stable and odorless [14]. Mechanical disruption, such as crushing or chopping, activates the enzyme alliinase, catalyzing the rapid conversion of alliin into allicin (diallyl thio-sulfinate). Allicin is responsible for garlic's characteristic pungent aroma and is widely regarded as the primary contributor to its pharmacological effects [15–17]. However, allicin is highly unstable and readily degrades into a range of lipid-soluble organosulphur compounds, including diallyl disulfide (DADS), diallyl trisulfide (DATS), ajoene and vinylthiins [18, 19]. Garlic also contains water-soluble sulphur compounds such as S-allyl cysteine (SAC) and S-allyl mercaptocysteine (SAMC), particularly abundant in aged garlic preparations. These compounds are comparatively more stable and bio-available and have been extensively investigated for their neuroprotective, hepatoprotective and chemopreventive effects [20–23]. In addition, garlic accumulates pyruvic acid (PA), an important organic acid involved in cellular metabolism. Pyruvic acid constitutes nearly 61% of the total organic acid pool in garlic and serves as a biochemical indicator of pungency intensity [24, 25].

Beyond its well-documented health benefits such as cardiovascular protection, immunomodulatory activity, antimicrobial action and anticancer potential [26, 27] garlic possesses significant functional value in food systems. Its sulphur compounds and phenolic constituents exhibit strong antioxidant and antimicrobial properties, which can inhibit lipid oxidation, extend shelf life and improve sensory attributes of food products [28, 29]. Despite extensive research on garlic bioactives, systematic comparative information on sugar composition, pungency indices and antioxidant potential among Indian short-day

garlic genotypes remains limited. Such data are essential for targeted varietal selection aimed at specific food-industry applications, including natural preservative formulations, flavor-enriched foods and health-oriented nutraceuticals. Therefore, the present study evaluated 25 Indian garlic genotypes under short-day conditions for total, reducing and non-reducing sugars; pyruvic acid and allicin content; flavonoids, phenols and multiple antioxidant assays (FRAP, DPPH, ABTS). The objective was to identify superior genotypes suitable for next-generation functional foods, natural preservative systems and flavor-enhancement applications.

2 Materials and methods

2.1 Plant materials

Twenty-five genotypes (Table 1) were selected from the garlic germplasm collection under the Distinctness, Uniformity and Stability (DUS) project. Field trials were conducted at the ICAR-Directorate of Onion and Garlic Research (ICAR-DOGR), Rajgurunagar, Pune, Maharashtra, India (18.32°N, 73.51°E) during the two *rabi* (winter crop) seasons of 2020–2021 and 2021–2022 under randomized block design with three replications. Each replication consisted of 70 plants arranged in seven rows. Within each replication, five plants were randomly chosen for data recording, giving a total of 15 sampled plants per genotype (5 plants × 3 replications). The recorded observations were used for statistical analysis with replication effects considered in the model. The crop was planted at a spacing of 15 cm between rows and 10 cm between plants. Standard agronomic practices recommended for garlic cultivation by ICAR-DOGR were followed. At physiological maturity, determined by neck-fall and leaf drying, bulbs were harvested, shade-cured for seven days and stored in a well-ventilated room. Clove colour was determined based on visual assessment of the outer skin of garlic cloves and genotypes were categorized into white, purple and pink groups according to their predominant colour under uniform lighting conditions. For biochemical analyses, cloves were randomly sampled from each genotype. Biochemical parameters namely total soluble solids (TSS), moisture content, total sugars, reducing sugars, non-reducing sugars, total flavonoids, total phenols, pyruvic acid, allicin content and antioxidant activity were estimated. Antioxidant activity was assessed using three assays, ferric-reducing antioxidant

Table 1 List of 25 garlic genotypes used in the study

Sr. No.	Genotype	Source	Sr. No.	Genotype	Source
1.	Bhima Omkar	ICAR-DOGR, Pune	14.	GAG-7	AAU, Anand
2.	Bhima Purple	ICAR-DOGR, Pune	15.	PG-17	PAU, Ludhiana
3.	G-1	NHRDF, Karnal	16.	PG-18	PAU, Ludhiana
4.	G-41	NHRDF, Karnal	17.	Godawari	MPKV, Rahuri
5.	G-50	NHRDF, Karnal	18.	Phule Baswant	MPKV, Rahuri
6.	G-282	NHRDF, Karnal	19.	Ooty Local	Landrace
7.	G-323	NHRDF, Karnal	20.	Rani Benneur Local	Landrace
8.	G-384	NHRDF, Karnal	21.	Sikkim Local	Landrace
9.	G-386	NHRDF, Karnal	22.	Silkuei Local	Landrace
10.	GG-2	JAU, Junagadh	23.	Navapur Local	Landrace
11.	GG-3	JAU, Junagadh	24.	VNS Local-1	Landrace
12.	GG-4	JAU, Junagadh	25.	VNS Local-2	Landrace
13.	GAG-6	AAU, Anand			

ICAR-DOGR: ICAR-Directorate of Onion and Garlic Research; NHRDF: National Horticultural Research and Development Foundation; JAU: Junagadh Agricultural University; AAU: Anand Agricultural University; PAU: Punjab Agricultural University; MPKV: Mahatma Phule Krishi Vidyapeeth

power (FRAP), 2, 2-diphenyl-1-picrylhydrazyl (DPPH) and 2, 2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS).

2.2 Biochemical compositional analysis

2.2.1 TSS

TSS content of the 25 garlic genotypes was determined using a handheld refractometer (Avantor, India) and expressed as °Brix [30]. Fresh garlic cloves were homogenized using a blender and the resulting slurry was filtered through a strainer to obtain clear juice. A drop of juice was placed on the prism surface of the refractometer, ensuring uniform spreading and the °Brix value was recorded. The prism was thoroughly rinsed with distilled water and wiped dry with a soft, lint-free cloth after each reading to prevent cross-sample contamination.

2.2.2 Moisture content

Moisture percentage was estimated using the oven drying method. Approximately 5 g of fresh garlic clove samples were weighed into Petri dishes and initially dried at 60 °C for 6 h. The temperature was then increased to 105 °C until a constant weight was achieved. Moisture content was calculated as the percentage difference between the initial fresh weight and the final dry weight [31, 32].

2.2.3 Estimation of total sugars, reducing sugars and non-reducing sugars

Total sugar content was quantified using the anthrone method described by Yemm and Willis [33]. Finely ground garlic paste (0.1 g) was hydrolyzed with 5 mL of 2.5 N HCl by heating in a boiling water bath for 3 h. After cooling, the hydrolysate was neutralized with sodium carbonate until effervescence ceased and the volume was adjusted to 50 mL using distilled water. An aliquot (0.5 mL) of this extract was diluted with 0.5 mL distilled water, followed by the addition of 4 mL anthrone reagent prepared in concentrated sulfuric acid. The reaction mixture was heated for 8 min in a boiling water bath, cooled and absorbance was recorded at 630 nm using a spectrophotometer.

Reducing sugars were estimated following the dinitrosalicylic acid (DNS) method of Miller [34]. Garlic samples (0.5 g) were subjected to alkaline digestion using water adjusted to pH 8.0. The digestion process was carried out sequentially with 20, 15 and 10 mL of alkaline water, each followed by boiling for 20 min. The extracts were filtered and collected in test tube. One millilitre of the extract was reacted with an equal volume of DNS reagent prepared using Rochelle salt and 2 mM NaOH. After boiling for 5 min, absorbance was measured at 540 nm.

Non-reducing sugar content was determined using a thiobarbituric acid (TBA)-based method. A 50 µL aliquot of the alkaline extract (used for reducing sugars) was mixed with 200 µL of 0.5 N NaOH and heated at 100 °C for 10 min. After cooling to room temperature, 600 µL of TBA-HCl reagent was added and the mixture was reheated at 100 °C for 7 min. Absorbance was measured at 432 nm.

2.2.4 Total phenolic content

Total phenolic compounds were quantified using the Folin-Ciocalteu (FC) method [35]. Garlic tissue (2 g) was extracted with 10 mL of 80% methanol and incubated overnight at room temperature. The extracts were centrifuged at 7000 rpm for 10 min and the

supernatant was used for analysis. A diluted FC reagent (10% v/v) was prepared by mixing reagent and distilled water in a 1:10 ratio. To 200 μL of extract, 1 mL of diluted FC reagent was added and mixed thoroughly, followed by the addition of 800 μL sodium carbonate solution (700 mM). The mixture was incubated in the dark for 2 h and absorbance was recorded at 765 nm in UV-VIS spectrophotometer. Total phenols were calculated using a gallic acid standard curve and expressed as mg gallic acid equivalents (GAE) per g fresh weight (fw).

2.2.5 Total flavonoid content

Flavonoid concentration was estimated using the same methanolic extract prepared for phenolic analysis following the aluminium chloride colorimetric method of Zhishen et al. [36]. One milliliter of extract was combined with 1 mL distilled water, followed by the addition of 300 μL of 5% NaOH and 300 μL of 10% AlCl_3 . After incubation at room temperature for 6 min, 2 mL of 1 N NaOH and 2.4 mL distilled water were added. Absorbance was measured at 510 nm. Quercetin was used as the reference standard and results were expressed as mg quercetin equivalents (QE) per g fw.

2.2.6 Pyruvic acid content

Pyruvic acid concentration was determined using a colorimetric assay based on the reaction with 2,4-dinitrophenylhydrazine (DNPH), as described by Anthon and Barrett [37] and Beretta et al. [38]. Appropriately diluted garlic juice was reacted with 1 mL DNPH solution (0.25 g L^{-1} in 1 M HCl) and incubated at 37 °C for 10 min. The reaction was stopped by adding 1 mL of 1.5 M NaOH. Absorbance was measured at 515 nm and pyruvic acid concentration was calculated using a sodium pyruvate standard curve. Results were expressed as μmol pyruvic acid per g fresh weight.

2.2.7 Allicin (diallyl thiosulfinate)

Allicin content was quantified using a spectrophotometric method described by Han et al. [39], with modifications proposed by Miron et al. [40] and Mansor et al. [41]. Garlic extract (1 g) was dissolved in 15 mL of 50 mM HEPES buffer (pH 7.6) and centrifuged. The supernatant was mixed with 1.2 mL of 2 mM L-cysteine and incubated at 37 °C for 15–20 min to facilitate reaction with thiosulfonates. Subsequently, 3 mL of HEPES buffer and 1 mL of 1.5 mM DTNB solution were added. Absorbance was recorded at 412 nm and allicin concentration was expressed as mg g^{-1} fresh weight.

2.2.8 Antioxidant activity

Antioxidant potential was evaluated using FRAP, ABTS and DPPH assays. The FRAP assay was performed following Benzie and Strain [42]. The FRAP reagent consisted of 300 mM sodium acetate (pH 3.6), 10 mM 2, 4, 6-Tris (2-pyridyl)-s-triazine (TPTZ) and 20 mM $\text{FeCl}_3 \cdot 6 \text{H}_2\text{O}$ mixed in a 10:1:1 ratio. A reaction mixture containing 30 μL of sample extract, 900 μL of FRAP reagent and 90 μL distilled water was incubated at 37 °C for 4–5 min. Absorbance was measured at 593 nm. Trolox was used as the calibration standard and antioxidant activity was expressed as μmol Trolox equivalents (TE) per g fw.

ABTS radical scavenging activity was determined using the method described by Re et al. [43] and Shahinuzzaman et al. [44]. The ABTS $\cdot^+$ radical solution was generated by reacting 7 mM ABTS with 2.45 mM potassium persulfate (1:1) and incubating the

mixture in darkness for 12 h. The solution was diluted with ethanol to obtain an absorbance of 0.7 ± 0.02 at 743 nm. For analysis, 100 μL of sample extract was added to 3.9 mL of ABTS $^{\bullet+}$ working solution and incubated for 6 min at room temperature. Absorbance was measured at 743 nm and results were expressed as $\mu\text{mol TE per g fw}$.

DPPH radical scavenging activity was assessed following Shimamura et al. [45] and Xiao et al. [46], with minor modifications. A DPPH stock solution was prepared by dissolving 7.89 mg of DPPH in 100 mL of 99.5% ethanol and incubating the solution in darkness for 2 h. For the blank, 1 mL of DPPH solution was mixed with 800 μL Tris-HCl buffer (pH 7.4) and 4.5 mL ethanol and incubated for 30 min in the dark before recording absorbance at 517 nm. For sample analysis, 1 mL DPPH solution was combined with 800 μL Tris-HCl buffer and 200 μL of extract, followed by incubation under identical conditions. The reduction in absorbance at 517 nm was used to calculate free radical scavenging activity.

2.3 Statistical analysis

All measurements were performed in triplicate using five bulbs per replicate and the results represent pooled means over two growing seasons. Obtained data was subjected to variance analysis (ANOVA), Tukey's HSD test at significance level $p < 0.05$, Pearson correlation and principal component analysis with K-means clustering. All statistical analyses were carried out in R version 4.3.1.

3 Results and discussion

3.1 Sugars profiling

The biochemical profiling of twenty-five garlic genotypes revealed substantial variation in all measured sugar fractions and related traits. Total sugars (TS) spanned almost an order of magnitude, from as low as 53.33 mg/g fresh weight (fw) in Phule Baswant to 441.16 mg/g fw in G-384 (Table 2). Non-reducing sugars (NRS) predominantly sucrose ranged from just 0.35 mg/g fw in Silkuei Local to 118.60 mg/g fw in G-384, indicating the exceptionally high sucrose accumulation in these genotypes. These TS values far exceed those reported for Greek landraces, where total sugars typically fall below 100 mg/g fw [47]. In contrast, Italian and Argentinian varieties report NRS at 19.9–32.9 mg/g fw [48], indicating that our Indian germplasm harbors unique sugar-accumulation potential. Reducing sugars (RS) principally glucose and fructose also varied markedly, from 4.64 mg/g fw in GG-2 to 21.03 mg/g fw in G-386. Fresh garlic bulbs typically contain 22–26% carbohydrates by fresh weight, most of which are fructans; mono- and disaccharides account for only 4–8% of fw [49]. Among these free sugars, fructose generally predominates, followed by glucose and then sucrose in an approximate 57:7:8 ratios in processed (black) garlic [50, 51]. Although fresh cloves exhibit similar relative proportions, their absolute concentrations are considerably lower. The ratio of reducing to non-reducing sugars has critical implications for both sensory quality and postharvest performance. During thermal processing, reducing sugars participate in Maillard browning, generating the characteristic dark color and complex flavor profile of black garlic [52]. Thus, high RS genotypes such as G-386 are likely to yield darker, more intensely flavored products upon roasting or drying, whereas low RS lines like GG-2 may be preferable for applications demanding lighter coloration. However, under cold storage high total- and reducing-sugar content can accelerate sprouting. Chilling at 4 °C breaks down

Table 2 Mean $\pm$ SD of biochemical traits in 25 garlic genotypes over two years

Genotype	TS (mg/g fw)	RS (mg/g fw)	NRS (mg/g fw)	PA (μ mol PA/g fw)	Allicin (mg/g fw)	TSS (%)	MC (%)
Bhima Omkar	303.28 $\pm$ 8.17	7.66 $\pm$ 0.19	18.28 $\pm$ 0.52	31.60 $\pm$ 1.33	3.18 $\pm$ 0.13	30.43 $\pm$ 1.18	64.73 $\pm$ 1.06
Bhima Purple	330.05 $\pm$ 2.08	7.44 $\pm$ 0.05	56.97 $\pm$ 2.00	39.89 $\pm$ 0.25	3.40 $\pm$ 0.10	30.47 $\pm$ 0.44	63.71 $\pm$ 0.12
G-1	237.28 $\pm$ 1.50	7.14 $\pm$ 0.10	51.00 $\pm$ 0.28	25.49 $\pm$ 0.12	2.18 $\pm$ 0.04	27.43 $\pm$ 0.25	61.61 $\pm$ 2.52
G-41	323.16 $\pm$ 10.49	7.48 $\pm$ 0.24	25.06 $\pm$ 0.05	29.33 $\pm$ 0.16	2.93 $\pm$ 0.11	30.07 $\pm$ 0.06	60.77 $\pm$ 1.40
G-50	353.45 $\pm$ 5.10	7.54 $\pm$ 0.05	75.01 $\pm$ 1.91	31.86 $\pm$ 0.03	2.72 $\pm$ 0.11	31.90 $\pm$ 0.70	67.57 $\pm$ 0.18
G-282	184.74 $\pm$ 4.50	13.32 $\pm$ 0.56	43.01 $\pm$ 0.65	32.81 $\pm$ 1.15	3.17 $\pm$ 0.03	28.90 $\pm$ 0.34	66.84 $\pm$ 1.50
G-323	153.62 $\pm$ 6.64	8.95 $\pm$ 0.31	46.40 $\pm$ 0.46	33.08 $\pm$ 1.33	1.61 $\pm$ 0.02	30.40 $\pm$ 0.73	67.29 $\pm$ 2.46
G-384	441.16 $\pm$ 2.79	5.16 $\pm$ 0.23	118.60 $\pm$ 1.81	33.85 $\pm$ 0.24	1.91 $\pm$ 0.06	37.60 $\pm$ 0.54	60.01 $\pm$ 0.21
G-386	165.06 $\pm$ 6.40	21.03 $\pm$ 0.34	20.23 $\pm$ 0.51	40.48 $\pm$ 1.18	2.44 $\pm$ 0.05	28.50 $\pm$ 0.36	65.22 $\pm$ 2.15
GG-2	277.25 $\pm$ 7.50	4.64 $\pm$ 0.05	89.17 $\pm$ 2.72	35.30 $\pm$ 0.23	2.19 $\pm$ 0.02	34.07 $\pm$ 0.15	61.48 $\pm$ 1.98
GG-3	124.73 $\pm$ 2.70	10.30 $\pm$ 0.32	29.80 $\pm$ 0.41	37.49 $\pm$ 0.44	1.75 $\pm$ 0.06	35.10 $\pm$ 0.29	61.91 $\pm$ 1.86
GG-4	187.02 $\pm$ 6.07	12.92 $\pm$ 0.23	46.06 $\pm$ 0.95	34.30 $\pm$ 0.70	1.53 $\pm$ 0.03	33.90 $\pm$ 1.15	63.32 $\pm$ 0.90
GAG-6	147.67 $\pm$ 5.72	10.17 $\pm$ 0.14	27.26 $\pm$ 0.27	41.49 $\pm$ 1.71	2.85 $\pm$ 0.12	36.90 $\pm$ 1.21	58.98 $\pm$ 1.52
GAG-7	370.28 $\pm$ 11.68	7.68 $\pm$ 0.20	2.23 $\pm$ 0.05	47.42 $\pm$ 0.68	3.05 $\pm$ 0.05	32.53 $\pm$ 0.32	62.95 $\pm$ 0.83
PG-17	168.05 $\pm$ 5.30	12.74 $\pm$ 0.38	2.35 $\pm$ 0.03	32.96 $\pm$ 1.34	2.14 $\pm$ 0.09	34.53 $\pm$ 0.43	59.21 $\pm$ 0.21
PG-18	189.56 $\pm$ 1.20	8.77 $\pm$ 0.36	49.41 $\pm$ 0.76	39.74 $\pm$ 0.11	2.70 $\pm$ 0.09	32.23 $\pm$ 0.35	61.76 $\pm$ 0.45
Godawari	257.86 $\pm$ 8.14	7.14 $\pm$ 0.15	20.42 $\pm$ 0.37	41.31 $\pm$ 0.88	2.77 $\pm$ 0.00	30.50 $\pm$ 1.19	64.54 $\pm$ 1.78
Phule Baswant	53.33 $\pm$ 2.31	20.85 $\pm$ 0.83	25.93 $\pm$ 0.79	43.75 $\pm$ 1.67	3.08 $\pm$ 0.01	35.13 $\pm$ 0.48	61.53 $\pm$ 0.11
Ooty Local	125.30 $\pm$ 4.29	14.51 $\pm$ 0.25	48.15 $\pm$ 1.04	41.91 $\pm$ 0.19	2.89 $\pm$ 0.13	33.30 $\pm$ 0.44	62.03 $\pm$ 2.28
Rani B. Local	321.67 $\pm$ 4.93	7.28 $\pm$ 0.30	3.75 $\pm$ 0.14	40.49 $\pm$ 1.72	2.92 $\pm$ 0.06	27.43 $\pm$ 1.15	68.43 $\pm$ 1.98
Sikkim Local	327.60 $\pm$ 0.60	7.20 $\pm$ 0.07	7.45 $\pm$ 0.02	40.87 $\pm$ 1.20	3.01 $\pm$ 0.04	29.57 $\pm$ 0.84	65.28 $\pm$ 2.66
Silkuei Local	262.66 $\pm$ 2.61	7.07 $\pm$ 0.19	0.35 $\pm$ 0.01	34.20 $\pm$ 1.50	2.50 $\pm$ 0.07	26.67 $\pm$ 0.33	68.88 $\pm$ 0.12
Navapur Local	175.28 $\pm$ 4.43	8.88 $\pm$ 0.20	2.22 $\pm$ 0.06	39.16 $\pm$ 1.60	2.99 $\pm$ 0.11	29.03 $\pm$ 0.05	68.17 $\pm$ 2.24
VNS Local-1	197.90 $\pm$ 4.82	7.13 $\pm$ 0.17	1.90 $\pm$ 0.04	37.84 $\pm$ 1.29	2.68 $\pm$ 0.12	26.67 $\pm$ 0.58	65.33 $\pm$ 1.35
VNS Local-2	218.54 $\pm$ 6.70	7.91 $\pm$ 0.11	6.84 $\pm$ 0.00	43.99 $\pm$ 1.33	2.99 $\pm$ 0.05	29.73 $\pm$ 0.86	67.42 $\pm$ 2.44
Mean	235.86	9.64	32.71	37.22	2.62	31.32	63.96
CV (%)	9.47	12.51	4.93	1.68	1.03	3.08	2.34

TS: Total sugars, RS: Reducing sugars, NRS: non reducing sugars, PA: Pyruvic acid, TSS: Total soluble solids, MC: moisture content

fructans into simple sugars, stimulating bud break unless storage conditions are carefully managed [53].

3.2 Pungency profiling

Pungency in garlic is measured in the form of pyruvic acid released by alliinase or by directly measuring allicin content [54]. Pyruvic acid (PA) in Indian garlic genotypes ranged from 25.49 in G-1 to 47.42 μ mol PA g⁻¹ fw in GAG-7. Our PA values (25.5–47.4 μ mol g⁻¹ fw) fall below ranges reported by Abedi et al. [55] and Tripathi et al. [56] in peeled cloves. Based on the classification proposed by Natale et al. [57], garlic genotypes with pyruvic acid values below 60 μ mol g⁻¹ fresh weight are considered low pungency. Accordingly, all the evaluated genotypes in the present study can be classified as low pungency. Allicin content was relatively uniform varying between 1.53 mg/g fw (GG-4) and 3.40 mg/g fw (Bhima Purple) (Table 2). Allicin (diallyl thiosulfinate) is the principal pungent molecule produced when garlic cells are cut, the enzyme alliinase mixes

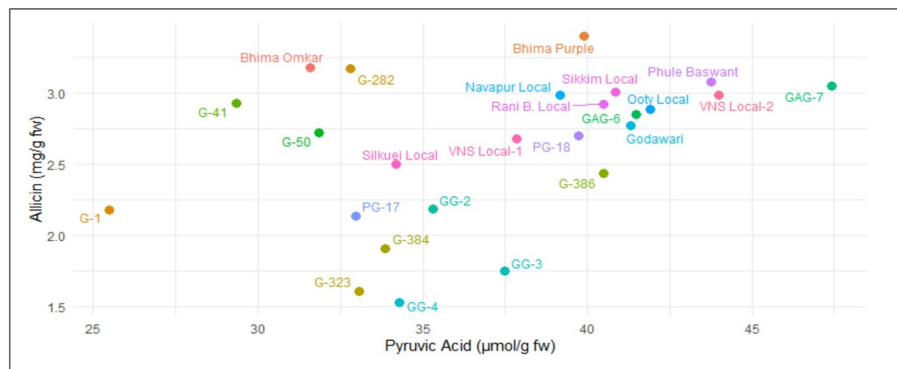


Fig. 1 Relationship between alliin and pyruvic acid in 25 genotypes of garlic

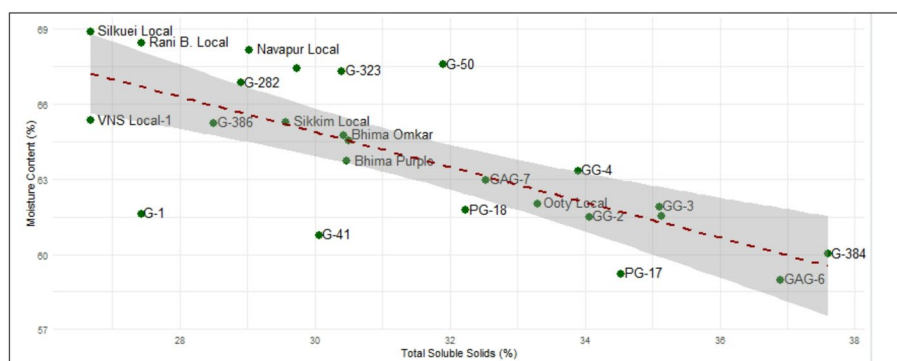


Fig. 2 Relationship between TSS and moisture content in 25 genotypes of garlic

with alliin to rapidly produce alliin [58]. Alliin is unstable and quickly decomposes into various sulfur volatiles such as Diallyl disulfide, Vinylthiols and Ajoene [59]. It was observed that genotypes with higher pyruvic acid tend to possess elevated alliin content (Fig. 1). Genotypes such as GAG-7, VNS Local-2, Phule Baswant, Ooty Local, GAG-6 and Godawari possess superior pungency and bioactive potential. Bhima Omkar and G-282 presented relatively high alliin content (> 3.0 mg/g fw) with only moderate pyruvic acid (~ 32 – 34 $\mu\text{mol/g fw}$), implying that these genotypes might possess efficient alliin biosynthesis pathways, possibly due to higher alliin or alliinase activity. Genotypes GG-4 and G-323 displayed lower alliin content despite moderate pyruvic acid levels, suggesting a possible block in the conversion pathway or reduced enzyme activity [60, 61]. This disparity between PA and alliin requires further enzymatic profiling to understand biochemical bottlenecks.

3.3 TSS and moisture profiling

TSS ranged from 26.67% (Silkuei Local and VNS Local-1) to 37.60% (G-384), while moisture content (MC) varied from 58.98% (GAG-6) to 68.88% (Silkuei Local) (Table 2; Fig. 2). A negative relationship between TSS and MC was observed (Fig. 2), indicating that genotypes with higher soluble solids tend to have lower moisture levels. This inverse association is important for post-harvest storage, as lower moisture content reduces microbial spoilage, respiration rate and physiological deterioration, thereby enhancing shelf life. Higher TSS is also associated with increased dry matter content, which improves processing quality and storability. Similar trends have been reported in garlic

and related *Allium* crops [62, 63]. Genotypes such as G-384 and GAG-6, with high TSS and low MC, can therefore be considered promising for both fresh consumption and processing due to their superior storage and quality attributes.

3.4 Antioxidants activity profiling

Organosulphur compounds, phenols and flavonoids in garlic contribute to antioxidant properties of garlic [64–67]. Total flavonoid content ranged from 0.46 mg/g QE fw in Rani B. Local to 1.80 mg/g QE fw in G-41, while total phenolics ranged from 4.21 (Bhima Purple) to 6.34 mg/g GAE fw (G-50). Notably, white cloved genotype such as G-50, exhibited high TP content, whereas purple cloved genotypes like Rani B. Local and VNS Local-2 showed moderate levels (Table 3).

The antioxidant potential of 25 garlic genotypes was assessed using three widely accepted assays FRAP, DPPH and ABTS. Figure 3 provides a comparative visualization of the antioxidant activities across genotypes of garlic included in the study. The FRAP assay measures the reducing capacity of antioxidants, with peak values observed in VNS Local-1 followed by Rani B. Local, Ooty Local, Godawari and GG-3. The DPPH assay reflects free radical scavenging through hydrogen donation. Maximum activity was recorded in Bhima Omkar, followed closely by Ooty Local and VNS Local-2. Notably, the ABTS assay, which assesses both hydrophilic and lipophilic antioxidant activities, revealed that genotypes such as G-50, Bhima Omkar, G-323 and Ooty Local had

Table 3 Mean $\pm$ SD of antioxidant parameters in 25 garlic genotypes over two years

Genotype	Clove colour	TF (mg/g QE fw)	TP (mg/g GAE fw)	FRAP (μ mol/g TE fw)	DPPH (μ mol/g TE fw)	ABTS (μ mol/g TE fw)
Bhima Omkar	White	1.18 $\pm$ 0.00	5.01 $\pm$ 0.06	0.37 $\pm$ 0.02	0.41 $\pm$ 0.01	1.21 $\pm$ 0.02
Bhima Purple	Purple	1.25 $\pm$ 0.05	4.21 $\pm$ 0.00	0.37 $\pm$ 0.01	0.30 $\pm$ 0.01	1.01 $\pm$ 0.05
G-1	White	1.35 $\pm$ 0.02	4.51 $\pm$ 0.06	0.38 $\pm$ 0.00	0.30 $\pm$ 0.01	1.10 $\pm$ 0.04
G-41	White	1.80 $\pm$ 0.01	5.02 $\pm$ 0.17	0.24 $\pm$ 0.00	0.34 $\pm$ 0.01	0.65 $\pm$ 0.01
G-50	White	1.35 $\pm$ 0.05	6.34 $\pm$ 0.19	0.32 $\pm$ 0.00	0.29 $\pm$ 0.01	1.30 $\pm$ 0.02
G-282	White	1.20 $\pm$ 0.00	4.34 $\pm$ 0.07	0.39 $\pm$ 0.01	0.33 $\pm$ 0.01	1.09 $\pm$ 0.00
G-323	White	1.70 $\pm$ 0.02	4.83 $\pm$ 0.16	0.39 $\pm$ 0.02	0.36 $\pm$ 0.01	1.20 $\pm$ 0.00
G-384	White	1.52 $\pm$ 0.01	4.70 $\pm$ 0.21	0.46 $\pm$ 0.00	0.32 $\pm$ 0.00	0.77 $\pm$ 0.01
G-386	Purple	0.97 $\pm$ 0.05	4.61 $\pm$ 0.17	0.45 $\pm$ 0.00	0.30 $\pm$ 0.01	0.58 $\pm$ 0.00
GG-2	White	1.75 $\pm$ 0.02	4.69 $\pm$ 0.11	0.47 $\pm$ 0.02	0.34 $\pm$ 0.00	0.97 $\pm$ 0.01
GG-3	White	1.21 $\pm$ 0.04	5.05 $\pm$ 0.06	0.53 $\pm$ 0.00	0.37 $\pm$ 0.01	0.90 $\pm$ 0.02
GG-4	White	0.94 $\pm$ 0.00	4.89 $\pm$ 0.02	0.36 $\pm$ 0.00	0.31 $\pm$ 0.01	0.95 $\pm$ 0.02
GAG-6	Pink	1.49 $\pm$ 0.04	4.70 $\pm$ 0.17	0.47 $\pm$ 0.01	0.35 $\pm$ 0.01	0.76 $\pm$ 0.04
GAG-7	Purple	1.16 $\pm$ 0.01	4.46 $\pm$ 0.04	0.44 $\pm$ 0.00	0.35 $\pm$ 0.00	0.77 $\pm$ 0.03
PG-17	White	0.60 $\pm$ 0.01	4.65 $\pm$ 0.12	0.45 $\pm$ 0.00	0.35 $\pm$ 0.01	0.97 $\pm$ 0.04
PG-18	White	1.54 $\pm$ 0.04	4.54 $\pm$ 0.16	0.51 $\pm$ 0.02	0.37 $\pm$ 0.01	0.99 $\pm$ 0.01
Godawari	Purple	1.04 $\pm$ 0.02	4.64 $\pm$ 0.10	0.53 $\pm$ 0.01	0.35 $\pm$ 0.00	0.75 $\pm$ 0.02
Phule Baswant	Purple	1.02 $\pm$ 0.02	4.78 $\pm$ 0.02	0.46 $\pm$ 0.01	0.36 $\pm$ 0.02	0.80 $\pm$ 0.02
Ooty Local	White	1.20 $\pm$ 0.03	4.85 $\pm$ 0.20	0.53 $\pm$ 0.02	0.40 $\pm$ 0.02	1.17 $\pm$ 0.03
Rani B. Local	Purple	0.46 $\pm$ 0.02	4.31 $\pm$ 0.03	0.55 $\pm$ 0.02	0.37 $\pm$ 0.01	0.87 $\pm$ 0.04
Sikkim Local	White	1.22 $\pm$ 0.03	4.68 $\pm$ 0.14	0.52 $\pm$ 0.00	0.38 $\pm$ 0.01	0.91 $\pm$ 0.02
Silkuei Local	Purple	0.95 $\pm$ 0.02	5.12 $\pm$ 0.00	0.38 $\pm$ 0.01	0.39 $\pm$ 0.01	0.92 $\pm$ 0.00
Navapur Local	Pink	1.03 $\pm$ 0.01	5.13 $\pm$ 0.09	0.47 $\pm$ 0.02	0.38 $\pm$ 0.01	1.10 $\pm$ 0.01
VNS Local-1	Purple	1.11 $\pm$ 0.04	5.61 $\pm$ 0.17	0.56 $\pm$ 0.02	0.37 $\pm$ 0.00	1.09 $\pm$ 0.05
VNS Local-2	Purple	0.74 $\pm$ 0.02	5.36 $\pm$ 0.22	0.43 $\pm$ 0.01	0.40 $\pm$ 0.02	1.13 $\pm$ 0.05
Mean	-	1.19	4.84	0.44	0.35	0.96
CV (%)	-	20.62	2.96	6.83	3.40	9.53

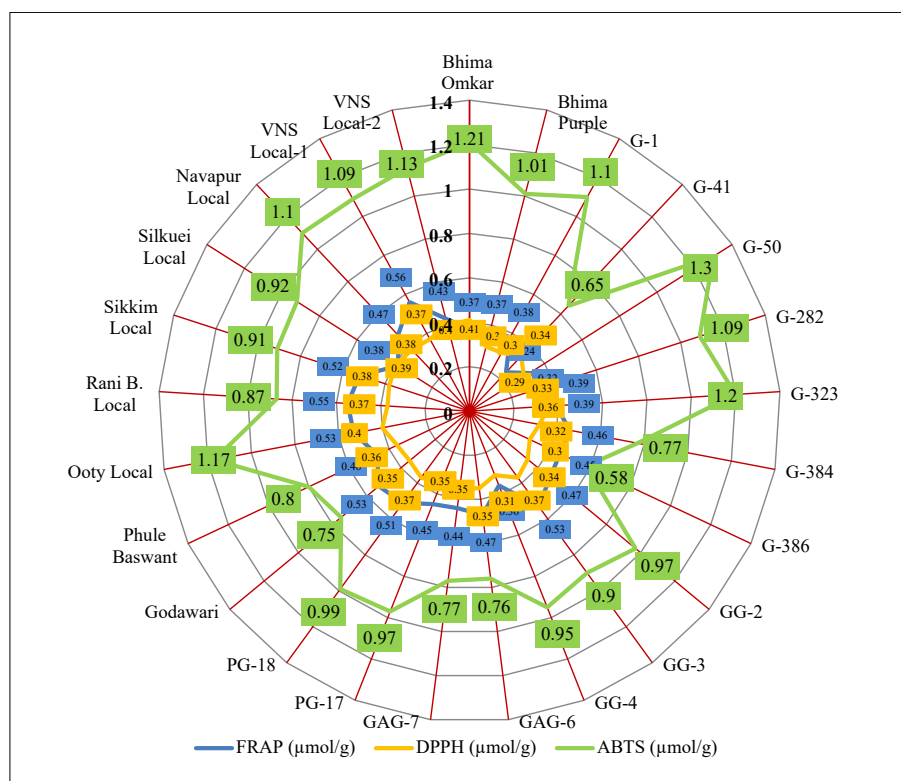


Fig. 3 Antioxidant activity estimated through FRAP, ABTS and DPPH in 25 genotypes of garlic

the highest values ($> 1.2 \mu\text{mol/g TE fw}$), highlighting their potential to neutralize free radicals in diverse biological environments. This is particularly relevant given that garlic extracts with high antioxidant capacity have been shown to prevent lipid peroxidation, thereby reducing oxidative stress in diabetic patients [68]. Bhima Omkar stood out across all assays, especially in ABTS ($1.21 \mu\text{mol/g TE fw}$) and DPPH ($0.41 \mu\text{mol/g TE fw}$), indicating broad-spectrum antioxidant activity. G-50 recorded the highest ABTS value ($1.30 \mu\text{mol/g TE fw}$), though its FRAP and DPPH values were moderate. This selective high ABTS activity could reflect the presence of compounds active in aqueous-organic systems. VNS Local-1 exhibited high FRAP ($0.56 \mu\text{mol/g TE fw}$) and ABTS ($1.09 \mu\text{mol/g TE fw}$), showing excellent reducing power and radical scavenging potential. G-41 exhibited the lowest FRAPS ($0.24 \mu\text{mol/g TE fw}$) and relatively low DPPH and ABTS values despite having the highest total flavonoid content (1.80 mg/g QE fw). This suggests that all flavonoids may not contribute equally to antioxidant activity [69]. G-386 and GG-4 showed the lowest ABTS values, indicating limited scavenging ability in mixed solvent systems. Though FRAP and ABTS trends were somewhat aligned for many genotypes, DPPH values remained relatively stable across most entries. This may imply that the garlic antioxidants are more efficient in electron transfer (FRAP) and radical neutralization in aqueous-organic environments (ABTS) than in hydrogen atom donation (DPPH) [67, 70,71].

3.5 Effect of clove colour on biochemical composition of garlic

We also analyzed the influence of clove colour on the biochemical composition of garlic. While many studies have reported comparative biochemical differences between

black and white garlic, there are few or no studies examining such variations among purple, pink and white clove garlands (Fig. 4) [49, 72–74]. Such influences of skin colour on bioactive compositions are well documented in onion [75–77]. Significant differences ($p < 0.05$) were observed among clove colour groups for all traits except total sugars (Table 4). Significant differences were observed in the partitioning between reducing (RS) and non-reducing sugars (NRS). Purple garlic exhibited the highest RS content (10.42 mg/g), while white garlic recorded the highest NRS (46.41 mg/g fw), suggesting that coloured garlic types accumulate more simple sugars. In contrast Yuan et al. [78] reported highest RS in white and reduced in black colour garlic. Similar patterns of carbohydrate partitioning have been reported by Petropoulos et al. [48], indicating genotypic and pigment-related variation in garlic sugar profiles. White garlic also exhibited significantly higher levels of total flavonoids (TF, 1.33 mg/g QE fw) and total phenols (TP, 4.86 mg/g GAE fw), aligning with its superior ABTS antioxidant activity (1.01 $\mu\text{mol/g TE fw}$). This suggests a strong contribution of hydrophilic phenolic compounds to the radical scavenging ability in white genotypes. In contrast, purple and pink garlic despite having lower phenolic content demonstrated higher levels of pyruvic acid (39.94 and 40.37 $\mu\text{mol PA/g fw}$, respectively) and allicin (2.78 and 2.85 mg/g fw, respectively), compounds closely linked to pungency and sulfur-based antioxidant mechanisms. These findings support earlier work by Miron et al. [40] and Bagiu et al. [79], which highlighted that sulfur-containing compounds like allicin are key contributors to garlic's bioactivity and are often more abundant in pigmented cloves due to enhanced alliinase activity.

While, the influence of genotypes, temperature, storage conditions and black garlic processing on antioxidant potential has been widely documented, limited studies have explored the effect of naturally occurring clove colour variation in garlic [80–82]. Our study provides new insights into this understudied aspect, revealing that clove colour significantly influences antioxidant activity as determined by FRAP, ABTS and DPPH assays. A notable variation among white, purple and pink cloved garlands was observed. Purple garlic showed the highest FRAP (0.47 $\mu\text{mol/g TE fw}$), indicating superior ferric reducing antioxidant power compared to white (0.42 $\mu\text{mol/g TE fw}$), although differences between pink and purple were marginal. Similarly, DPPH radical scavenging potential was comparable among the three groups, with a slight edge in pink (0.36 $\mu\text{mol/g TE fw}$) and purple (0.36 $\mu\text{mol/g TE fw}$) cloves, both significantly higher than white (0.35 $\mu\text{mol/g TE fw}$). In contrast, ABTS scavenging activity was highest in white garlic (1.01 $\mu\text{mol/g TE fw}$), followed by purple (0.93 $\mu\text{mol/g TE fw}$) and pink (0.90 $\mu\text{mol/g TE fw}$), with a significant ($p < 0.05$) reduction in pink cloves.



Fig. 4 Clove colour variability observed in the garlic genotypes

Table 4 Effect of clove colour on biochemical composition of garlic

Clove colour	TS	RS	NRS	TF	TP	PA	Allicin	FRAP	ABTS	DPPH	TSS	MC
White	242.59	9.17 ^b	46.41 ^a	1.33 ^a	4.86 ^a	34.33 ^c	2.42 ^c	0.42 ^b	1.01 ^a	0.35 ^b	32.10 ^a	63.13 ^b
Purple	230.75	10.42 ^a	20.88 ^b	1.04 ^b	4.76 ^b	39.94 ^b	2.78 ^b	0.47 ^a	0.93 ^b	0.36 ^a	30.67 ^b	64.24 ^a
Pink	235.80	9.95 ^{ab}	17.35 ^c	1.06 ^b	4.80 ^{ab}	40.37 ^a	2.85 ^a	0.46 ^a	0.90 ^b	0.36 ^a	30.42 ^b	64.84 ^a
CV (%)	3.42	2.74	0.42	2.85	0.48	0.36	0.29	1.32	2.64	0.85	0.54	0.33
Sign	NS	*	*	*	*	*	*	*	*	*	*	*

The numbers following same letters are not significantly different at a 5% level Tukey/HSD test. NS Not significant; * Significant at a 5%, TS: Total sugars, RS: Reducing sugars, NRS: Non-reducing sugars, TP: Total phenols, TF: Total Flavonoids, PA: Pyruvic acid, TSS: Total soluble solids, MC: Moisture content

TSS an indicator of sugar content, also varied significantly. White garlic recorded the highest TSS (32.10%), followed by purple (30.67%) and pink (30.42%). The lower TSS in pink garlic could relate to its lower carbohydrate biosynthesis or dilution effect due to higher moisture content. Such inverse relationships between TSS and moisture have been reported in garlic and other *Allium* species [83–85]. In contrast, moisture content (MC) was highest in pink cloves (64.84%), whereas white had the lowest (63.13%), suggesting possible genotype-related variation in bulb water retention capacity.

3.6 Correlation among the biochemical components

The correlation analysis (Fig. 5) revealed key relationships among biochemical traits in garlic. Total sugars (TS) showed a strong negative correlation with reducing sugars (RS) and a positive correlation with non-reducing sugars (NRS), indicating compositional shifts between sugar forms. Such type of correlation was also reported by Atashi et al. [86]. Allicin correlated positively with pyruvic acid (PA), supporting their biosynthetic link, but negatively with TSS. Antioxidant activities, particularly FRAP, were positively associated with PA, while DPPH and ABTS showed moderate correlations with total flavonoids (TF). In this study, total phenols (TP) showed no correlation with FRAP and DPPH and only a slight positive correlation with ABTS. In contrast, Akan [87] reported a significant positive correlation between TP and antioxidant activities. Moisture content (MC) was inversely related to TSS and NRS. The correlation values reported in this study are slightly higher than Pasupula et al. [88] and lower than reported by Locatelli et al. [89].

3.7 PCA with K-means clustering

The PCA coupled with K-means clustering provides a robust approach to visualize and interpret the inherent diversity among garlic genotypes. PC1 and PC2 explain 17% and 15.4% of the total variance, respectively, cumulatively capturing a meaningful portion of the variability among genotypes (Fig. 6). K-means clustering effectively grouped the genotypes into three distinct clusters; however, some overlap among clusters was observed. Cluster 1 includes genotypes such as G1 (Bhima Omkar), G5 (G-50), G6 (G-282), G8 (G-384), G13 (GAG-6), G20 (Rani Benneur Local), G22 (Silkuei Local) and G23 (Navapur Local). These genotypes exhibit intermediate to high scores along PC1 and moderate

	TS	RS	NRS	PA	Allicin	TSS	MC	TF	TP	FRAP	DPPH	ABTS
TS	1	-0.7	0.29	-0.17	0.16	-0.1	0.1	0.17	0.01	-0.27	-0.24	-0.08
RS	-0.7	1	-0.18	0.25	0.01	0.16	-0.12	-0.3	-0.14	0.06	-0.11	-0.24
NRS	0.29	-0.18	1	-0.36	-0.36	0.49	-0.34	0.61	-0.01	-0.2	-0.53	0.13
PA	-0.17	0.25	-0.36	1	0.41	0.15	0.06	-0.33	-0.18	0.59	0.34	-0.3
Allicin	0.16	0.01	-0.36	0.41	1	-0.31	0.22	-0.16	-0.08	0	0.26	0.02
TSS	-0.1	0.16	0.49	0.15	-0.31	1	-0.73	0.27	-0.07	0.1	-0.12	-0.22
MC	0.1	-0.12	-0.34	0.06	0.22	-0.73	1	-0.36	0.31	-0.04	0.21	0.39
TF	0.17	-0.3	0.61	-0.33	-0.16	0.27	-0.36	1	0.04	-0.32	-0.23	0.01
TP	0.01	-0.14	-0.01	-0.18	-0.08	-0.07	0.31	0.04	1	-0.2	0.1	0.43
FRAP	-0.27	0.06	-0.2	0.59	0	0.1	-0.04	-0.32	-0.2	1	0.41	-0.11
DPPH	-0.24	-0.11	-0.53	0.34	0.26	-0.12	0.21	-0.23	0.1	0.41	1	0.21
ABTS	-0.08	-0.24	0.13	-0.3	0.02	-0.22	0.39	0.01	0.43	-0.11	0.21	1

Fig. 5 Pearson correlation between biochemical components of garlic. The color gradient represents correlation coefficients, where blue and red indicate positive and negative correlations, respectively and color intensity reflects the strength of the relationship

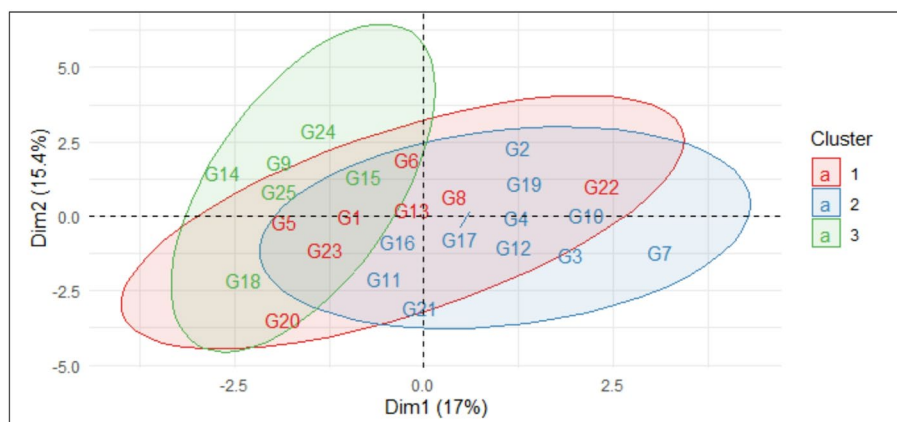


Fig. 6 PCA biplot of garlic genotypes based on biochemical traits with K-means clustering. The first two principal components (PC1 and PC2) explain 17% and 15.4% of the total variance, respectively. Different colors represent distinct clusters identified through K-means clustering

variability on PC2, suggesting balanced expression of the measured biochemical traits. Cluster 2 includes G2 (Bhima Purple), G3 (G-1), G4 (G-41), G7 (G-323), G10 (GG-2), G11 (GG-3), G12 (GG-4), G16 (PG-18), G17 (Godawari), G19 (Ooty Local) and G21 (Sikkim Local). These genotypes show high positive scores along PC1 and negative to neutral PC2, indicating close association and relatively similar biochemical profiles. Cluster 3 comprises G9 (G-386), G14 (GAG-7), G15 (PG-17), G18 (Phule Baswant), G24 (VNS Local-1) and G25 (VNS Local-2). This cluster lies predominantly on the negative side of PC1 and positive PC2, reflecting greater dispersion and variability among genotypes. The observed clustering pattern suggests that the diversity among garlic genotypes is governed by the combined influence of multiple biochemical traits. Similar variability in antioxidant and biochemical characteristics among garlic genotypes has been reported in earlier studies [90–92], supporting the present findings.

4 Conclusion

This study reveals substantial biochemical diversity among 25 Indian garlic genotypes grown under short-day conditions, encompassing wide variation in sugars (total, reducing and non-reducing), pungency (pyruvic acid and allicin), TSS, moisture content and antioxidant activity evaluated through FRAP, DPPH and ABTS assays. Although studies examining the biochemical implications of clove colour in garlic are limited, the current work clearly establishes that clove colour significantly influences most biochemical traits ($p < 0.05$), with the exception of total sugar content. Purple-cloved genotypes were characterized by higher reducing sugar concentrations, whereas white-cloved types exhibited greater accumulation of non-reducing sugars, phenolics, flavonoids and ABTS antioxidant activity. In contrast, purple and pink genotypes showed elevated levels of pyruvic acid and allicin, linking these clove colours to enhanced pungency and sulphur-mediated bioactivity. Correlation analysis revealed strong interdependence among sugar fractions, with total sugars shifting between reducing and non-reducing fractions. A close association between pyruvic acid and allicin further confirmed their coordinated role in determining pungency. Moreover, antioxidant activity was more strongly associated with sulphur compounds and flavonoids than with total phenolic content, underscoring the distinct metabolic contributors to garlic's functional properties. Multivariate

analysis (PCA and k-means clustering) further grouped the genotypes into three functional clusters, enabling the identification of genotypes with distinct biochemical and nutraceutical potential. Collectively, the results clarify how clove colour associated metabolic differentiation shapes biochemical composition in garlic and offer practical guidance for genotype selection in breeding and value-added food applications emphasizing pungency, functional quality and nutraceutical potential.

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Author contributions

Authors [Amar Jeet Gupta] and [Major Singh] contributed to the study conception and design. Material preparation and data collection were performed by [Amar Jeet Gupta]. The manuscript was prepared by [Amar Jeet Gupta], [Ashok Kumar], [Kalyani Gorrepati] and [Ashwini P. Benke]. Analysis of data and interpretation was performed by [Amar Jeet Gupta] and [Hina Chauhan]. Authors [Hina Chauhan] and [Kavya V. Aribenchi] performed the literature search and prepared the draft. Final revision and manuscript finalization were performed by [Amar Jeet Gupta], [Kalyani Gorrepati] and [Vijay Mahajan]. All authors reviewed, read, and approved the final manuscript.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the manuscript.

Declarations

Ethics approval and consent to participate

The study did not involve human participants or animals. All procedures involving plant materials were conducted in accordance with institutional and national guidelines governing plant research. Consent to participate is not applicable.

Plant guidelines and permissions to collect the plants

Plant material used in the present study comprised 25 cultivated garlic genotypes maintained at the ICAR-Directorate of Onion and Garlic Research (ICAR-DOGR), Rajgurunagar, Pune. ICAR-DOGR functions as the nodal agency under the Indian Council of Agricultural Research (ICAR), Government of India, for research and development of onion and garlic crops. The above genotypes were maintained under the Distinctness, Uniformity and Stability (DUS) project entitled "DUS testing of onion and garlic", funded by the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA), New Delhi, with ICAR-DOGR serving as the main centre at the national level. The garlic genotypes included in this study were collected from different regions of India, representing public sector breeding programs and diverse landraces. The collection, conservation and utilization of the plant material were carried out in accordance with institutional and national guidelines governing plant genetic resources. ICAR-DOGR also functions as a nodal centre for varietal protection of onion and garlic under the mandate of the PPV&FRA through ICAR. As the plant materials were part of an institutional research program, no additional permits or licenses were required.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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References

1. Shamseer L, Charrois TL, Vohra S. Complementary, holistic and integrative medicine: garlic. *Pediatr Rev*. 2006;27(12):e77–80. <https://doi.org/10.1542/pir.27-12-e77>.
2. Joshi VK, Joshi A. Garlic in traditional Indian medicine (Ayurveda) for health and healing. In: Ahmad RS, editor. *Herbs and spices: new processing technologies*. Springer; 2021. pp. 185–95.
3. Petrovska BB, Cekovska S. Extracts from the history and medical properties of garlic. *Pharmacogn Rev*. 2010;4(7):106. <https://doi.org/10.4103/0973-7847.65321>.
4. Patil N, Chawla P, Bains A. Onion and garlic: processing and culinary uses. In: Morya S, Bhasin A, editors. *Recent advances in spices, herbs and plantation crops*. Springer; 2023. pp. 463–92.
5. Block E, Cody RB, Dane AJ, Sheridan R, Vattekkatte A, Wang K. *Allium* chemistry: use of new instrumental techniques to see reactive organosulfur species formed upon crushing garlic and onion. *Pure Appl Chem*. 2010;82(3):535–9. <https://doi.org/10.1351/PAC-CON-09-08-12>.

6. Chandrashekara PM, Venkatesh YP. Immunostimulatory properties of fructans derived from raw garlic (*Allium sativum* L). *Bioact Carbohydr Diet Fibre*. 2016;8(2):65–70. <https://doi.org/10.1016/j.bcdf.2016.11.003>.
7. Lanzotti V, Scala F, Bonanomi G. Compounds from *Allium* species with cytotoxic and antimicrobial activity. *Phytochem Rev*. 2014;13(4):769–91. <https://doi.org/10.1007/s11101-014-9366-0>.
8. FAOSTAT. Production data of garlic. Food and Agriculture Organization of the United Nations. 2023. <https://www.fao.org/faostat/en/#data/QCL>. Accessed 21 July 2025.
9. Oosthuizen C, Arbach M, Meyer D, Hamilton C, Lall N. Diallyl polysulfides from *Allium sativum* as immunomodulators, hepatoprotectors and antimycobacterial agents. *J Med Food*. 2017;20(7):685–90. <https://doi.org/10.1089/jmf.2016.0137>.
10. Zhang Y, Liu X, Ruan J, Zhuang X, Zhang X, Li Z. Phytochemicals of garlic: promising genotypes for cancer therapy. *Biomed Pharmacother*. 2020;123:109730. <https://doi.org/10.1016/j.biopha.2019.109730>.
11. Gupta AJ, Mainkar P, Mahajan V. Exploring the nutritional-nutraceutical composition and phytochemical potential of garlic agents in preclinical and clinical studies with a focus on drug likeness. *J Herb Med*. 2024;46:100911. <https://doi.org/10.1016/j.hermed.2024.100911>.
12. Ceccanti C, Rocchetti G, Lucini L, Giuberti G, Landi M, Biagiotti S, Guidi L. Comparative phytochemical profile of elephant garlic (*Allium ampeloprasum* var. *holmense*) and common garlic (*Allium sativum*) from the Val di Chiana area (Tuscany, Italy) before and after in vitro gastrointestinal digestion. *Food Chem*. 2021;338:128011. <https://doi.org/10.1016/j.foodchem.2020.128011>.
13. Puvača N. Bioactive compounds in dietary spices and medicinal plants. *J Agron Technol Eng Manag*. 2022;5:704–11. <https://doi.org/10.55817/UHFO5592>.
14. Yamaguchi Y, Kumagai H. Characteristics, biosynthesis, decomposition, metabolism and functions of the garlic odour precursor, S-allyl-L-cysteine sulfoxide. *Exp Ther Med*. 2020;19(2):1528–35. <https://doi.org/10.3892/etm.2019.8385>.
15. DeCagna D. Inhibiting enzymatic formation of blue-green pigments in garlic cloves. MSc dissertation, Kansas State University, Manhattan, 2023.
16. Prati P, Henrique CM, Souza ASD, Silva VSnd, Pacheco MTB. Evaluation of allicin stability in processed garlic of different cultivars. *Food Sci Technol*. 2014;34:623–8. <https://doi.org/10.1590/1678-457x.6397>.
17. Borlinghaus J, Foerster J, Kappler U, Antelmann H, Noll U, Gruhke MC, Slusarenko AJ. Allicin, the odor of freshly crushed garlic: a review of recent progress in understanding allicin's effects on cells. *Molecules*. 2021;26:1505. <https://doi.org/10.3390/molecules26061505>.
18. El-Saber Batiha G, Beshbishy AM, Wasef G, Elewa YH, Al-Sagan A, Abd El-Hack ME, Taha AE, Abd-Elhakim YM, Devkota HP. Chemical constituents and pharmacological activities of garlic (*Allium sativum* L.): a review. *Nutrients*. 2020;12:872. <https://doi.org/10.3390/nu12030872>.
19. Sarvzadeh M, Hasanpour O, Naderi Ghale-Noie Z, Mollazadeh S, Rezaei M, Pourghadamyari H, Khooy MM, Aschner M, Khan H, Rezaei N, Shojale L. Allicin and digestive system cancers: from chemical structure to its therapeutic opportunities. *Front Oncol*. 2021;11:650256. <https://doi.org/10.3389/fonc.2021.650256>.
20. Iciek M, Kwiecień I, Włodek L. Biological properties of garlic and garlic-derived organosulfur compounds. *Environ Mol Mutagen*. 2009;50:247–65. <https://doi.org/10.1002/em.20474>.
21. Ray B, Chauhan NB, Lahiri DK. The aged garlic extract (AGE) and one of its active ingredients S-allyl-L-cysteine (SAC) as potential preventive and therapeutic agents for Alzheimer's disease (AD). *Curr Med Chem*. 2011;18:3306–13. <https://doi.org/10.2174/092986711796504664>.
22. Koda Y, Kurita M, Nakamoto M, Matsutomo T. Chemistry of aged garlic: diversity of constituents in aged garlic extract and their production mechanisms via the combination of chemical and enzymatic reactions. *Exp Ther Med*. 2020;19:1574–84. <https://doi.org/10.3892/etm.2019.8393>.
23. Rais N, Ved A, Ahmad R, Kumar M, Barbhai MD, Chandran D, Dey A, Dhupal S, Senapathy M, Deshmukh VP, Anitha T. S-allyl-L-cysteine-a garlic bioactive: physicochemical nature, mechanism, pharmacokinetics and health-promoting activities. *J Funct Foods*. 2023;107:105657. <https://doi.org/10.1016/j.jff.2023.105657>.
24. Ritola M, Casciani L, Han BZ, Cozzolino S, Leita L, Sequi P, et al. Traceability of Italian garlic (*Allium sativum* L.) by means of HRMAS-NMR spectroscopy and multivariate data analysis. *Food Chem*. 2012;135. <https://doi.org/10.1016/j.foodchem.2012.05.032>.
25. Vargas VCS, González RE, Sance MM, Burba JL, Camargo AB. Efecto de la interacción genotipo-ambiente sobre la expresión del contenido de alicina y ácido pirúvico en ajo (*Allium sativum* L). *Rev Fac Cs Agrarias*. 2010;42: 15–22.
26. Lee JY, Gao Y. Review of the application of garlic (*Allium sativum*) in aquaculture. *J World Aquac Soc*. 2012;43:447–58. <https://doi.org/10.1111/j.1749-7345.2012.00581.x>.
27. Guan MJ, Zhao N, Xie KQ, Zeng T. Hepatoprotective effects of garlic against ethanol-induced liver injury: a mini-review. *Food Chem Toxicol*. 2018;111:467–73. <https://doi.org/10.1016/j.fct.2017.11.059>.
28. Rahman MS. Allicin and other functional active components in garlic: health benefits and bioavailability. *Int J Food Prop*. 2007;10:245–68. <https://doi.org/10.1080/10942910601113327>.
29. Huang CH, Hsu FY, Wu YH, Zhong L, Tseng MY, Kuo CJ, et al. Analysis of lifespan-promoting effect of garlic extract by an integrated metabolite-proteomics approach. *J Nutr Biochem*. 2015;26:808–17. <https://doi.org/10.1016/j.jnutbio.2015.02.010>.
30. Bradley RL. Moisture and total solids analysis. Moisture and total solids analysis. Boston, MA: Springer; 2010. pp. 85–104. https://doi.org/10.1007/978-1-4419-1478-1_6.
31. AOAC. Official Methods of Analysis of AOAC International. 21st ed. Gaithersburg, MD, USA: AOAC International; 2019.
32. Padhi SK, Sahoo A, Panda D. Nutritional and nutraceutical variability in neglected Niger (*Guizotia abyssinica* (L.f.) Cass.) accessions from Eastern Ghats of India. *Oil Crop Sci*. 2023;8(3):174–83. <https://doi.org/10.1016/j.ocsci.2023.09.001>.
33. Yemm EW, Willis A. The estimation of carbohydrates in plant extracts by anthrone. *Biochem J*. 1954;57:508.
34. Miller GL. Use of dinitrosalicylic acid reagent for determination of reducing sugar. *Anal Chem*. 1959;31:426–8. <https://doi.org/10.1021/ac60147a030>.
35. Singleton VL, Orthofer R, Lamuela-Raventós RM. Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin-Ciocalteu reagent. *Methods Enzymol*. 1999;299:152–78. [https://doi.org/10.1016/S0076-6879\(99\)99017-1](https://doi.org/10.1016/S0076-6879(99)99017-1).
36. Zhishen J, Mengcheng T, Jianming W. The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chem*. 1999;64(4):555–9. [https://doi.org/10.1016/S0308-8146\(98\)00102-2](https://doi.org/10.1016/S0308-8146(98)00102-2).

37. Anthon GE, Barrett DM. Modified method for the determination of pyruvic acid with dinitrophenylhydrazine in the assessment of onion pungency. *J Sci Food Agric*. 2003;83:1210–3. <https://doi.org/10.1002/jsfa.1525>.
38. Beretta VH, Bannoud F, Insani M, Galmarini CR, Cavagnaro PF. Variability in spectrophotometric pyruvate analyses for predicting onion pungency and nutraceutical value. *Food Chem*. 2017;224:201–6. <https://doi.org/10.1016/j.foodchem.2016.12.031>.
39. Han J, Lawson L, Han G, Han P. Spectrophotometric method for quantitative determination of allicin and total garlic thiosulfonates. *Anal Biochem*. 1995;225:157–60. <https://doi.org/10.1006/abio.1995.1124>.
40. Miron T, Shin I, Feigenblat G, Weiner L, Mirelman D, Wilchek M, et al. A spectrophotometric assay for allicin, alliin and alliinase (alliin lyase) with a chromogenic thiol: reaction of 4-mercaptopyridine with thiosulfonates. *Anal Biochem*. 2002;307:76–83. [https://doi.org/10.1016/S0003-2697\(02\)00010-6](https://doi.org/10.1016/S0003-2697(02)00010-6).
41. Mansor N, Hereng HJ, Samsudin SJ, Sufian S, Uemura Y. Quantification and characterization of allicin in garlic extract. *J Med Bioeng*. 2016;5:24–7. <https://doi.org/10.12720/jomb.5.1.24-27>.
42. Benzie IF, Strain JJ. The ferric reducing ability of plasma (FRAP) as a measure of antioxidant power: the FRAP assay. *Anal Biochem*. 1996;239:70–6. <https://doi.org/10.1006/abio.1996.0292>.
43. Re R, Pellegrini N, Proteggente A, Pannala A, Yang M, Rice-Evans C. Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free Radic Biol Med*. 1999;26:1231–7. [https://doi.org/10.1016/S0891-5849\(98\)00315-3](https://doi.org/10.1016/S0891-5849(98)00315-3).
44. Shahinuzzaman M, Yaakob Z, Anuar FH, Akhtar P, Kadir NHA, Hasan AKM, et al. In vitro antioxidant activity of *Ficus carica* L. latex from 18 different cultivars. *Sci Rep*. 2020;10:1–14. <https://doi.org/10.1038/s41598-020-67765-1>.
45. Shimamura T, Sumikura Y, Yamazaki T, Tada A, Kashiwagi T, Ishikawa H, et al. Applicability of the DPPH assay for evaluating the antioxidant capacity of food additives: inter-laboratory evaluation study. *Anal Sci*. 2014;30:717–21. <https://doi.org/10.116/anal30.717>.
46. Xiao F, Xu T, Lu B, Liu R. Guidelines for antioxidant assays for food components. *Food Front*. 2020;1:60–9. <https://doi.org/10.1002/fft2.10>.
47. Avgeri I, Zeliou K, Petropoulos SA, Bebeli PJ, Papatotopoulos V, Lamari FN. Variability in bulb organosulfur compounds, sugars, phenolics and pyruvate among Greek garlic genotypes: association with antioxidant properties. *Antioxidants*. 2020;9(10):967. <https://doi.org/10.3390/antiox9100967>.
48. Petropoulos SA, Fernandes A, Ntatsi G, Petrotos K, Barros L, Ferreira IC. Nutritional value, chemical characterization and bulb morphology of Greek garlic landraces. *Molecules*. 2018;23:319. <https://doi.org/10.3390/molecules23020319>.
49. Najman K, Sadowska A, Hallmann E. Evaluation of bioactive and physicochemical properties of white and black garlic (*Allium sativum* L.) from conventional and organic cultivation. *Appl Sci*. 2021;11:874. <https://doi.org/10.3390/app11020874>.
50. Plata-Guerrero R, Guerra-Hernandez E, Garcia-Villanova B. Determination of reducing sugar and asparagine in potatoes. *J Liq Chromatogr Relat Technol*. 2009;32:2556–68. <https://doi.org/10.1080/10826070903249732>.
51. Aoudeh E, Oz E, Kelebek H, Brennan C, Ahmad N, Elbeid T, Oz F. Black garlic production: the influence of ageing temperature and duration on some physicochemical and antioxidant properties and sugar content. *Int J Food Sci Technol*. 2023;58:3580–90. <https://doi.org/10.1111/ijfs.16456>.
52. Mashayekhi K, Mohammadi Chiane S, Mianabadi M, Ghaderifar F, Mousavizadeh SJ. Change in carbohydrate and enzymes from harvest to sprouting in garlic. *Food Sci Nutr*. 2016;4:370–6. <https://doi.org/10.1002/fsn3.299>.
53. Guevara-Figueroa T, López-Hernández L, López MG, Hurtado MD, et al. Conditioning garlic seed cloves at low temperature modifies plant growth, sugar and fructan content and sucrose fructosyl transferase (1-SST) expression. *Sci Hortic*. 2015;189:150–8. <https://doi.org/10.1016/j.scienta.2015.03.030>.
54. Kim MR, Yun JH, Sok DE. Correlation between pungency and allicin content of pickled garlic during aging. *J Korean Soc Food Sci Nutr*. 1994;23(5):805–10.
55. Abedi M, Biat F, Nosrati AE. Evaluation of agronomical traits and pyruvic acid content in Hamedan garlic (*Allium sativum* L.) ecotypes. *Eur J Exp Biol*. 2013;3:541–4.
56. Tripathi PC, Jadhav HM, Qureshi AA, Sankar V, Mahajan V, Lawande KE. Morphological and biochemical properties of garlic (*Allium sativum* L.) collections: characterization of garlic collections. *J Spices Aromat Crops*. 2021;30(1):81–9. <https://doi.org/10.25081/josac.2021.v30i1.6571>.
57. Natale PJ, Camargo A, Galmarini CR. Characterization of Argentine garlic cultivars by their pungency. IV Inter Sympo Edi Alliaceae. 2004;688:313–6. <https://doi.org/10.17660/ActaHortic.2005.688.45>.
58. Cavallito CJ, Bailey JH, Buck JS. The antibacterial principle of *Allium sativum*. III. Its precursor and essential oil of garlic. *J Am Chem Soc*. 1945;67:1032–3. <https://doi.org/10.1021/ja01222a501>.
59. Borlinghaus J, Albrecht F, Gruhlke MC, Nwachukwu ID, Slusarenko AJ. Allicin: chemistry and biological properties. *Molecules*. 2014;19:12591–618. <https://doi.org/10.3390/molecules190812591>.
60. Wills ED. Enzyme inhibition by allicin, the active principle of garlic. *Biochem J*. 1956;63:514. <https://doi.org/10.1042/bj0630514>.
61. Janská P, Knejzlík Z, Perumal AS, Jurok R, Tokárová V, Nicolau DV, Štěpánek F, Kašpar O. Effect of physicochemical parameters on the stability and activity of garlic alliinase and its use for in situ allicin synthesis. *PLoS ONE*. 2021;16:e0248878. <https://doi.org/10.1371/journal.pone.0248878>.
62. Desta B, Woldetsadik K, Ali WM. Effect of harvesting time, curing and storage methods on storability of garlic bulbs. *Open Biotechnol J*. 2021;15:36–45. <https://doi.org/10.2174/1874070702115010036>.
63. Kar S, Sutar PP. Shelf-life prediction of dried garlic powder under accelerated storage conditions. *J Food Sci Technol*. 2023;60:996–1005. <https://doi.org/10.1007/s13197-022-05431-2>.
64. Amagase H. Clarifying the real bioactive constituents of garlic. *J Nutr*. 2006;136(3):716. <https://doi.org/10.1093/jn/136.3.716>.
65. Corzo-Martínez M, Corzo N, Villamiel M. Biological properties of onions and garlic. *Trends Food Sci Technol*. 2007;18(12):609–25. <https://doi.org/10.1016/j.tifs.2007.07.011>.
66. Gupta AJ, Aribenchi KV, Volaguthala S, Sanjay DP, Mahajan V. Biochemical properties of garlic (*Allium sativum* L.) and their impact on human health. *Food Sci Rep*. 2026;7(1):18–24.
67. Furdak P, Pierkowska N, Kapusta I, Bartosz G, Sadowska-Bartoszyk I. Comparison of antioxidant and antiproliferative effects of various forms of garlic and ramsons. *Molecules*. 2023;28:6512. <https://doi.org/10.3390/molecules28186512>.

68. Fenercioglu AK, Saler T, Genc E, Sabuncu H, Altuntas Y. The effects of polyphenol-containing antioxidants on oxidative stress and lipid peroxidation in type 2 diabetes mellitus without complications. *J Endocrinol Invest*. 2010;33:118–24. <https://doi.org/10.1007/BF03346565>.
69. Furdak P, Bartosz G, Sadowska-Bartos I. Which constituents determine the antioxidant activity and cytotoxicity of garlic? Role of organosulfur compounds and phenolics. *Int J Mol Sci*. 2024;25:8391. <https://doi.org/10.3390/ijms25158391>.
70. Jang HJ, Lee HJ, Yoon DK, Ji DS, Kim JH, Lee CH. Antioxidant and antimicrobial activities of fresh garlic and aged garlic by-products extracted with different solvents. *Food Sci Biotechnol*. 2018;27:219–25. <https://doi.org/10.1007/s10068-017-0246-4>.
71. Pabón-Baquero LC, Otálvaro-Álvarez ÁM, Fernández MRR, Chaparro-González MP. Plant extracts as antioxidant additives for food industry. In: Shalaby E, Azzam GM, editors. *Antioxidants in foods and its applications*. InTech; 2018. <https://doi.org/10.5772/intechopen.75444>.
72. Botas J, Fernandes Â, Barros L, Alves MJ, Carvalho AM, Ferreira IC. A comparative study of black and white *Allium sativum* L.: nutritional composition and bioactive properties. *Molecules*. 2019;24:2194. <https://doi.org/10.3390/molecules24112194>.
73. Sasmaz HK, Sevidik O, Kadiroglu P, Adal E, Erkin ÖC, Selli S, Kelebek H. Comparative assessment of quality parameters and bioactive compounds of white and black garlic. *Eur Food Res Technol*. 2022;248:2393–407. <https://doi.org/10.1007/s00217-022-04055-2>.
74. Martínez-Casas L, Lage-Yusty M, López-Hernández J. Changes in the aromatic profile, sugars and bioactive compounds when purple garlic is transformed into black garlic. *J Agric Food Chem*. 2017;65:10804–11. <https://doi.org/10.1021/acs.jafc.7b04423>.
75. Gökçe AF, Kaya C, Serçe S, Özgen M. Effect of scale color on the antioxidant capacity of onions. *Sci Hortic*. 2010;123:431–5. <https://doi.org/10.1016/j.scienta.2009.11.007>.
76. Tabussam N, Rana RM, Shah MKN, Ahmad MS, Sajjad M, Lu Y. Nutraceutical profiling of elite onion germplasm and breeding hybrids with improved nutraceutical quality. *PLoS ONE*. 2022;17:e0262705. <https://doi.org/10.1371/journal.pone.0262705>.
77. Gupta AJ, Gorrepati K, Bibwe B, Kaldete S, Volaguthala S, Mahajan V. Studies on biochemical and nutraceutical profiling of 43 Indian onion (*Allium cepa* L.) genotypes. *J Food Meas Charact*. 2025;2025:1–11. <https://doi.org/10.1007/s11694-025-03425-0>.
78. Yuan H, Sun L, Chen M, Wang J. The comparison of the contents of sugar, Amadori and Heyns compounds in fresh and black garlic. *J Food Sci*. 2016;81:C1662–8. <https://doi.org/10.1111/1750-3841.13365>.
79. Bagiu R, Vlaicu B, Butnariu M. Chemical composition and in vitro antifungal activity screening of *Allium ursinum* L. (Liliaceae). *Int J Mol Sci*. 2012;13:1426–36. <https://doi.org/10.3390/ijms13021426>.
80. Pakakaew P, Phimolsiripol Y, Taesuwan S, et al. The shortest innovative process for enhancing the S-allylcysteine content and antioxidant activity of black and golden garlic. *Sci Rep*. 2022;12:11493. <https://doi.org/10.1038/s41598-022-15635-3>.
81. Dinu M, Soare R, Băbeanu C, Botu M. Evaluation of productivity components and antioxidant activity of different types of garlic depending on the morphological organs. *Horticulturae*. 2023;9:1039. <https://doi.org/10.3390/horticulturae9091039>.
82. Skoczylas J, Jędraszczyk E, Dziadek K, Dacewicz E, Kopeć A. Basic chemical composition, antioxidant activity and selected polyphenolic compounds profile in garlic leaves and bulbs collected at various stages of development. *Molecules*. 2023;28:6653. <https://doi.org/10.3390/molecules28186653>.
83. Akinwande BA, Olatunde SJ. Comparative evaluation of the mineral profile and other selected components of onion and garlic. *Int Food Res J*. 2015;22:332–6.
84. Diriba-Shiferaw G, Nigussie-Dechassa R, Woldetsadik GK, Sharma JJ. Bulb quality of garlic (*Allium sativum* L.) as influenced by the application of inorganic fertilizers. *Afr J Agric Res*. 2013;8:5387–98.
85. Rathore N, Gayen R, Mahajan V, Thangasamy A, Ghodke P, Gorrepati K. Comparative study of physiological compounds and variability studies in different *Allium* species. *Int J Chem Stud*. 2020;8:2520–3.
86. Atashi S, Akbarpour V, Mashayekhi K, Mousavizadeh SJ. Garlic physiological characteristics from harvest to sprouting in response to low temperature. *J Stored Prod Postharvest Res*. 2011;2:285–91. <https://doi.org/10.5897/JSPR11.023>.
87. Akan S. Evaluation and comparison of some parameters in four garlic varieties. *J Inst Sci Technol*. 2019;9:1866–75. <https://doi.org/10.21597/jist.541783>.
88. Pasupula K, Verma P, Zimik M, Kaur C, Vasudev S, Khar A. Morphological, biochemical and molecular characterization of short-day tropical Indian garlic (*Allium sativum* L.). *Heliyon*. 2024;10:18.
89. Locatelli DA, Nazareno MA, Fusari CM, Camargo AB. Cooked garlic and antioxidant activity: correlation with organosulfur compound composition. *Food Chem*. 2017;220:219–24. <https://doi.org/10.1016/j.foodchem.2016.10.001>.
90. Gorinstein S, Drzewiecki J, Leontowicz H, Leontowicz M, Najman K, Jastrzebski Z, Zachwieja Z, Barton H, Shtabsky B, Katrich E, Trakhtenberg S. Comparison of the bioactive compounds and antioxidant potentials of fresh and cooked Polish, Ukrainian, and Israeli garlic. *J Agric Food Chem*. 2005;53(7):2726–32. <https://doi.org/10.1021/jf0404593>.
91. Baghalian K, Ziai SA, Naghavi MR, Badi HN, Khalighi A. Evaluation of allicin content and botanical traits in Iranian garlic (*Allium sativum* L.) ecotypes. *Sci Hort*. 2005;103(2):155–66. <https://doi.org/10.1016/j.scienta.2004.07.001>.
92. Rahman MM, Fazlic V, Saad NW. Antioxidant properties of raw garlic (*Allium sativum*) extract. *Int Food Res J*. 2012;19(2):589–91.

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