

INFLUENCE OF CULTIVARS AND DRYING METHODS ON THE PHYSICOCHEMICAL AND FUNCTIONAL PROPERTIES OF AMBIENT-STORED GREEN CHILLI POWDER

Rahul Sur¹, Pinky Maity¹, Soumitra Chatterjee², Anindita Karmakar³, Ivi Chakraborty^{1*}
and Arup Chattopadhyay⁴

¹*Department of Post Harvest Technology, ⁴Department of Vegetable Science, Faculty of Horticulture, Bidhan Chandra Krishi Viswavidyalaya (BCKV), Mohanpur - 741 252, Nadia, West Bengal (India)*

²*Department of Agricultural Economics, Faculty of Agriculture, BCKV, Mohanpur - 741 252, Nadia, West Bengal (India)*

³*Department of Post Harvest Engineering, Faculty of Agricultural Engineering, BCKV, Mohanpur - 741 252, Nadia, West Bengal (India)*

*e-mail: ivcpht@gmail.com

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ABSTRACT

Dehydration of green chillies is a highly effective preservation technique that reduces moisture content, enhances storability, and ensures year-round availability, particularly in tropical and subtropical regions. This study evaluated the influence of three cultivars namely 'Beldanga', 'Bidhan Chilli-4', and 'Bullet' on the physicochemical and functional properties of green chilli powder (GCP) produced using different drying methods under ambient storage conditions (21-39°C and 42-93% relative humidity). The drying treatments included: sun drying for 8 ± 1 days; hot air drying at 60°C for 48 ± 1 h; osmotic treatment in 30% salt solution for 120 min followed by hot air drying at 60°C for 30 ± 1 h; and osmotic treatments in 30% salt: sugar (3:1) and 30% salt: vinegar (3:1) solutions, each followed by hot air drying at 60°C for 30 ± 1 h. The results showed GCP had low moisture content (9.50%), low bulk density (470 kg m⁻³), relatively high tapped density (690 kg m⁻³), and poor flowability (Carr index: 28.78%), depicting a compact and highly compressible powder structure. These properties remained stable even after 180 days of ambient storage. Among the cultivars, 'Bidhan Chilli-4' demonstrated superior quality attributes. Hot air drying proved most effective processing method, followed by osmotic pre-treatment combined with hot air drying using salt + sugar (3:1) and salt + vinegar (3:1) solutions. Overall, the findings emphasize that careful cultivar selection and optimized drying techniques are critical for preserving the quality and nutritional value of GCP during extended storage.

Keywords: Ambient storage, cultivar, drying techniques, green chilli powder, quality attributes

INTRODUCTION

Chilli (*Capsicum annuum* L.) is an economically and nutritionally important spice crop, valued for its rich carotenoids, ascorbic acid, tocopherols, and phenolic compound contents. The concentration of these bioactive constituents is strongly influenced by cultivar, agro-climatic conditions, maturity stage, and postharvest handling practices (Bhattacharya *et al.*, 2010). Fresh green chillies possess high moisture content, making them highly perishable and unsuitable for long-term storage without

appropriate processing. Drying is, therefore, a critical postharvest operation, as reduction in moisture content enhances microbiological safety, minimizes enzymatic and oxidative deterioration, and improves shelf stability (Woldemariam *et al.*, 2021).

To make chillies last longer, they must be processed into wet or dry forms. The use of granular materials such as powders is beneficial for multiple reasons in industrial applications (Richard *et al.*, 2005). Several drying techniques such as sun drying, tray drying, hot air drying, vacuum drying, and freeze drying have been studied for chilli processing. Among these, hot air drying is widely practiced due to its operational simplicity, cost-effectiveness, uniform heat transfer, and better hygienic control. However, drying methods markedly affect not only the retention of bioactive compounds but also the techno-functional properties of chilli powder, including bulk density, tapped density, flowability, and compressibility, which are essential for packaging, transportation, and industrial utilization (Kashaninejad *et al.*, 2006). Although de-spiking and drying are recognized as the primary steps in chilli processing (Dumulin and Lozada, 1982), systematic evaluation of powder functionality remains limited.

Previous research works have primarily focused on either the impact of drying methods on the preservation of bioactive components or on comparing different varieties subject to single drying method (Koraddi, 1995; Tummala *et al.*, 2008). For instance, Alsebaei *et al.* (2017) reported superior retention of bioactive compounds in cv. 'Pusa Jwala' than cv. 'Jalapeno M', particularly with freeze drying proving most effective. Nonetheless, such studies rarely examined multiple commercial cultivars alongside different drying methods under controlled experimental settings, restricting their practical usefulness. Additionally, most existing studies emphasize on quality attributes immediately after drying process, while little information is available on storage stability and quality evaluation of dried green chilli powder under typical tropical conditions. The information on how cultivars, drying process, and storage duration together influence both the physicochemical and functional properties are notably lacking. Hence, this study aimed to assess the functional, physicochemical, and storage properties of dried green chilli powder, derived from three commercial cultivars using five different drying methods. By linking drying-induced changes with storage viability in ambient conditions, this research seeks to fill the critical gaps in the current literature and offers scientifically validated recommendations for choosing the best cultivar–drying method combinations to improve the shelf life and quality of green chilli powder without relying on chemical preservatives.

MATERIALS AND METHODS

Plant materials and pre-treatments

Fresh green fruits of three widely used commercial chilli cultivars ('Beldanga', 'Bidhan Chilli-4' and 'Bullet') of Eastern India were harvested at physiologically mature stage (65-75 days after transplanting) based on their shape, size, firmness, colour, etc. during winter season 2023 and brought to the laboratory of Regional Nuclear Agriculture Research Centre, Bidhan Chandra Krishi Viswavidyalaya (BCKV), West Bengal (India) for imposing pre-treatments. Freshly harvested green chilli fruits were thoroughly washed in running tap water with 50 ppm chlorine to get rid of any dirt and foreign material that may be adhering to the fruit surface. Fruits were spread under fan for surface drying and turned many times for proper drying.

Treatment details and powder preparation

The fruits of three chili cultivars without stalk, weighing 500 g for each treatment, were cut/chopped to approximately 2 cm length. These were then dried using five drying methods: T₁) Hot air drying at 60°C for 48 ± 1 h; T₂) Sun drying for 8 ± 1 day; T₃) Osmo-hot air drying (dipping in 30% salt for 120 min and draining out the solution) followed by hot air drying at 60°C for 30 ± 1 h; T₄) Osmo-hot



Plate 1: Chilli fruits of three cultivars before drying

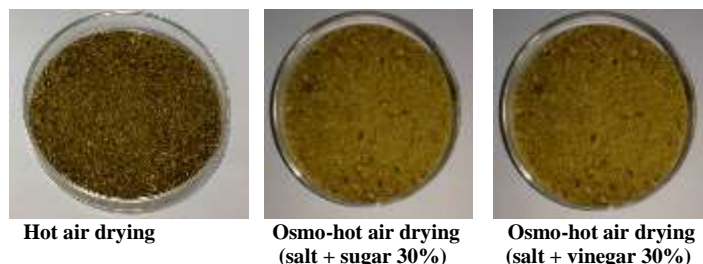


Plate 2: Green chilli powder prepared from Bidhan Chilli-4

air drying (dipping in 30% salt: sugar, 3:1 for 120 min) followed by hot air drying at 60°C for 30 ± 1 h; T₃) Osmo-hot air drying (dipping in 30% salt: vinegar, 3:1) for 120 min followed by hot air drying at 60°C for 30 ± 1 h. The dried chillies were ground to powder (Plate 1-2) by grinding machine (Crompton Ameo-750 Watt with MaxiGrind and Motor Vent-X Technology). The particle size of final GCP prepared from the 3 varieties and drying methods was measured with 70 mesh sieve as per Phat *et al.* (2015). The particle size varied from 186 to 215 µm. Each prepared GCP was packed in polypropylene pouch packet (0.1 mm thickness) and stored at room condition (25-28°C; 42-93% RH) for storage study.

Physicochemical analysis

The various functional and physicochemical attributes of GCP were evaluated at 0, 60, 120 and 180 days interval during ambient storage (25-28°C; 42-93% RH). The bulk density of GCP was measured as per Meghwal and Goswami (2013). The tapped density (kg m⁻³) was determined as per Santomaso *et al.* (2003). Carr's index (CI) is commonly used to determine the flowability of food powders. CI was calculated using the equation of Fitzpatrick (2013). The per cent moisture content of dried chilli powder samples was determined using moisture analyzer (model: MB 54; Citizen, India). The water activity (*a_w*) of GCP was calculated by using a water activity meter (model 40530 Aqualab 4TE, Decagan Devices, USA). The vapour pressure (*p*) of the water-containing medium divided by pure water pressure (*p₀*) is represented by the *a_w* value.

The capsaicin content was extracted using ethyl acetate and allowed to react with ethyl acetate solution of vanadium oxychloride (Sadasivam and Manickam, 1996). Then spectrophotometric (Shimadzu 1609, Tokyo, Japan) reading were taken at 720 nm wavelength, and compared with standard curve prepared by using 0.5, 1.0, 1.5, 2.0 and 2.5 mL standard capsaicin solution containing 50, 100, 150, 200 and 250 µg capsaicin, respectively.

The titratable acid content was estimated as per Sadasivam and Manickam (1996) which measures organic acids content in powder and is expressed in terms of % anhydrous citric acid. The pH value of chilli powder samples was determined by digital pH meter (Labard, India). The ascorbic acid content was estimated using 2, 6 dichloro-indophenol dye titration method (Ranganna, 2000). Total phenols were estimated spectrophotometrically as per Sadasivam and Manickam (1996). Standard curve was prepared by using gallic acid as standard. Different concentrations of gallic acid were prepared and optical density values read at 750 nm wavelength using a spectrophotometer (Shimadzu 1609, Tokyo, Japan). The concentration of samples was calculated by comparing the value against standard curve. The total antioxidant activity of extracts was measured by 2,2-diphenylpicrylhydrazyl (DPPH) radical scavenging assay as per Williams *et al.* (1995).

Sensory evaluation

The overall acceptability of chilli powder was assessed by their taste, colour, pungency, and flavour. GCPs were mixed with boiled and mashed potatoes and a pinch of salt added to it and then

evaluated by a panel of 15 experienced taste panelists using 1-9 hedonic scale (9 = like extremely; 8 = like very much; 7 = like moderately; 6 = like slightly; 5 = neither like nor dislike; 4 = dislike slightly; 3 = dislike moderately; 2 = dislike very much; 1 = dislike extremely). The sensory evaluation was performed at regular storage intervals (Toontom *et al.*, 2012).

Statistical analysis

The data of all functional and physicochemical parameters were subjected to ANOVA in a factorial completely randomized design (Gomez and Gomez, 1984). Subsequently Tukey's honest significant difference (HSD) test was computed across GCP prepared through different varieties and drying techniques at different ambient storage intervals to compare factor means. The data were analysed using SAS 9.3 version.

RESULTS AND DISCUSSION

Effect on bulk density, tapped density, Carr index and moisture content

Bulk density, tapped density, Carr index (CI), and moisture content of green chilli powder (GCP) were significantly influenced by the cultivar, drying method, and storage duration (Table 1). During storage, bulk and tapped density gradually decreased, whereas CI and moisture content showed a progressive increase. These parameters are closely interrelated and collectively describe the packing behaviour, compressibility, and flow properties of powdered materials (Fitzpatrick, 2013).

Among the cultivars, cv. 'Bidhan Chilli-4' consistently recorded higher bulk and tapped density with comparatively lower CI and moisture content than cv. 'Bullet' and 'Beldanga', indicating superior

Table 1: Effect of cultivars and drying methods on bulk density, tapped density, Carr index and moisture content of green chilli powder at different storage intervals

Days in storage	Cultivars			MSD	Drying methods					MSD
	Beldanga	Bidhan Chilli-4	Bullet		T1	T2	T3	T4	T5	
Bulk density (kg m⁻³)										
0	480 ^c	510 ^a	490 ^b	5.30 ^{**}	473 ^e	513 ^a	483 ^d	503 ^b	493 ^c	8.00 ^{**}
60	470 ^c	500 ^a	480 ^b	4.74 ^{**}	463 ^e	503 ^a	473 ^d	493 ^b	483 ^c	7.15 ^{**}
120	445 ^c	475 ^a	455 ^b	4.86 ^{**}	438 ^e	478 ^a	448 ^d	468 ^b	458 ^c	7.33 ^{**}
180	410 ^c	440 ^a	420 ^b	2.31 ^{**}	403 ^e	443 ^a	413 ^d	433 ^b	423 ^c	3.48 ^{**}
Mean	451.25	481.25	461.25	-	444.25	484.25	454.25	474.25	464.25	-
Tapped density (kg m⁻³)										
0	650 ^c	670 ^a	660 ^b	0.00 ^{**}	640 ^e	680 ^a	650 ^d	670 ^b	660 ^c	0.00 ^{**}
60	645 ^c	665 ^a	655 ^b	0.00 ^{**}	635 ^e	675 ^a	645 ^d	665 ^b	655 ^c	0.00 ^{**}
120	632.5 ^c	652.5 ^a	642.5 ^b	0.00 ^{**}	622.5 ^e	662.5 ^a	632.5 ^d	652.5 ^b	642.5 ^c	0.00 ^{**}
180	615 ^c	635 ^a	625 ^b	0.00 ^{**}	605 ^e	645 ^a	615 ^d	635 ^b	625 ^c	0.00 ^{**}
Mean	635.63	655.63	645.63	-	625.63	665.63	635.63	655.63	645.63	-
Carr index (%)										
0	26.16 ^a	23.89 ^c	25.77 ^b	0.02 ^{**}	26.05 ^a	24.52 ^e	25.65 ^b	24.88 ^d	25.26 ^c	0.03 ^{**}
60	27.14 ^a	24.82 ^c	26.73 ^b	0.02 ^{**}	27.05 ^a	25.44 ^e	26.63 ^b	25.82 ^d	26.22 ^c	0.03 ^{**}
120	29.66 ^a	27.21 ^c	29.19 ^b	0.02 ^{**}	29.60 ^a	27.81 ^e	29.13 ^b	28.24 ^d	28.67 ^c	0.03 ^{**}
180	33.36 ^a	30.73 ^c	32.82 ^b	0.03 ^{**}	32.35 ^a	31.28 ^e	32.81 ^b	31.78 ^d	32.28 ^c	0.05 ^{**}
Mean	29.08	26.66	28.63	-	28.76	27.26	28.56	27.68	28.11	-
Moisture content (%)										
0	7.38 ^a	7.28 ^c	7.34 ^b	0.02 ^{**}	7.25 ^d	7.39 ^a	7.32 ^c	7.34 ^{bc}	7.36 ^{ba}	0.04 ^{**}
60	7.81 ^a	7.67 ^c	7.75 ^a	0.07 ^{**}	7.53 ^c	7.90 ^a	7.72 ^b	7.75 ^b	7.80 ^{ba}	0.10 ^{**}
120	8.44 ^a	8.25 ^c	8.35 ^{ba}	0.10 ^{**}	8.03 ^c	8.61 ^a	8.30 ^b	8.37 ^b	8.43 ^b	0.15 ^{**}
180	10.10 ^a	9.86 ^c	9.98 ^a	0.10 ^{**}	9.62 ^c	10.30 ^a	9.92 ^b	10.00 ^b	10.06 ^b	0.15 ^{**}
Mean	8.43	8.27	8.36	-	8.11	8.55	8.32	8.37	8.41	-

^aT1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt: sugar - 3:1 (30%) + Hot air drying, T5 = Salt: vinegar - 3:1 (30%) + Hot air drying. MSD = Mean significant difference; ** Means significant at 1% level; Values in columns followed by the same letter are not significantly different, $p < 0.05$, Tukey's post hoc test.

particle packing, improved compressibility and better flow behaviour. These variations may be attributed to differences in tissue structure, particle size distribution, and solid content of powder obtained after drying. Cultivars with more stable cellular structures and higher cuticular wax content tend to resist moisture migration more effectively, thereby improves the storage stability of powder (Maalekuu *et al.*, 2006).

Drying method also played a crucial role in determining the physical and moisture characteristics of GCP. Hot air drying combined with salt and sugar treatment produced comparatively denser powder beds with lower CI values, indicating improved particle compactness and better initial flowability. The highest bulk and tapped density along with the lowest CI and moisture content were observed in cv. 'Bidhan Chilli-4' subjected to hot air drying with salt and sugar (Table 2 and 3). Osmotic pre-treatment likely induced partial cellular collapse and reduced structural porosity, resulting in enhanced particle compactness and packing efficiency.

Table 2: Interaction effects (mean \pm SD) between cultivars and drying methods on bulk density and tapped density of green chilli powder at different storage intervals

Interaction effects*	Bulk density (kg m ⁻³)				Tapped density (kg m ⁻³)			
	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day
V1T1	470 \pm 0.01 ^{de}	460 \pm 0.01 ^{ef}	440 \pm 0.01 ^{egf}	410 \pm 0.01 ^{fg}	640 \pm 0.01 ^f	635 \pm 0.01 ^f	625 \pm 0.01 ^f	610 \pm 0.01 ^f
V1T2	460 \pm 0.01 ^e	450 \pm 0.01 ^f	430 \pm 0.01 ^{gf}	400 \pm 0.01 ^{hg}	630 \pm 0.01 ^g	625 \pm 0.01 ^g	615 \pm 0.01 ^g	600 \pm 0.01 ^g
V1T3	490 \pm 0.01 ^{bdec}	480 \pm 0.01 ^{edc}	460 \pm 0.01 ^{edc}	430 \pm 0.01 ^{de}	660 \pm 0.01 ^d	655 \pm 0.01 ^d	645 \pm 0.01 ^d	630 \pm 0.01 ^d
V1T4	500 \pm 0.01 ^{bdac}	490 \pm 0.01 ^{bdc}	470 \pm 0.01 ^{bdc}	440 \pm 0.01 ^{dc}	670 \pm 0.01 ^c	665 \pm 0.01 ^c	655 \pm 0.01 ^c	640 \pm 0.01 ^c
V1T5	480 \pm 0.01 ^{dec}	470 \pm 0.01 ^{edf}	450 \pm 0.01 ^{edf}	420 \pm 0.01 ^{fe}	650 \pm 0.01 ^e	645 \pm 0.01 ^e	635 \pm 0.01 ^e	620 \pm 0.01 ^e
V2T1	500 \pm 0.01 ^{bdac}	490 \pm 0.01 ^{bdc}	470 \pm 0.01 ^{bdc}	440 \pm 0.01 ^{dc}	660 \pm 0.01 ^d	655 \pm 0.01 ^d	645 \pm 0.01 ^d	630 \pm 0.01 ^d
V2T2	490 \pm 0.01 ^{bdec}	480 \pm 0.01 ^{edc}	460 \pm 0.01 ^{edc}	430 \pm 0.01 ^{de}	650 \pm 0.01 ^e	645 \pm 0.01 ^e	635 \pm 0.01 ^e	620 \pm 0.01 ^e
V2T3	520 \pm 0.01 ^{ba}	510 \pm 0.01 ^{ba}	490 \pm 0.01 ^{ba}	460 \pm 0.01 ^{ba}	680 \pm 0.01 ^b	675 \pm 0.01 ^b	665 \pm 0.01 ^b	650 \pm 0.01 ^b
V2T4	530 \pm 0.01 ^a	520 \pm 0.01 ^a	500 \pm 0.01 ^a	470 \pm 0.01 ^a	690 \pm 0.01 ^a	685 \pm 0.01 ^a	675 \pm 0.01 ^a	660 \pm 0.01 ^a
V2T5	510 \pm 0.01 ^{bac}	500 \pm 0.01 ^{bac}	480 \pm 0.01 ^{bac}	450 \pm 0.01 ^{bc}	670 \pm 0.01 ^c	665 \pm 0.01 ^c	655 \pm 0.01 ^c	640 \pm 0.01 ^c
V3T1	480 \pm 0.01 ^{dec}	470 \pm 0.01 ^{edf}	450 \pm 0.01 ^{edf}	420 \pm 0.01 ^{fe}	650 \pm 0.01 ^e	645 \pm 0.01 ^e	635 \pm 0.01 ^e	620 \pm 0.01 ^e
V3T2	470 \pm 0.01 ^{de}	460 \pm 0.01 ^{ef}	440 \pm 0.01 ^{egf}	410 \pm 0.01 ^{fg}	640 \pm 0.01 ^f	635 \pm 0.01 ^f	625 \pm 0.01 ^f	610 \pm 0.01 ^f
V3T3	500 \pm 0.01 ^{bdac}	490 \pm 0.01 ^{bdc}	470 \pm 0.01 ^{bdc}	440 \pm 0.01 ^{dc}	670 \pm 0.01 ^c	665 \pm 0.01 ^c	655 \pm 0.01 ^c	640 \pm 0.01 ^c
V3T4	510 \pm 0.01 ^{bac}	500 \pm 0.01 ^{bac}	480 \pm 0.01 ^{bac}	450 \pm 0.01 ^{bc}	680 \pm 0.01 ^b	675 \pm 0.01 ^b	665 \pm 0.01 ^b	650 \pm 0.01 ^b
V3T5	490 \pm 0.01 ^{bdec}	480 \pm 0.01 ^{edc}	460 \pm 0.01 ^{edc}	430 \pm 0.01 ^{de}	660 \pm 0.01 ^d	655 \pm 0.01 ^d	645 \pm 0.01 ^d	630 \pm 0.01 ^d

* V1 = Beldanga, V2 = Bidhan Chilli-4; V3 = Bullet; T1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt + sugar - 3:1 (30%) + Hot air drying, T5 = Salt + vinegar - 3:1 (30%) + Hot air drying;

Data in the interaction analysed with Least Squares Means and means separated with Tukey's post hoc test, at $p \leq 0.01$.

The gradual decline in bulk and tapped density during storage was primarily associated with moisture absorption by the powder matrix. The increase in moisture content reflects the hygroscopic nature of GCP and the migration of environmental moisture into the powder during storage. Moisture uptake promotes particle swelling and agglomeration, which increases the void volume and reduces packing efficiency during free pouring. Although tapping helps particles rearrange into a more compact structure, moisture-induced cohesiveness restricts complete particle movement, resulting in reduced tapped density over time (Meghwal and Goswami, 2013; Al-Sebaei *et al.*, 2017). Consequently, the increasing difference between tapped and bulk density led to higher CI values, indicating increased compressibility and cohesiveness of the powder.

Carr's index is widely used as an indicator of powder flowability, where higher CI values correspond to poorer flow behaviour due to increased inter-particle friction and cohesion (Carr, 1965). The progressive increase in CI noticed during storage therefore suggests a gradual deterioration in the flowability of GCP. Moisture absorption promotes the formation of liquid bridges between particles, increasing cohesive forces and restricting free particle movement, which ultimately reduces flow efficiency (Kashaninejad *et al.*, 2006).

Moisture content of GCP increased steadily during storage but remained within a safe range for dried chilli products. Moisture levels around 8% are considered optimal for dried chilli, whereas values $> 11\%$ may favour mould growth and the levels $< 4\%$ may lead to excessive colour degradation (Wall and Bosland, 1993). Additionally, chilli powders should generally be dried below

Table 3: Interaction effects (mean \pm SD) between cultivars and drying methods on Carr index and moisture content of green chilli powder at different storage intervals

Interaction effects*	Carr index (%)				Moisture content (%)			
	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day
V1T1	26.56 $\pm 1.04^b$	27.56 $\pm 1.08^b$	29.60 $\pm 1.15^b$	32.78 $\pm 1.23^b$	7.30 $\pm 0.03^{bcd}$	7.57 $\pm 0.04^{bcd}$	8.02 $\pm 0.09^{edf}$	9.56 $\pm 0.08^{ihg}$
V1T2	26.98 $\pm 1.05^a$	28.00 $\pm 1.09^a$	30.08 $\pm 1.16^a$	33.33 $\pm 1.25^a$	7.46 $\pm 0.04^a$	7.93 $\pm 0.07^{ba}$	8.56 $\pm 0.08^{bdac}$	10.20 $\pm 0.13^{ebdacf}$
V1T3	25.75 $\pm 1.03^d$	26.71 $\pm 1.07^d$	28.68 $\pm 1.13^d$	31.74 $\pm 1.22^d$	7.37 $\pm 0.03^{bac}$	7.75 $\pm 0.05^{bdac}$	8.29 $\pm 0.13^{ebdacf}$	9.85 $\pm 0.17^{edihgcf}$
V1T4	25.37 $\pm 1.02^e$	26.31 $\pm 1.06^e$	28.24 $\pm 1.12^e$	31.25 $\pm 1.21^e$	7.39 $\pm 0.07^{bac}$	7.76 $\pm 0.08^{bdac}$	8.36 $\pm 0.10^{ebdacf}$	9.92 $\pm 0.16^{edihgcf}$
V1T5	26.15 $\pm 1.03^c$	27.13 $\pm 1.08^c$	29.13 $\pm 1.15^c$	32.25 $\pm 1.23^c$	7.41 $\pm 0.03^{ba}$	7.82 $\pm 0.08^{bdac}$	8.42 $\pm 0.13^{ebdacf}$	9.98 $\pm 0.03^{ebdihgcf}$
V2T1	24.24 $\pm 1.01^h$	25.19 $\pm 1.05^h$	27.13 $\pm 1.12^h$	30.15 $\pm 1.21^h$	7.21 $\pm 0.02^d$	7.44 $\pm 0.15^d$	7.87 $\pm 0.16^f$	9.37 $\pm 0.19^i$
V2T2	24.61 $\pm 1.02^g$	25.58 $\pm 1.05^g$	27.55 $\pm 1.11^g$	30.64 $\pm 1.18^g$	7.33 $\pm 0.03^{bdac}$	7.77 $\pm 0.15^{bdac}$	8.38 $\pm 0.17^{ebdacf}$	9.98 $\pm 0.20^{ebdihgcf}$
V2T3	23.52 $\pm 1.01^j$	24.44 $\pm 1.03^j$	26.31 $\pm 1.10^j$	29.23 $\pm 1.19^j$	7.27 $\pm 0.05^{bcd}$	7.61 $\pm 0.21^{bcd}$	8.11 $\pm 0.24^{edcf}$	9.63 $\pm 0.19^{ihgf}$
V2T4	23.18 $\pm 1.00^k$	24.08 $\pm 1.04^k$	25.92 $\pm 1.11^k$	28.78 $\pm 1.20^k$	7.28 $\pm 0.06^{bcd}$	7.63 $\pm 0.21^{bcd}$	8.17 $\pm 0.19^{ebdacf}$	9.69 $\pm 0.28^{edihgcf}$
V2T5	23.88 $\pm 1.01^i$	24.81 $\pm 1.03^i$	26.71 $\pm 1.10^i$	29.68 $\pm 1.19^i$	7.30 $\pm 0.03^{bcd}$	7.68 $\pm 0.18^{bdac}$	8.22 $\pm 0.35^{ebdacf}$	9.74 $\pm 0.23^{edihgcf}$
V3T1	26.15 $\pm 1.02^c$	27.13 $\pm 1.06^c$	29.13 $\pm 1.14^c$	32.25 $\pm 1.23^c$	7.25 $\pm 0.02^{dc}$	7.50 $\pm 0.15^{dc}$	7.94 $\pm 0.16^{ef}$	9.46 $\pm 0.19^{ih}$
V3T2	26.56 $\pm 1.03^b$	27.56 $\pm 1.06^b$	29.60 $\pm 1.12^b$	32.78 $\pm 1.20^b$	7.39 $\pm 0.03^{bac}$	7.84 $\pm 0.23^{bdac}$	8.46 $\pm 0.20^{ebdacf}$	10.08 $\pm 0.13^{ebdihgcf}$
V3T3	25.37 $\pm 1.02^e$	26.31 $\pm 1.04^e$	28.24 $\pm 1.14^e$	31.25 $\pm 1.21^e$	7.32 $\pm 0.03^{bdac}$	7.68 $\pm 0.16^{bdac}$	8.20 $\pm 0.35^{ebdacf}$	9.74 $\pm 0.28^{edihgcf}$
V3T4	25.00 $\pm 1.01^f$	25.92 $\pm 1.05^f$	27.81 $\pm 1.13^f$	30.76 $\pm 1.22^f$	7.36 $\pm 0.05^{bac}$	7.73 $\pm 0.12^{bdac}$	8.29 $\pm 0.31^{ebdacf}$	9.83 $\pm 0.23^{edihgcf}$
V3T5	25.75 $\pm 1.02^d$	26.71 $\pm 1.04^d$	28.68 $\pm 1.14^d$	31.74 $\pm 1.21^d$	7.38 $\pm 0.07^{bac}$	7.77 $\pm 0.07^{bdac}$	8.34 $\pm 0.17^{ebdacf}$	9.88 $\pm 0.20^{edihgcf}$

* V1 = Beldanga, V2 = Bidhan Chilli-4; V3 = Bullet; T1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt + sugar - 3:1 (30%) + Hot air drying, T5 = Salt + vinegar - 3:1 (30%) + Hot air drying; Data in the interaction analysed with Least Squares Means and means separated with Tukey's post hoc test, at $p \leq 0.01$.

13% moisture content to minimize the risk of aflatoxin development (Pitt and Hocking, 1997). Therefore, the comparatively lower moisture content maintained by cv. 'Bidhan Chilli-4', especially when dried using hot air drying, indicates better storage stability and suitability for long-term preservation. Overall, the combined effects of cultivar characteristics, drying treatment, and storage-induced moisture changes play a critical role in determining the packing behaviour, flowability, and shelf stability of green chilli powder.

Effect on water activity and capsaicin content

Water activity (a_w) and capsaicin content of GCP were significantly influenced by the cultivar, drying method, and storage duration (Table 4). Water activity gradually increased during storage, while capsaicin content showed a consistent decline. The rise in a_w indicates progressive moisture adsorption by the powder, leading to greater availability of unbound water in the matrix.

Among the cultivars, 'Bidhan Chilli-4' consistently maintained lower a_w values than 'Bullet' and 'Beldanga', suggesting better resistance to moisture migration and improved physicochemical stability during storage. In contrast, cv. 'Bullet' exhibited higher capsaicin content throughout the storage period, reflecting inherent genotypic differences in capsaicinoid biosynthesis.

Drying methods also significantly affected water activity and capsaicin content. Powders obtained by hot air drying recorded the lowest a_w and the highest capsaicin retention, followed by osmo-hot air drying with salt. Hot air drying has been reported to be effective in preserving capsaicinoids, the bioactive compounds responsible for the pungency and characteristic flavour of

Table 4: Main effects between cultivars and drying methods on water activity and capsaicin content of green chilli powder at different storage intervals

Days in storage	Cultivars			MSD	Drying methods					MSD
	Beldanga	Bidhan Chilli-4	Bullet		T1	T2	T3	T4	T5	
Water activity (a_w)										
0	0.533 ^a	0.496 ^c	0.515 ^b	0.003 ^{**}	0.486 ^e	0.541 ^a	0.508 ^d	0.515 ^c	0.522 ^b	0.005 ^{**}
60	0.537 ^a	0.500 ^c	0.519 ^b	0.003 ^{**}	0.490 ^e	0.547 ^a	0.512 ^d	0.520 ^c	0.526 ^b	0.005 ^{**}
120	0.545 ^a	0.508 ^c	0.527 ^b	0.003 ^{**}	0.496 ^e	0.557 ^a	0.520 ^d	0.527 ^c	0.534 ^b	0.005 ^{**}
180	0.554 ^a	0.517 ^c	0.536 ^b	0.003 ^{**}	0.504 ^e	0.567 ^a	0.529 ^d	0.536 ^c	0.542 ^b	0.005 ^{**}
Mean	0.54	0.51	0.52		0.49	0.55	0.52	0.52	0.53	-
Capsaicin content (%)										
0	0.196 ^c	0.254 ^b	0.328 ^a	0.003 ^{**}	0.274 ^a	0.264 ^b	0.253 ^d	0.248 ^e	0.258 ^c	0.004 ^{**}
60	0.192 ^c	0.250 ^b	0.323 ^a	0.002 ^{**}	0.268 ^a	0.260 ^b	0.249 ^d	0.243 ^e	0.254 ^c	0.004 ^{**}
120	0.185 ^c	0.242 ^b	0.315 ^a	0.002 ^{**}	0.259 ^a	0.253 ^b	0.242 ^d	0.236 ^e	0.245 ^c	0.003 ^{**}
180	0.173 ^c	0.229 ^b	0.300 ^a	0.002 ^{**}	0.245 ^a	0.240 ^b	0.230 ^d	0.224 ^e	0.232 ^c	0.003 ^{**}
Mean	0.19	0.24	0.32		0.26	0.25	0.24	0.24	0.25	-

^aT1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt: sugar - 3:1 (30%) + Hot air drying, T5 = Salt: vinegar - 3:1 (30%) + Hot air drying. MSD = Mean significant difference; ** Means significant at 1% level; The values in columns followed by the same letter do not significantly differ from each other at $p < 0.01$, Tukey's post hoc test.

chilli (Khatun *et al.*, 2022). These compounds also possess several health-promoting properties, including antioxidant and anti-inflammatory activities. Wu *et al.* (2025) also reported that properly controlled hot air drying conditions help minimizing the degradation of capsaicinoids during moisture removal and hence it is highly suitable for industrial processing for their retention of flavour quality and functional bioactive compounds.

The highest capsaicin retention was observed in cv. 'Bullet' dried in a hot air dryer, whereas 'Bidhan Chilli-4' dried by hot air drying showed the lowest water activity during storage (Table 5). The lower a_w obtained through hot air drying may be attributed to efficient removal of free and loosely bound water, which limits moisture reabsorption and improves product stability.

Water activity is an important quality parameter influencing the microbial growth and biochemical reactions in dried chilli powder (Kim *et al.*, 1982). Lower a_w restricts enzymatic activity and enhances shelf stability. The decline in capsaicin during storage is mainly attributed to the oxidative degradation mediated by residual peroxidase enzymes, which catalyze capsaicinoid

Table 5: Interaction effects (Mean \pm SD) between cultivars and drying methods on water activity and capsaicin content of green chilli powder at different storage intervals

Interaction effects*	Water activity (a_w)				Capsaicin content (%)			
	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day
V1T1	0.502 \pm 0.01 ⁱ	0.505 \pm 0.01 ^j	0.511 \pm 0.01 ^j	0.519 \pm 0.01 ^k	0.208 \pm 0.004 ^g	0.204 \pm 0.001 ^h	0.196 \pm 0.003 ^j	0.184 \pm 0.003 ^k
V1T2	0.572 \pm 0.01 ^a	0.577 \pm 0.01 ^a	0.586 \pm 0.01 ^a	0.596 \pm 0.01 ^a	0.200 \pm 0.003 ^{hg}	0.197 \pm 0.003 ^{ih}	0.191 \pm 0.003 ^{klj}	0.181 \pm 0.003 ^{lk}
V1T3	0.523 \pm 0.01 ^f	0.527 \pm 0.01 ^f	0.534 \pm 0.01 ^e	0.542 \pm 0.01 ^g	0.191 \pm 0.002 ^h	0.188 \pm 0.002 ^{ikj}	0.182 \pm 0.002 ^{ml}	0.172 \pm 0.002 ^{lm}
V1T4	0.532 \pm 0.01 ^d	0.536 \pm 0.01 ^d	0.543 \pm 0.01 ^c	0.551 \pm 0.01 ^d	0.186 \pm 0.002 ^h	0.183 \pm 0.002 ^{klj}	0.177 \pm 0.002 ^m	0.167 \pm 0.002 ^{nm}
V1T5	0.537 \pm 0.01 ^b	0.541 \pm 0.01 ^b	0.548 \pm 0.01 ^b	0.556 \pm 0.01 ^c	0.195 \pm 0.003 ^{hg}	0.192 \pm 0.003 ^{ikhj}	0.185 \pm 0.003 ^{kmjl}	0.174 \pm 0.002 ^{lm}
V2T1	0.471 \pm 0.01 ⁿ	0.474 \pm 0.01 ⁿ	0.480 \pm 0.01 ⁿ	0.488 \pm 0.01 ^o	0.268 \pm 0.005 ^d	0.264 \pm 0.005 ^e	0.255 \pm 0.004 ^f	0.242 \pm 0.004 ^f
V2T2	0.519 \pm 0.01 ^g	0.524 \pm 0.01 ^g	0.533 \pm 0.01 ^f	0.543 \pm 0.01 ^f	0.259 \pm 0.005 ^{ed}	0.256 \pm 0.005 ^{fe}	0.249 \pm 0.004 ^{ef}	0.238 \pm 0.004 ^{ef}
V2T3	0.492 \pm 0.01 ^l	0.496 \pm 0.01 ^l	0.503 \pm 0.01 ^l	0.511 \pm 0.01 ^m	0.248 \pm 0.004 ^{ef}	0.245 \pm 0.004 ^{fg}	0.238 \pm 0.004 ^{gih}	0.227 \pm 0.003 ^{ih}
V2T4	0.495 \pm 0.01 ^k	0.499 \pm 0.01 ^k	0.506 \pm 0.01 ^k	0.514 \pm 0.01 ^l	0.242 \pm 0.004 ^{df}	0.239 \pm 0.004 ^g	0.232 \pm 0.003 ⁱ	0.221 \pm 0.003 ^{ji}
V2T5	0.501 \pm 0.01 ^j	0.505 \pm 0.01 ^j	0.512 \pm 0.01 ⁱ	0.520 \pm 0.01 ^j	0.252 \pm 0.005 ^{ef}	0.249 \pm 0.004 ^{fg}	0.241 \pm 0.004 ^{gih}	0.229 \pm 0.004 ^{gih}
V3T1	0.486 \pm 0.01 ^m	0.489 \pm 0.01 ^m	0.495 \pm 0.01 ^m	0.503 \pm 0.01 ⁿ	0.345 \pm 0.006 ^a	0.340 \pm 0.005 ^a	0.331 \pm 0.005 ^a	0.317 \pm 0.004 ^a
V3T2	0.534 \pm 0.01 ^c	0.539 \pm 0.01 ^c	0.548 \pm 0.01 ^b	0.558 \pm 0.01 ^b	0.334 \pm 0.006 ^{ba}	0.330 \pm 0.005 ^{ba}	0.323 \pm 0.005 ^{ba}	0.311 \pm 0.004 ^{ba}
V3T3	0.510 \pm 0.01 ^h	0.514 \pm 0.01 ⁱ	0.521 \pm 0.01 ^h	0.529 \pm 0.01 ⁱ	0.321 \pm 0.005 ^{bc}	0.317 \pm 0.005 ^{bdc}	0.310 \pm 0.005 ^{edc}	0.298 \pm 0.003 ^{dc}
V3T4	0.519 \pm 0.01 ^g	0.523 \pm 0.01 ^h	0.530 \pm 0.01 ^g	0.538 \pm 0.01 ^h	0.315 \pm 0.005 ^c	0.311 \pm 0.005 ^d	0.304 \pm 0.005 ^{ed}	0.292 \pm 0.003 ^{de}
V3T5	0.528 \pm 0.01 ^e	0.532 \pm 0.01 ^e	0.539 \pm 0.01 ^d	0.547 \pm 0.01 ^e	0.326 \pm 0.005 ^{bc}	0.322 \pm 0.005 ^{bdc}	0.314 \pm 0.005 ^{bdc}	0.301 \pm 0.004 ^{dc}

*V1 = Beldanga, V2 = Bidhan Chilli-4; V3 = Bullet; T1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt + Sugar - 3:1 (30%) + Hot air drying, T5 = Salt + Vinegar - 3:1 (30%) + Hot air drying. Data in the interaction analyzed with Least Squares Means and means separated with Tukey's post hoc test, at $p \leq 0.01$.

oxidation (Yu *et al.*, 2005). Similar moisture-mediated degradation of capsaicin during storage has been reported in dried chilli products (Bernal and Barceló, 1996; Tummala *et al.*, 2008). The results indicate that the selection of high-pungency cultivars combined with hot air drying is effective for maintaining lower water activity and better capsaicin retention during storage.

Effect on titratable acid content and pH value

Titratable acidity (TAC) and pH of GCP were significantly influenced by the cultivar, drying method, and storage duration (Table 6). TAC showed a consistent decline, whereas pH gradually increased during storage. The decrease in TAC indicates progressive degradation or utilization of organic acids due to oxidative reactions and biochemical changes in the dried matrix. Correspondingly, the rise in pH reflects the reduction of organic acid concentration during storage.

Table 6: Main effects between cultivars and drying methods on titratable acidity content and pH value of green chilli powder at different storage intervals

Days in storage	Chilli cultivars			MSD	Drying methods					MSD
	Beldanga	Bidhan Chilli-4	Bullet		T1	T2	T3	T4	T5	
Titratable acidity content (%)										
0	0.089 ^a	0.065 ^b	0.053 ^c	0.0017 ^{**}	0.056 ^c	0.061 ^b	0.052 ^d	0.048 ^e	0.129 ^a	0.0026 ^{**}
60	0.079 ^a	0.058 ^b	0.047 ^c	0.0017 ^{**}	0.049 ^c	0.054 ^b	0.046 ^d	0.042 ^e	0.115 ^a	0.0025 ^{**}
120	0.064 ^a	0.048 ^b	0.035 ^c	0.002 ^{**}	0.039 ^c	0.045 ^b	0.036 ^d	0.031 ^e	0.094 ^a	0.0031 ^{**}
180	0.047 ^a	0.033 ^b	0.022 ^c	0.0022 ^{**}	0.028 ^c	0.034 ^b	0.025 ^d	0.021 ^e	0.062 ^a	0.0033 ^{**}
Mean	0.070	0.051	0.039	-	0.048	0.049	0.040	0.036	0.100	-
pH value										
0	6.502 ^b	6.581 ^a	6.567 ^a	0.056 ^{**}	6.590 ^a	6.487 ^b	6.609 ^a	6.623 ^a	6.442 ^b	0.084 ^{**}
60	6.535 ^b	6.592 ^{ba}	6.629 ^a	0.055 ^{**}	6.617 ^a	6.595 ^a	6.613 ^a	6.634 ^a	6.469 ^b	0.083 ^{**}
120	6.581 ^b	6.625 ^{ba}	6.640 ^a	0.041 ^{**}	6.637 ^a	6.628 ^a	6.646 ^a	6.660 ^a	6.505 ^b	0.062 ^{**}
180	6.620 ^c	6.646 ^b	6.666 ^a	0.013 ^{**}	6.662 ^a	6.650 ^b	6.668 ^a	6.672 ^a	6.567 ^c	0.019 ^{**}
Mean	6.56	6.61	6.63	-	6.63	6.59	6.63	6.65	6.50	-

^aT1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt: sugar - 3:1 (30%) + Hot air drying, T5 = Salt: vinegar - 3:1 (30%) + Hot air drying. MSD = Mean significant difference; ** Means significant at 1% level; Values in columns followed by same letter do not significantly differ from each other, $p < 0.01$, Tukey's post hoc test.

Among the cultivars, 'Beldanga' maintained relatively higher TAC throughout the storage period, followed by cv. 'Bidhan Chilli-4' and 'Bullet', indicating inherent genotypic differences in organic acid composition and stability. In contrast, cv. 'Bidhan Chilli-4' consistently exhibited comparatively higher pH values, followed by 'Bullet' and 'Beldanga', suggesting varietal differences in acid composition and buffering capacity.

The interaction of cultivar and drying method significantly affected acidity and pH (Table 7). The cultivar 'Beldanga' subjected to osmo-hot air drying with salt and vinegar maintained the highest TAC during storage, indicating better preservation of organic acids compared to other cultivar-drying combinations (Table 7). In contrast, cv. 'Bullet' dried by osmo-hot air treatment with salt and sugar consistently recorded the highest pH values, reflecting comparatively lower acidity and the possible influence of osmotic treatment on the acid-base balance of the dried powder.

Drying methods had a pronounced effect on acid retention. Osmo-hot air drying with salt and vinegar resulted in higher TAC, suggesting that osmotic pre-treatment combined with acidification enhanced organic acid retention. Conversely, osmo-hot air drying with salt and sugar resulted in relatively higher pH values, possibly due to partial leaching of organic acids during osmotic treatment and the buffering effect of sugars.

Citric acid is the principal organic acid in chilli, and largely determines titratable acidity (Koh, 2005). The decline in acidity during storage is in agreement with Castro *et al.* (2002), while the increase in pH corresponds with the inverse relationship between pH and titratable acidity due to depletion of organic acids (González-Aguilar *et al.*, 1999). Organic acids may be gradually metabolized during storage, resulting in reduced acidity and a corresponding rise in pH (Mizrach *et al.*, 1997). The

Table 7: Interaction effects (mean ± SD) between cultivars and drying methods on titratable acidity content and pH value of green chilli powder at different storage intervals

Interaction effects*	Titratable acidity content (%)				pH value			
	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day
V1T1	0.076±0.004e	0.069±0.002feg	0.057±0.002fe	0.044±0.002e	6.526±0.03 ^{ba}	6.549±0.03 ^a	6.582±0.02 ^a	6.637±0.03 ^b
V1T2	0.083±0.003d	0.074±0.002e	0.062±0.002e	0.050±0.002d	6.511±0.03 ^{ba}	6.534±0.12 ^a	6.576±0.02 ^a	6.594±0.01 ^c
V1T3	0.071±0.001fe	0.064±0.002ihg	0.052±0.002fg	0.039±0.002f	6.542±0.10 ^{ba}	6.557±0.01 ^a	6.589±0.12 ^a	6.656±0.01 ^{ba}
V1T4	0.066±0.002f	0.058±0.002ikj	0.044±0.002hi	0.032±0.002h	6.566±0.07 ^{ba}	6.580±0.09 ^a	6.637±0.07 ^a	6.665±0.01 ^{ba}
V1T5	0.153±0.003a	0.138±0.003a	0.115±0.003a	0.083±0.003a	6.366±0.07 ^b	6.402±0.12 ^a	6.485±0.16 ^a	6.511±0.01 ^d
V2T1	0.051±0.001h	0.047±0.002onm	0.040±0.002ji	0.031±0.002h	6.591±0.06 ^{ba}	6.624±0.12 ^a	6.654±0.11 ^a	6.663±0.01 ^{ba}
V2T2	0.057±0.002g	0.053±0.002lkm	0.047±0.002hg	0.038±0.002g	6.582±0.16 ^{ba}	6.589±0.13 ^a	6.624±0.12 ^a	6.661±0.01 ^{ba}
V2T3	0.047±0.002ih	0.043±0.002oqp	0.038±0.002jik	0.029±0.002h	6.623±0.13 ^{ba}	6.642±0.10 ^a	6.661±0.01 ^a	6.666±0.01 ^{ba}
V2T4	0.044±0.002ij	0.039±0.002rqp	0.031±0.002mln	0.022±0.002i	6.637±0.05 ^{ba}	6.654±0.14 ^a	6.665±0.01 ^a	6.669±0.01 ^a
V2T5	0.128±0.003b	0.117±0.003b	0.101±0.003b	0.070±0.002b	6.470±0.04 ^{ba}	6.482±0.10 ^a	6.496±0.12 ^a	6.537±0.01 ^d
V3T1	0.040±0.002kj	0.035±0.002rst	0.026±0.002mopn	0.018±0.002k	6.654±0.14 ^a	6.663±0.16 ^a	6.668±0.01 ^a	6.676±0.01 ^a
V3T2	0.044±0.002ij	0.040±0.002rqp	0.032±0.002mlk	0.023±0.002i	6.637±0.04 ^a	6.654±0.14 ^a	6.665±0.01 ^a	6.672±0.01 ^a
V3T3	0.038±0.002k	0.034±0.002rst	0.025±0.002opn	0.016±0.002j	6.661±0.06 ^a	6.664±0.01 ^a	6.669±0.01 ^a	6.677±0.01 ^a
V3T4	0.035±0.002k	0.032±0.002st	0.023±0.002op	0.014±0.002j	6.663±0.07 ^a	6.665±0.01 ^a	6.672±0.01 ^a	6.679±0.01 ^a
V3T5	0.108±0.003c	0.100±0.003d	0.081±0.002c	0.051±0.002c	6.489±0.06 ^{ba}	6.496±0.06 ^a	6.513±0.05 ^a	6.591±0.01 ^c

*V1 = Beldanga, V2 = Bidhan Chilli-4; V3 = Bullet; T1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt + sugar - 3:1 (30%) + Hot air drying, T5 = Salt + vinegar - 3:1 (30%) + Hot air drying.

Data in the interaction analyzed with Least Squares Means and means separated with Tukey's post hoc test, at $p \leq 0.01$.

findings highlight that appropriate cultivar selection and drying strategies, particularly osmotic treatments incorporating acidulants, are important for maintaining acidity and ensuring the chemical stability of green chilli powder during storage.

Effect on ascorbic acid content, total phenol content and total antioxidant activity

Ascorbic acid content (AAC), total phenolic content (TPC), and total antioxidant activity (TAC) of GCP were significantly influenced by cultivar, drying method, and storage duration (Table 8). All these three parameters exhibited a consistent decline during storage period. The reduction in AAC during storage reflects the high sensitivity of ascorbic acid to oxidative and environmental stresses

Table 8: Effect of cultivars and drying methods on ascorbic acid content, total phenol content and total antioxidant activity (%) of green chilli powder at different storage intervals

Days in storage	Cultivars			MSD	Drying methods					MSD
	Beldanga	Bidhan Chilli-4	Bullet		T1 ^a	T2	T3	T4	T5	
Ascorbic acid content (mg 100 g⁻¹)										
0	47.40 ^a	46.20 ^b	44.20 ^c	0.469 ^{**}	45.67 ^c	47.67 ^b	43.67 ^d	42.67 ^e	50.00 ^a	0.708 ^{**}
60	46.15 ^a	44.95 ^b	42.95 ^c	0.343 ^{**}	44.42 ^c	46.42 ^b	42.42 ^d	41.42 ^e	48.75 ^a	0.517 ^{**}
120	43.90 ^a	42.70 ^b	40.70 ^c	0.355 ^{**}	42.17 ^c	44.17 ^b	40.17 ^d	39.17 ^e	46.50 ^a	0.535 ^{**}
180	40.20 ^a	39.10 ^b	37.10 ^c	0.230 ^{**}	38.67 ^c	40.67 ^b	36.67 ^d	35.67 ^e	42.33 ^a	0.346 ^{**}
Mean	44.41	43.24	41.24	-	42.73	44.73	40.73	39.73	46.90	-
Total phenol content (mg GAE 100 g⁻¹)										
0	415.52 ^a	395.71 ^b	367.89 ^c	5.02 ^{**}	380.62 ^d	370.47 ^e	391.21 ^c	422.12 ^a	400.78 ^b	7.57 ^{**}
60	402.53 ^a	385.24 ^b	358.85 ^c	4.15 ^{**}	370.18 ^d	360.65 ^e	379.54 ^c	410.67 ^a	390.00 ^b	6.26 ^{**}
120	378.41 ^a	365.91 ^b	338.86 ^c	4.27 ^{**}	349.93 ^d	340.33 ^e	359.18 ^c	386.38 ^a	369.49 ^b	6.44 ^{**}
180	342.94 ^a	336.40 ^b	311.02 ^c	5.18 ^{**}	320.15 ^d	311.47 ^e	329.02 ^c	351.56 ^a	338.42 ^b	7.82 ^{**}
Mean	384.85	370.82	344.16	-	355.22	345.73	364.74	392.68	374.67	-
Total antioxidant activity (%)										
0	74.76 ^c	82.56 ^a	80.72 ^b	0.635 ^{**}	78.93 ^{bc}	78.30 ^c	79.35 ^{bac}	80.30 ^a	79.86 ^{ba}	0.958 ^{**}
60	74.24 ^c	81.90 ^a	80.13 ^b	0.462 ^{**}	78.36 ^{dc}	77.78 ^d	78.75 ^{bc}	79.66 ^a	79.25 ^{ba}	0.698 ^{**}
120	73.31 ^c	80.84 ^a	79.14 ^b	0.654 ^{**}	77.40 ^c	76.85 ^c	77.74 ^{bac}	78.62 ^a	78.22 ^{ba}	0.986 ^{**}
180	71.01 ^c	78.20 ^a	76.67 ^b	0.444 ^{**}	74.97 ^{bc}	74.54 ^c	75.24 ^{bc}	76.05 ^a	75.68 ^{ba}	0.669 ^{**}
Mean	73.33	80.88	79.17	-	77.42	76.87	77.77	78.66	78.25	-

^aT1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt: sugar - 3:1 (30%) + Hot air drying, T5 = Salt: vinegar - 3:1 (30%) + Hot air drying. MSD = Mean significant difference; ^{**} Means significant at 1% level; Values in columns followed by same letter do not significantly differ from each other, $p < 0.01$, Tukey's post hoc test

such as oxygen, light, and residual moisture, even in dried products. Similarly, total phenolic content showed a gradual decrease throughout storage across all cultivars and drying treatments, indicating progressive degradation and transformation of phenolic compounds, which are highly susceptible to oxidative and enzymatic reactions. The slow but consistent decline in total antioxidant activity further suggests a cumulative loss of antioxidant capacity during storage, mainly due to the degradation of bioactive compounds such as ascorbic acid and phenolics.

Among the cultivars, cv. 'Beldanga' consistently retained higher AAC and TPC than other two cultivars, indicating inherent varietal differences in initial vitamin C concentration, phenolic composition and its stability during processing and storage. In contrast, cv. 'Bidhan Chilli-4' consistently exhibited higher TAC compared to other cultivars, indicating better retention of antioxidant constituents and greater resistance to storage-induced oxidative degradation.

Drying method also played a crucial role in the preservation of these bioactive compounds. Osmo-hot air drying with salt and vinegar resulted in higher retention of AAC during storage, possibly due to the combined effects of osmotic dehydration and acidification, which reduced oxygen availability and inhibited oxidative degradation of vitamin C. Conversely, osmo-hot air drying with salt and sugar maintained comparatively higher TPC and TAC values, indicating that osmotic pre-treatment may protect phenolic compounds and antioxidant molecules by limiting oxygen diffusion and minimizing structural damage to heat-sensitive constituents. The superior retention of AAC in 'Beldanga' under osmo-hot air drying with salt and vinegar, and the higher TPC and TAC observed in 'Beldanga' and 'Bidhan Chilli-4', respectively, under osmo-hot air drying

Table 9: Interaction effects (mean \pm SD) between cultivars and drying methods on ascorbic acid content, total phenol content and total antioxidant activity of green chilli powder at different storage intervals

Interaction effects*	Ascorbic acid content (mg 100 g ⁻¹)				Total phenol content (mg GAE 100 g ⁻¹)				Total antioxidant activity (%)			
	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day	0 day	60 day	120 day	180 day
V1T1	47.00 $\pm 1.00^{cd}$	46.00 $\pm 0.40^{higi}$	44.00 $\pm 0.62^{df}$	41.00 $\pm 0.50^{ed}$	403.57 $\pm 17.27^{bedc}$	392.37 $\pm 5.92^{egdfh}$	370.64 $\pm 5.64^{egfhi}$	336.12 $\pm 6.59^{fgdech}$	74.37 $\pm 1.47^c$	73.89 $\pm 1.46^d$	73.01 $\pm 0.30^c$	70.81 $\pm 0.29^e$
V1T2	49.00 $\pm 1.41^{bc}$	48.00 $\pm 0.72^{dce}$	46.00 $\pm 1.00^{bcd}$	43.00 $\pm 1.00^{cb}$	391.12 $\pm 15.68^{fged}$	380.54 $\pm 9.43^{gikih}$	358.15 $\pm 4.65^{mgilkhi}$	324.61 $\pm 7.87^{fgiejh}$	73.83 $\pm 1.76^c$	73.38 $\pm 1.45^d$	72.53 $\pm 0.30^c$	70.41 $\pm 0.80^e$
V1T3	45.00 $\pm 1.10^{efg}$	44.00 $\pm 0.45^{jkm}$	42.00 $\pm 0.62^{hgf}$	39.00 $\pm 0.25^{ef}$	414.69 $\pm 6.00^{bcd}$	402.15 $\pm 8.26^{egdfc}$	379.28 $\pm 7.94^{egdfc}$	345.03 $\pm 8.24^{fbdec}$	74.7 $\pm 1.01^c$	74.2 $\pm 1.46^d$	73.3 $\pm 1.04^c$	71.05 $\pm 0.29^e$
V1T4	44.00 $\pm 0.62^{hfg}$	43.00 $\pm 0.49^{lnom}$	41.00 $\pm 0.48^{hgi}$	38.00 $\pm 0.25^{sh}$	445.48 $\pm 6.52^a$	433.30 $\pm 8.53^a$	409.73 $\pm 5.45^a$	374.24 $\pm 15.38^a$	75.66 $\pm 1.11^c$	75.14 $\pm 0.31^d$	74.22 $\pm 1.51^{bc}$	71.92 $\pm 1.42^e$
V1T5	52.00 $\pm 0.75^a$	51.00 $\pm 0.52^a$	49.00 $\pm 1.00^a$	45.00 $\pm 1.00^a$	422.73 $\pm 6.11^{bac}$	411.06 $\pm 3.64^{ebdac}$	388.92 $\pm 9.57^{ebdac}$	354.37 $\pm 6.47^{bdac}$	75.24 $\pm 1.06^c$	74.73 $\pm 0.31^d$	73.82 $\pm 1.46^c$	71.55 $\pm 0.84^e$
V2T1	46.00 $\pm 0.50^{efd}$	45.00 $\pm 0.45^{hiki}$	43.00 $\pm 0.62^{gfr}$	40.00 $\pm 0.46^{ef}$	382.64 $\pm 10.49^{geh}$	373.48 $\pm 5.29^{jkih}$	355.46 $\pm 7.36^{mjnkhi}$	328.37 $\pm 8.29^{fgeih}$	82.11 $\pm 2.00^{ba}$	81.52 $\pm 1.61^{bac}$	80.53 $\pm 1.59^a$	78.06 $\pm 1.30^{bdac}$
V2T2	48.00 $\pm 1.45^{bcd}$	47.00 $\pm 0.48^{dfge}$	45.00 $\pm 1.00^{edc}$	42.00 $\pm 0.50^{ed}$	373.21 $\pm 15.59^{fghi}$	364.18 $\pm 7.52^{lkjkn}$	346.24 $\pm 2.31^{moqnp}$	319.48 $\pm 6.25^{fgikih}$	81.43 $\pm 1.66^{ba}$	80.89 $\pm 0.72^{bac}$	79.95 $\pm 0.34^a$	77.6 $\pm 0.93^{bdac}$
V2T3	44.00 $\pm 0.61^{hfg}$	43.00 $\pm 0.63^{lnom}$	41.00 $\pm 0.48^{hgi}$	38.00 $\pm 0.20^{sh}$	394.43 $\pm 5.98^{fgedc}$	384.24 $\pm 1.94^{gjfih}$	366.52 $\pm 10.41^{egjfkhi}$	337.61 $\pm 6.30^{fgdech}$	82.62 $\pm 1.64^{ba}$	81.99 $\pm 1.62^{ba}$	80.96 $\pm 1.60^a$	78.39 $\pm 0.38^{bdac}$
V2T4	43.00 $\pm 0.62^{hig}$	42.00 $\pm 0.57^{pmoq}$	40.00 $\pm 1.00^{hji}$	37.00 $\pm 0.50^{ih}$	426.12 $\pm 6.21^{ba}$	417.36 $\pm 8.53^{bac}$	399.75 $\pm 5.09^{bac}$	368.57 $\pm 8.94^{ba}$	83.56 $\pm 0.35^a$	82.91 $\pm 0.35^a$	81.86 $\pm 1.20^a$	79.23 $\pm 0.56^a$
V2T5	50.00 $\pm 0.70^{ba}$	49.00 $\pm 0.51^{bc}$	47.00 $\pm 1.00^{bac}$	43.50 $\pm 0.50^b$	402.14 $\pm 9.93^{fbdec}$	393.37 $\pm 8.18^{egdfch}$	375.63 $\pm 6.00^{egdfh}$	346.73 $\pm 11.14^{bdec}$	83.11 $\pm 0.64^{ba}$	82.47 $\pm 0.35^{ba}$	81.43 $\pm 1.15^a$	78.83 $\pm 1.61^{ba}$
V3T1	44.00 $\pm 0.60^{hfg}$	43.00 $\pm 0.54^{lnom}$	41.00 $\pm 0.25^{hgi}$	38.00 $\pm 0.25^{sh}$	355.65 $\pm 7.11^{hi}$	348.61 $\pm 3.48^{mnop}$	332.25 $\pm 10.13^{opqr}$	307.37 $\pm 3.89^{jki}$	80.31 $\pm 1.04^{ba}$	79.78 $\pm 0.34^{bc}$	78.85 $\pm 1.92^a$	76.53 $\pm 0.79^{bdac}$
V3T2	46.00 $\pm 1.00^{efcd}$	45.00 $\pm 0.43^{hiki}$	43.00 $\pm 0.50^{egf}$	40.00 $\pm 0.50^{ef}$	347.09 $\pm 6.17^i$	340.45 $\pm 7.40^{op}$	324.19 $\pm 3.89^{qr}$	300.79 $\pm 4.46^{jk}$	79.65 $\pm 0.34^b$	79.15 $\pm 0.33^c$	78.25 $\pm 1.59^a$	76.81 $\pm 0.32^d$
V3T3	42.00 $\pm 0.62^{hi}$	41.00 $\pm 0.57^{pmsq}$	39.00 $\pm 0.36^{kji}$	36.00 $\pm 0.25^{ij}$	364.52 $\pm 7.72^{shi}$	356.25 $\pm 6.78^{lmknop}$	340.32 $\pm 5.42^{moqnp}$	315.82 $\pm 7.28^{gikih}$	80.73 $\pm 0.66^{ba}$	80.17 $\pm 0.62^{bac}$	79.21 $\pm 0.33^a$	76.81 $\pm 1.52^{bdac}$
V3T4	41.00 $\pm 0.48^i$	40.00 $\pm 0.36^{rs}$	38.00 $\pm 0.25^{kj}$	35.00 $\pm 0.50^{kj}$	394.76 $\pm 12.35^{fgedc}$	385.48 $\pm 9.02^{gjfih}$	358.43 $\pm 8.07^{mgilkhi}$	323.46 $\pm 7.73^{fgiejh}$	81.67 $\pm 0.80^{ba}$	81.09 $\pm 0.33^{bac}$	80.11 $\pm 1.58^a$	77.66 $\pm 0.64^{bdac}$
V3T5	48.00 $\pm 0.23^{bcd}$	47.00 $\pm 0.18^{dfge}$	45.00 $\pm 0.50^{dc}$	41.50 $\pm 0.50^d$	377.44 $\pm 9.07^{fgeh}$	369.66 $\pm 11.44^{lmjknih}$	352.63 $\pm 7.37^{mojlunki}$	325.66 $\pm 8.40^{fgiejh}$	81.23 $\pm 0.34^{ba}$	80.66 $\pm 0.34^{bac}$	79.69 $\pm 0.33^a$	77.27 $\pm 0.33^{bdac}$

*V1 = Beldanga, V2 = Bidhan Chilli-4; V3 = Bullet; T1 = Hot air drying, T2 = Sun drying, T3 = Salt (30%) + Hot air drying, T4 = Salt + sugar - 3:1 (30%) + Hot air drying, T5 = Salt + vinegar - 3:1 (30%) + Hot air drying.

Data in the interaction analysed with Least Squares Means and means separated with Tukey's post hoc test, at $p \leq 0.01$

with salt and sugar, highlighting the combined influence of cultivar characteristics and drying strategies in preserving antioxidant compounds during storage (Table 9). The results demonstrate that both genetic factors and appropriate drying methods play vital role in maintaining the antioxidant quality of green chilli powder during storage.

The progressive decline in ascorbic acid content (AAC) during storage is consistent with the findings of Tummala *et al.* (2008), who reported similar reductions in chilli powder stored in polymeric packaging materials. Ascorbic acid degradation is accelerated by exposure to heat, light, oxygen, and unfavourable humidity conditions (Nunes and Emond, 1999). During drying and storage, ascorbic acid undergoes oxidative conversion to L-dehydroascorbic acid followed by further breakdown into other degradation products, particularly under elevated temperature and light exposure (Vega-Gálvez *et al.*, 2008). Although drying reduces enzymatic activity, non-enzymatic oxidative reactions may continue during storage, contributing to the gradual loss of AAC. These results highlight the importance of selecting suitable cultivar–drying combinations to improve vitamin C retention in green chilli powder.

Changes in total phenolic content (TPC) during drying and storage are associated with several chemical and biochemical reactions. Elevated drying temperatures can disrupt cellular structures, increasing interaction between phenolic substrates and oxidative enzymes, which promotes phenolic oxidation and subsequent losses (Torki-Harchegani *et al.*, 2016). Heat may also cause cleavage of glycosidic and ester linkages of phenolic compounds, further reducing measurable TPC (Zhou *et al.*, 2016). During storage, residual enzymatic activities such as phenylalanine ammonia lyase and polyphenol oxidase may continue at reduced rates, leading to gradual degradation of phenolic compounds (Hameed *et al.*, 2017). Therefore, cultivars rich in phenolics, such as ‘Beldanga’, combined with protective drying treatments can help improve phenolic retention.

Chillies are also valued for their overall antioxidant capacity. The observed decline in total antioxidant activity (TAC) during storage suggests progressive degradation and interactions among antioxidant constituents. This reduction may result from oxidative degradation or structural changes in key antioxidant compounds such as ascorbic acid, rutin, and phenolic acids (Teles *et al.*, 2018). Temperature and storage conditions strongly influence the rate of these reactions. Overall, the findings indicate that antioxidant stability in GCP depends on both cultivar and drying method, with osmo-hot air drying with salt and sugar appearing effective in maintaining antioxidant activity during storage.

Sensory evaluation

Green chilli powder incorporated into salted mashed potato was generally well accepted by the panelists, indicating its suitability for culinary application. Overall acceptability (OA) scores differed among the cultivars, with ‘Bidhan Chilli-4’ receiving higher preference than ‘Bullet’ and ‘Beldanga’ (Table 10). This suggests that cultivar-specific flavour profile, colour, and pungency intensity play a decisive role in consumer acceptance of chilli powder-based products.

Drying method significantly influenced sensory perception. Oven-dried chilli powder samples consistently received higher OA scores, primarily due to their distinct flavour and balanced pungency. The superior acceptability of oven-dried samples may be attributed to better retention of desirable aroma compounds and an optimal pungency level. In contrast, sun-dried and osmo-air dried samples exhibited comparatively lower acceptability, likely due to reduced pungency associated with lower capsaicin retention, which diminished the characteristic “chilli heat” expected by panelists.

A gradual decline in OA scores was observed from initial storage to the end of the storage period, irrespective of cultivar and drying method. This reduction in acceptability can be linked to storage-induced changes in flavour, aroma, and pungency, possibly resulting from degradation of capsaicin and volatile compounds over time. Although processing and cultivar selection strongly influence initial sensory quality, prolonged storage adversely affects consumer acceptance of GCP.

Overall, the results indicate that ‘Bidhan Chilli-4’ processed through oven drying offers the most

Table 10: Changes in the sensory attributes of green chilli powder during ambient storage

Treatment combinations	Cultivars	Colour		Flavour		Acceptability	
		Days in storage		Days in storage		Days in storage	
		0	180	0	180	0	180
T1- Hot air drying at 60°C for 48 ± 1 h	Beldanga	7.90 ^b	6.65 ^b	7.65 ^c	6.90 ^c	7.80 ^c	7.15 ^c
	Bidhan Chilli-4	8.30 ^a	7.01 ^a	8.15 ^b	7.40 ^b	8.20 ^a	7.55 ^a
	Bullet	7.69 ^c	6.50 ^c	8.50 ^a	7.75 ^a	7.92 ^b	7.45 ^b
T2 - Sun drying for 8 ± 1 day	Beldanga	7.54 ^b	5.94 ^b	7.35 ^c	6.30 ^c	7.50 ^c	6.34 ^c
	Bidhan Chilli-4	7.60 ^a	6.10 ^a	7.50 ^b	6.42 ^b	7.56 ^a	6.55 ^a
	Bullet	7.45 ^c	5.85 ^c	8.05 ^a	7.10 ^a	7.52 ^b	6.45 ^b
T3 - Osmo-hot air drying (dipping in 30% salt for 120 min, drained out the solution & then hot air drying at 60°C for 30 ± 1 h)	Beldanga	7.63 ^b	6.25 ^b	7.55 ^c	6.70 ^c	7.85 ^c	7.20 ^c
	Bidhan Chilli-4	8.02 ^a	6.80 ^a	8.05 ^b	7.21 ^b	8.27 ^a	7.64 ^a
	Bullet	7.48 ^c	6.18 ^c	8.30 ^a	7.50 ^a	8.06 ^b	7.52 ^b
T4 - Osmo-hot air drying (dipping in 30% salt + sugar (3:1) for 120 min [#] followed by hot air drying at 60°C for 30 ± 1 h)	Beldanga	7.70 ^b	6.34 ^b	7.52 ^c	6.65 ^c	7.90 ^c	7.25 ^c
	Bidhan Chilli-4	8.10 ^a	6.88 ^a	7.99 ^b	7.14 ^b	8.33 ^a	7.70 ^a
	Bullet	7.54 ^c	6.27 ^c	8.23 ^a	7.41 ^a	8.15 ^b	7.58 ^b
T5 - Osmo-hot air drying (dipping in 30% salt+vinegar (3:1) for 120 min followed by hot air drying at 60°C for 30 ± 1 h)	Beldanga	7.82 ^b	6.46 ^b	7.61 ^c	6.82 ^c	8.15 ^c	7.45 ^c
	Bidhan Chilli-4	8.21 ^a	6.94 ^a	8.10 ^b	7.31 ^b	8.48 ^a	7.87 ^a
	Bullet	7.62 ^c	6.41 ^c	8.37 ^a	7.64 ^a	8.33 ^b	7.64 ^b

Means with different superscripts differ significantly ($p < .01$, Tukey's post-hoc test). Sensory attributes were evaluated by 1-9 hedonic scale (9 = Like extremely; 8 = Like very much; 7 = Like moderately; 6 = Like slightly; 5 = Neither like nor dislike; 4 = Dislike slightly; 3 = Dislike moderately; 2 = Dislike very much; 1 = Dislike extremely)

most favourable balance of flavour and pungency, leading to higher consumer acceptability. Moreover, maintaining sensory quality during storage remains a key challenge and should be considered when selecting drying methods and storage conditions for chilli powder intended for long-term use.

Conclusions: The present study confirms that both cultivar and drying technique significantly affect the physicochemical, bioactive, and sensory attributes of green chilli powder during ambient storage. Osmo-hot air drying enhanced drying efficiency, while hot air drying ensured lower moisture content, better capsaicin retention, and improved pungency with good storage stability. In contrast, osmotic treatments with salt + sugar or salt + vinegar were more effective in preserving antioxidants and organic acids. Overall, appropriate cultivar–drying combinations are essential for producing nutritionally superior, storage-stable, and consumer-acceptable green chilli powder for commercial applications.

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Data availability statement: The data that support the findings of this study are available from the corresponding author, Ivi Chakraborty, upon reasonable request.

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