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Interaction effects of genotypes and storage media on corm storability and floral traits in gladiolus (*Gladiolus* × *grandiflorus*) under cold storage conditions

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ABSTRACT

Cold storage effectively breaks dormancy and synchronises sprouting in gladiolus (*Gladiolus* × *grandiflorus* L.) corms, yet sub-optimal relative humidity in these environments frequently induces severe physiological desiccation and the depletion of vital metabolic reserves. An experiment was conducted in 2024 and 2025 at ICAR-Indian Agricultural Research Institute, New Delhi to evaluate the efficacy of storage media in mitigating physiological desiccation of gladiolus corms under cold storage (6 ± 1°C). The experiment was laid out in a factorial completely randomised design (F-RCBD) with five genotypes ('Pusa Shanti', 'Pusa Mohini', 'Pusa Manmohak', 'Jyotsna' and 'Creamy Green') and three storage media (control, cocopeat and sand). Results revealed that cocopeat was most effective medium for preserving corm physiology, recording less deterioration of weight (4.87%) and advancing sprouting (92.35 days). Genotypically, 'Pusa Mohini' exhibited superior storage performance with maximum corm weight (72.30 g initial, 69.87 g final), while 'Creamy Green' showed the lowest shrinkage (3.75%). Although cocopeat accelerated spike emergence (74.36 days), sand proved superior for field performance, significantly enhancing sprouting (89.71%), floret longevity (4.91 days) and spike length (71.78 cm). Significant genotype × media interactions indicated that 'Pusa Mohini' stored in cocopeat is ideal for earliness and corm yield, whereas 'Creamy Green' stored in sand produced the longest spikes (79.25 cm), suitable for the cut-flower industry. Ultimately, this study concludes that cocopeat effectively buffers against cold-induced desiccation while sand optimises vegetative and floral quality. These findings support developing variety-specific storage protocols to minimise postharvest losses and enhance gladiolus productivity in India.

Keywords: Cold storage, Corm desiccation, Gladiolus, Post-harvest quality, Storage media

Gladiolus (*Gladiolus* × *grandiflorus* L.), a member of the family Iridaceae, is one of the most important bulbous ornamentals cultivated worldwide for its majestic spikes and excellent keeping quality. It occupies a significant position in both domestic and export floriculture markets (Bhattacharjee 2006). In India, the release of improved genotypes such as 'Pusa Shanti', 'Pusa Mohini', 'Pusa Manmohak', 'Jyotsna' and 'Creamy Green' has expanded the scope of cultivation across diverse agro-climatic zones. The commercial success of these cultivars is closely linked to the physiological health of corms, which determines vegetative vigour, spike quality and multiplication efficiency. Post-harvest management of corms is a critical stage in gladiolus production. Cold storage at 4–7°C is widely practiced to break dormancy and ensure uniform sprouting, but sub-optimal relative humidity in cold chambers often leads to desiccation, shrivelling and depletion of carbohydrate reserves essential for early growth. Identifying suitable storage media that stands against moisture loss without inducing fungal rot is needed for maintaining corm quality during storage (Dudhat *et al.* 2023). Larger corms with higher food reserves have been shown to perform better under storage and field conditions (Srivastav *et al.* 2025) while genotypic variation in corm density and dry matter content also influences storability.

Traditionally, river sand has been used for stratification because of its aeration and drainage properties. However, cocopeat, offers high porosity and superior water-holding capacity, making it a promising medium to counter cold-induced desiccation (Karaguzel 2023). Recent studies have also highlighted the role of substrate structure and aeration in influencing sprouting and spike quality (Dudhat *et al.* 2023). Pathological concerns remain important, as *Fusarium oxysporum* is a major cause of corm rot and integrated management strategies using resistant varieties and biocontrol agents have been reported (Yasmin *et al.* 2018). Despite the availability of storage protocols (Amingad *et al.* 2013), information on the specific interaction between improved Indian gladiolus genotypes and storage media under controlled cold conditions remains limited. Hence, the present study was undertaken to evaluate the efficacy of cocopeat and sand compared to open storage at 6 ± 1°C,

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with the objective of standardising variety-specific storage protocols to minimise post-harvest losses and enhance gladiolus productivity in India.

MATERIALS AND METHODS

Experimental setup: The experiment was conducted in 2024 and 2025 at ICAR-Indian Agricultural Research Institute (28°38´N, 77°09´E; at an elevation of 228.6 m amsl), New Delhi. The study utilised a factorial completely randomised design (FCRD) comprising 15 treatment combinations involving five gladiolus varieties [‘Pusa Shanti’ (V_1), ‘Pusa Mohini’ (V_2), ‘Pusa Manmohak’ (V_3), ‘Jyotsna’ (V_4) and ‘Creamy Green’ (V_5)] and three storage media [open condition/control (M_0), cocopeat (M_1) and sand (M_2)]. Healthy corms were treated with carbendazim (0.2%) for 30 min and air-dried. The corms were subsequently stored in plastic crates containing the respective sterilised media (or no media for the open conditions) inside a cold storage chamber maintained at 6 ± 1°C with 70 ± 5% relative humidity for 90 days. Each treatment was replicated 5 times with 10 corms/replication.

Physiological and pathological observations: Observations on corm attributes were recorded before and after storage. The per cent reduction in corm weight and diameter was calculated based on the difference between initial and final values. Corm rotting (%) and disease incidence (%) were recorded based on visual observations of softening, discolouration and decay. Sprouting parameters, including days taken to sprout, number of sprouts/corm and sprouting %, were recorded under both storage and field conditions.

Field performance and floral biology: After storage, corms were planted in the field to evaluate vegetative and reproductive recovery. Phenological data were recorded for days to spike emergence and days to first floret opening. Recorded quantitative traits included plant height, spike length, rachis length, number of florets/spike and floret longevity (days from opening to senescence of the basal floret).

Statistical analysis: Data from both seasons were pooled and subjected to two-way analysis of variance (ANOVA) using R software (version 4.5.2) (R Core Team 2024). Treatment means were compared using Duncan’s Multiple Range Test (DMRT) at $p \leq 0.05$. Percentage data (rotting, sprouting, weight loss) were arcsine-transformed to normalise variance. Trait associations were visualised through Pearson’s correlation heatmaps and hierarchical clustering (Euclidean distance, Ward’s linkage), following established approaches in gladiolus physiology and postharvest studies (Ahmed *et al.* 2019).

RESULTS AND DISCUSSION

Significant variations ($p \leq 0.05$) were observed in corm attributes across cultivars and storage media (Table 1). ‘Pusa Mohini’ recorded the maximum initial (72.30 g) and final (69.87 g) mean corm weight, whereas ‘Pusa Manmohak’ registered the minimum (33.95 and 31.40 g, respectively),

Table 1　Effect of storage media on the corm weight attributes in different gladiolus varieties

Variety	Initial corm weight (g)				Final corm weight (g)				Corm weight reduction (%)			
	M_0	M_1	M_2	Mean (V)	M_0	M_1	M_2	Mean (V)	M_0	M_1	M_2	Mean (V)
V_1	$52.66^{f} \pm 1.40$	$55.67^{e} \pm 1.66$	$58.19^{d} \pm 1.52$	$55.51^{B} \pm 2.74$	$47.28^{g} \pm 1.72$	$52.65^{de} \pm 1.14$	$54.21^{d} \pm 1.27$	$51.38^{B} \pm 3.37$	$10.21^{b} \pm 0.41$	$5.47^{e} \pm 0.18$	$6.54^{d} \pm 0.07$	$7.41^{A} \pm 2.17$
V_2	$65.82^{c} \pm 2.73$	$81.69^{a} \pm 0.07$	$69.39^{b} \pm 1.56$	$72.30^{A} \pm 7.38$	$63.46^{c} \pm 1.43$	$79.25^{a} \pm 0.29$	$66.91^{b} \pm 2.05$	$69.87^{A} \pm 7.30$	$3.77^{g} \pm 0.03$	$3.13^{h} \pm 0.13$	$3.60^{g} \pm 0.14$	$3.50^{D} \pm 0.30$
V_3	$35.95^{i} \pm 0.45$	$33.07^{j} \pm 0.54$	$32.84^{j} \pm 0.50$	$33.95^{E} \pm 1.56$	$31.89^{i} \pm 0.60$	$30.95^{i} \pm 0.81$	$31.37^{i} \pm 1.33$	$31.40^{E} \pm 0.93$	$11.34^{a} \pm 0.49$	$6.56^{d} \pm 0.26$	$4.47^{f} \pm 0.15$	$7.46^{A} \pm 3.06$
V_4	$39.50^{h} \pm 0.07$	$39.12^{h} \pm 0.74$	$35.32^{i} \pm 0.73$	$37.98^{D} \pm 2.07$	$37.36^{h} \pm 0.98$	$37.39^{h} \pm 1.52$	$32.64^{i} \pm 0.68$	$35.80^{D} \pm 2.56$	$5.34^{e} \pm 0.08$	$4.56^{f} \pm 0.15$	$7.57^{c} \pm 0.08$	$5.82^{B} \pm 1.36$
V_5	$47.76^{g} \pm 0.90$	$53.32^{f} \pm 0.73$	$51.54^{f} \pm 2.18$	$50.87^{C} \pm 2.75$	$46.04^{g} \pm 2.00$	$51.09^{ef} \pm 1.65$	$49.97^{f} \pm 1.62$	$49.03^{C} \pm 2.76$	$3.61^{g} \pm 0.07$	$4.63^{f} \pm 0.20$	$3.01^{h} \pm 0.06$	$3.75^{C} \pm 0.72$
Mean (M)	$48.34^{C} \pm 10.99$	$52.57^{A} \pm 17.46$	$49.46^{B} \pm 14.35$		$45.21^{C} \pm 11.19$	$50.27^{A} \pm 17.26$	$47.02^{B} \pm 14.00$		$6.85^{A} \pm 3.40$	$4.87^{C} \pm 1.18$	$5.04^{B} \pm 1.81$	
LSD ($p \leq 0.05$)	V = 1.239 M = 0.960 V × M= 2.146				V = 1.316 M = 1.020 V × M= 2.280				V = 0.201 M = 0.156 V × M= 0.349			

V, Variety; M, Medium. Values are Mean ± SEm. Means followed by the same letter(s) do not differ significantly at $p \leq 0.05$ (Fisher’s LSD). Treatment details are given under Materials and Methods.

attributed to inherent genetic constitution. Among media, cocopeat was superior with the highest initial mean weight (52.57 g), followed by sand (49.46 g) and open conditions (48.34 g). The significant variety × medium interaction showed 'Pusa Mohini' in cocopeat attained maximum initial (81.69 g) and final (79.25 g) weight. Regarding physiological loss in weight (PLW), 'Pusa Mohini' exhibited minimum reduction (3.50%), followed by 'Creamy Green' (3.75%), owing to thicker tunics. Cocopeat recorded the lowest PLW (4.87%), significantly superior to sand (5.04%) and open storage (6.85%), likely due to high porosity and moisture retention (Karaguzel 2023) and differential respiration rates (Kirad *et al.* 2001).

Corm diameter also varied significantly among the cultivars. 'Pusa Mohini' recorded maximum initial (66.96 mm) and final (62.48 mm) values, while 'Pusa Manmohak' (51.03 mm) and 'Jyotsna' (52.53 mm) were statistically at par with the minimum (Table 2), consistent with sink capacity evaluations (Kadam *et al.* 2014). Cocopeat (58.58 mm) and sand (58.24 mm) were at par and superior to open conditions (56.58 mm). 'Pusa Mohini' under cocopeat achieved the highest final diameter (64.92 mm). Corm shrinkage was lowest in 'Creamy Green' (5.17%) and highest in 'Pusa Manmohak' (9.73%), influenced by dry matter content (Swaroop *et al.* 2023). Notably, 'Jyotsna' showed high reduction in open conditions (12.71%) but improved in cocopeat (5.66%). Sand proved to be most effective in minimising shrinkage (6.00%) compared to cocopeat (6.84%) and open storage (8.79%), likely due to better aeration (Jabbar *et al.* 2018). Consequently, 'Pusa Shanti', 'Pusa Manmohak' and 'Creamy Green' peaked in sand, reinforcing genotype-specific drainage preferences (Kumar 2015).

Rotting and disease incidence: Significant variation in pathological parameters was observed among cultivars and storage media (Table 3). 'Pusa Shanti' recorded the maximum mean rotting (15.42%), whereas 'Jyotsna' (0.80%) and 'Creamy Green' (1.35%) recorded the minimum. Cocopeat exhibited significantly higher rotting (5.72%) compared to sand (4.17%) and open conditions (4.13%), attributed to high water-holding capacity favouring *Fusarium oxysporum* (Riaz *et al.* 2010). The significant variety × medium interaction revealed that 'Pusa Shanti' stored in cocopeat suffered the highest rotting (19.34%), while 'Jyotsna' remained resilient across media (0.62–0.93%), highlighting genetic resistance (Sriram and Chandran 2016). Similarly, the interaction for disease incidence showed 'Pusa Manmohak' in cocopeat recorded the maximum value (14.45%). Sand proved to be most effective for disease suppression, with 'Creamy Green' recording the lowest incidence (0.63%) in this medium, likely due to rapid drainage restricting pathogen colonisation (Singh *et al.* 2017).

Sprouting phenology: Significant differences in days to sprout were observed among cultivars and storage media (Table 3, Fig. 1). 'Pusa Manmohak' required the maximum mean duration (100.72 days), whereas 'Jyotsna' sprouted earliest (89.15 days), a variation governed by endogenous

Table 2 Effect of storage media on the corm diameter attributes in different gladiolus varieties

Variety	Initial corm diameter (mm)				Final corm diameter (mm)				Corm diameter reduction (%)			
	M_0	M_1	M_2	Mean (V)	M_0	M_1	M_2	Mean (V)	M_0	M_1	M_2	Mean (V)
V_1	$57.58^{d} \pm 0.91$	$59.28^{cd} \pm 2.24$	$60.55^{c} \pm 1.86$	$59.14^{B} \pm 2.00$	$53.37^{f} \pm 0.68$	$55.03^{ef} \pm 1.00$	$57.14^{cd} \pm 0.15$	$55.18^{C} \pm 1.75$	$7.31^{d} \pm 0.22$	$7.17^{d} \pm 0.17$	$5.63^{f} \pm 0.14$	$6.70^{C} \pm 0.82$
V_2	$66.27^{b} \pm 1.61$	$69.28^{a} \pm 2.81$	$65.32^{b} \pm 0.30$	$66.96^{A} \pm 2.42$	$62.01^{b} \pm 0.95$	$64.92^{a} \pm 0.29$	$60.52^{b} \pm 0.60$	$62.48^{A} \pm 2.02$	$6.43^{e} \pm 0.28$	$6.24^{e} \pm 0.22$	$7.35^{d} \pm 0.14$	$6.67^{C} \pm 0.55$
V_3	$49.12^{g} \pm 0.35$	$50.81^{fg} \pm 2.06$	$53.16^{ef} \pm 2.01$	$51.03^{C} \pm 2.28$	$43.14^{j} \pm 0.51$	$45.91^{i} \pm 1.70$	$49.24^{h} \pm 0.71$	$46.10^{E} \pm 2.81$	$12.17^{b} \pm 0.37$	$9.64^{c} \pm 0.14$	$7.37^{d} \pm 0.26$	$9.73^{A} \pm 2.09$
V_4	$52.79^{ef} \pm 0.43$	$54.05^{e} \pm 0.73$	$50.76^{fg} \pm 1.83$	$52.53^{C} \pm 1.76$	$46.08^{i} \pm 1.83$	$50.99^{g} \pm 0.09$	$48.23^{h} \pm 0.96$	$48.43^{D} \pm 2.37$	$12.71^{a} \pm 0.37$	$5.66^{f} \pm 0.06$	$4.98^{g} \pm 0.11$	$7.78^{B} \pm 3.71$
V_5	$57.14^{d} \pm 0.88$	$59.46^{cd} \pm 2.23$	$61.39^{c} \pm 2.21$	$59.33^{B} \pm 2.46$	$54.09^{f} \pm 0.10$	$56.25^{de} \pm 0.40$	$58.51^{c} \pm 2.00$	$56.28^{B} \pm 2.17$	$5.34^{f} \pm 0.20$	$5.48^{f} \pm 0.11$	$4.69^{g} \pm 0.08$	$5.17^{D} \pm 0.39$
Mean (M)	$56.58^{B} \pm 6.00$	$58.58^{A} \pm 6.74$	$58.24^{A} \pm 5.81$		$45.21^{C} \pm 11.19$	$50.27^{A} \pm 17.26$	$47.02^{B} \pm 14.00$		$8.79^{A} \pm 3.17$	$6.84^{B} \pm 1.58$	$6.00^{C} \pm 1.20$	
LSD ($p \leq 0.05$)	V = 1.630 M = 1.263 V × M= 2.823				V = 0.960 M = 0.744 V × M= 1.663				V = 0.205 M = 0.158 V × M= 0.354			

V, Variety; M, Medium. Values are Mean ± SEm. Means followed by the same letter(s) do not differ significantly at $p \leq 0.05$ (Fisher's LSD). Treatment details are given under Materials and Methods.

Table 3 Effect of storage media on rotting, disease incidence and sprouting characteristics of gladiolus varieties during cold storage in different storage media

Varieties	Rotting (%)			
	M_0	M_1	M_2	Mean (Varieties)
V_1	$11.78^c \pm 0.42$	$19.34^a \pm 0.77$	$15.13^b \pm 0.51$	$15.42^A \pm 3.32$
V_2	$3.25^f \pm 0.09$	$0.61^{ij} \pm 0.01$	$0.34^j \pm 0.01$	$1.40^C \pm 1.39$
V_3	$2.82^f \pm 0.05$	$6.18^d \pm 0.23$	$4.16^e \pm 0.04$	$4.39^B \pm 1.47$
V_4	$0.62^{ij} \pm 0.02$	$0.85^i \pm 0.04$	$0.93^i \pm 0.00$	$0.80^D \pm 0.14$
V_5	$2.16^g \pm 0.07$	$1.62^h \pm 0.02$	$0.28^j \pm 0.00$	$1.35^C \pm 0.84$
Mean (Media)	$4.13^B \pm 4.07$	$5.72^A \pm 7.36$	$4.17^B \pm 5.87$	
LSD ($p \leq 0.05$)	V = 0.260	M = 0.202	V × M= 0.451	
		Disease incidence (%)		
V_1	$9.41^d \pm 0.16$	$7.83^e \pm 0.16$	$9.68^{cd} \pm 0.39$	$8.97^B \pm 0.90$
V_2	$4.81^g \pm 0.01$	$1.62^{jk} \pm 0.05$	$0.84^l \pm 0.03$	$2.42^C \pm 1.82$
V_3	$9.95^c \pm 0.23$	$14.45^a \pm 0.20$	$11.98^b \pm 0.46$	$12.13^A \pm 1.97$
V_4	$3.12^h \pm 0.02$	$2.13^i \pm 0.06$	$1.83^{ij} \pm 0.06$	$2.36^C \pm 0.59$
V_5	$5.32^f \pm 0.19$	$1.33^k \pm 0.03$	$0.63^l \pm 0.02$	$2.43^C \pm 2.19$
Mean (Media)	$6.52^A \pm 2.78$	$5.47^B \pm 5.27$	$4.99^C \pm 5.01$	
LSD ($p \leq 0.05$)	V = 0.186	M= 0.144	V × M= 0.321	
		Days taken to sprout		
V_1	$98.98^{bc} \pm 0.97$	$95.56^d \pm 0.26$	$97.68^{cd} \pm 2.38$	$97.41^B \pm 1.98$
V_2	$95.45^d \pm 3.96$	$87.09^{gh} \pm 2.28$	$89.81^{fg} \pm 1.30$	$90.78^D \pm 4.39$
V_3	$97.67^{cd} \pm 2.11$	$101.67^{ab} \pm 1.92$	$102.81^a \pm 1.30$	$100.72^A \pm 2.82$
V_4	$89.97^{fg} \pm 3.24$	$86.06^h \pm 0.31$	$91.43^{ef} \pm 0.91$	$89.15^D \pm 2.94$
V_5	$96.48^{cd} \pm 3.22$	$91.38^{ef} \pm 0.80$	$94.63^{de} \pm 0.68$	$94.16^C \pm 2.80$
Mean (Media)	$95.71^A \pm 4.04$	$92.35^B \pm 6.07$	$95.27^A \pm 4.95$	
LSD ($p \leq 0.05$)	V = 1.956	M = 1.515	V × M= 3.388	
		No. of sprouts/corm		
V_1	$1.67^k \pm 0.07$	$3.17^b \pm 0.01$	$2.41^{ef} \pm 0.03$	$2.42^B \pm 0.65$
V_2	$1.85^j \pm 0.08$	$2.25^{gh} \pm 0.07$	$2.50^{de} \pm 0.10$	$2.20^C \pm 0.29$
V_3	$1.33^l \pm 0.05$	$2.16^{hi} \pm 0.09$	$2.75^c \pm 0.08$	$2.08^D \pm 0.62$
V_4	$2.17^{hi} \pm 0.09$	$2.33^{fg} \pm 0.05$	$2.13^i \pm 0.02$	$2.21^C \pm 0.11$
V_5	$2.59^d \pm 0.04$	$2.24^{ghi} \pm 0.07$	$3.36^a \pm 0.11$	$2.73^A \pm 0.50$
Mean (Media)	$1.92^C \pm 0.45$	$2.43^B \pm 0.39$	$2.63^A \pm 0.44$	
LSD ($p \leq 0.05$)	V = 0.068	M = 0.053	V × M= 0.118	

V, Variety; M, Medium. Values are mean ± SEm. Means followed by the same letter(s) within a column (lowercase) or for main effects across row/column (uppercase) do not differ significantly at $p \leq 0.05$ (Fisher's LSD).

Treatment details are given under Materials and Methods.

hormonal balance (Kumari *et al.* 2011). Among media, cocopeat (92.35 days) induced significantly faster sprouting compared to sand (95.27 days) and open conditions (95.71 days), attributed to superior thermal insulation and moisture retention triggering metabolic activation. The interaction effect was significant (LSD = 3.388); 'Jyotsna' stored in cocopeat sprouted earliest (86.06 days), while 'Pusa Manmohak' in sand took the longest (102.81 days). Similar genotype-specific responses to environmental cues for earliness have also been reported by Rao *et al.* (2020).

Sprouting percentage: Sprouting behaviour during storage and subsequent field performance varied significantly (Supplementary Table 1, Fig. 1). In storage, 'Pusa Mohini' recorded the highest mean sprouting (10.70%), while 'Pusa Manmohak' showed the minimum (0.64%). Storage media effect was profound with cocopeat (11.30%) resulting in significant higher sprouting than sand (4.71%) and open conditions (1.93%), consistent with moisture-promoted precocious sprouting (Wankhade *et al.* 2022). Conversely, field performance trends differed; 'Jyotsna' (89.95%) and 'Creamy Green' (89.55%) recorded the highest field sprouting, whereas 'Pusa Shanti' registered the lowest (80.50%). Sand proved to be significantly superior for field establishment (89.71%) compared to open conditions

Pic quality very poor

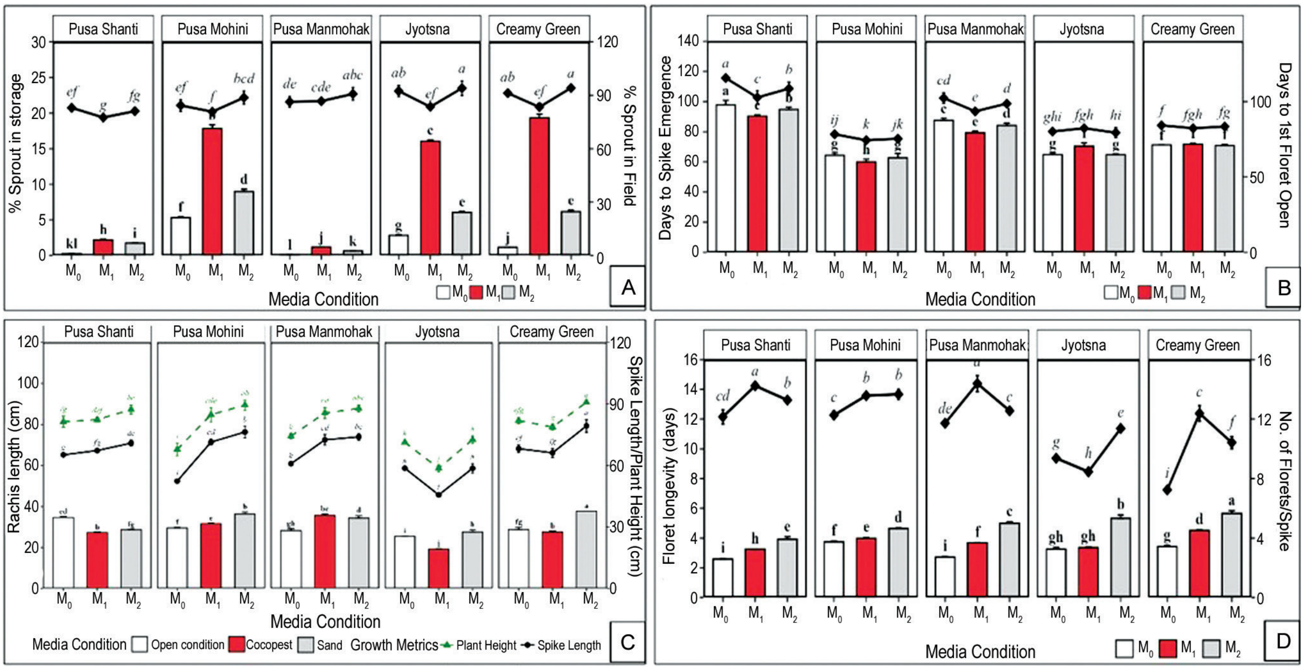

Fig. 1 Effect of storage media on sprouting percentage, phenology and vegetative growth of gladiolus varieties. (A) % sprout in storage vs field; (B) Days to spike emergence and 1st floret open; (C) Rachis length, spike length and plant height; (D) Floret longevity and no. of florets/spike.

Vertical bars represent standard deviation ($p \leq 0.05$). Treatment details are given under Materials and Methods.

(87.42%) and cocopeat (82.36%). The significant interaction (LSD = 4.061) confirmed that 'Creamy Green' stored in sand achieved maximum field sprouting (94.09%), while 'Pusa Shanti' in cocopeat had minimum sprouting (77.51%). This suggests that while moisture-retentive media trigger early bud break exhausting reserves, stable conditions preserve vigour (Kumar and Yadav 2005).

Number of sprouts/corm: The number of sprouts was significantly influenced by the treatments (Table 3). 'Creamy Green' produced the maximum mean sprouts (2.73), while 'Pusa Manmohak' recorded the minimum (2.08). Regarding media, sand (2.63) was significantly superior to cocopeat (2.43) and open conditions (1.92). The interaction (LSD = 0.118) revealed that 'Creamy Green' stored in sand produced the highest number of sprouts (3.36), whereas 'Pusa Manmohak' in open conditions recorded the lowest (1.33). The higher sprout count in sand suggests that structured, aerated substrates reduce mechanical resistance to multiple bud emergence and maintain better corm turgidity than open storage (Khan *et al.* 2002). Furthermore, recent studies on corm traits emphasise that specific nutrient and physical environments significantly enhance the multiplication ratio and sprout number in distinct gladiolus cultivars (Swaroop *et al.* 2023).

Flowering phenology: Flowering phenology showed significant variation ($p \leq 0.05$) among the genotypes and storage media (Supplementary Table 1, Fig. 1). 'Pusa Mohini' registered minimum mean days to spike emergence (62.32 days) and floret opening (76.02 days), whereas 'Pusa Shanti' registered maximum days to spike emergence and floret opening (94.33 and 109.02 days, respectively). This variation is largely attributed to the differential cumulative heat units required by specific genotypes for phasic development (Vanlalruati *et al.* 2019). Among media, cocopeat (74.36 days) and sand (75.48 days) were statistically at par for spike emergence and both were significantly earlier than open conditions (77.15 days). However, for floret opening, cocopeat (87.07 days) was significantly superior (earlier) to sand (89.10 days). The interaction (LSD = 2.681) revealed that 'Pusa Mohini' in cocopeat exhibited the earliest spike emergence (59.95 days). This acceleration in cocopeat is likely due to optimised hydrothermal regimes that facilitate faster nutrient mobilisation to the shoot apical meristem (Sudhakar and Kumar 2012). Regarding floral yield, 'Pusa Shanti' (13.22) and 'Pusa Mohini' (13.17) produced the maximum mean number of florets/spike and were statistically at par, while 'Jyotsna' recorded the minimum (9.73). Cocopeat proved superior for yield, supporting the highest floret count (12.61), significantly higher than sand (12.26). This enhancement is linked to the high nutrient-holding capacity of cocopeat, which ensures sustained availability during spike differentiation (Tiwari *et al.* 2018). These findings align with germplasm evaluations where distinct floral habits were governed by genotype-environment interactions (Sindhu *et al.* 2020).

Floral traits and vegetative growth: In contrast to phenology, floral quality dimensions and vegetative growth were maximised in sand-based media (Supplementary Table 2, Fig. 2). 'Creamy Green' exhibited the highest floret longevity (4.53 days) and spike length (71.18 cm),

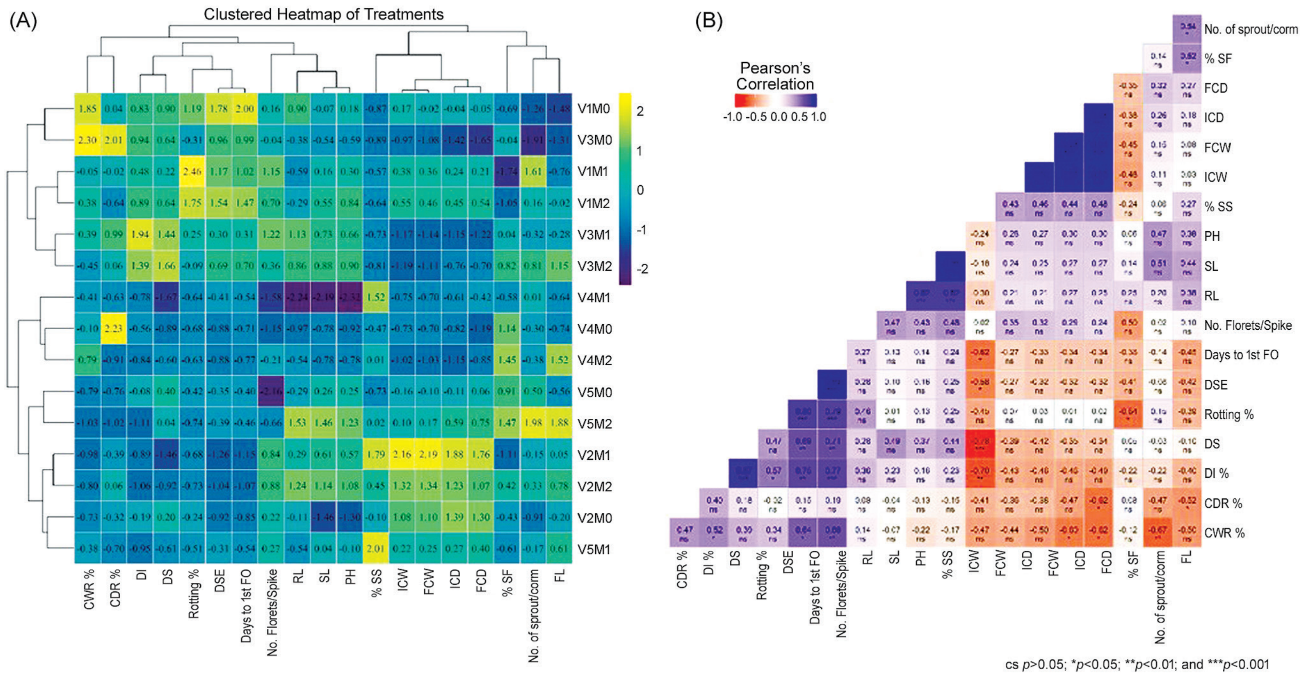

Fig. 2 Multivariate analysis of gladiolus traits undercold storage: (A) Two-way hierarchical cluster heat map showing associations between varieties; (B) Pearson's correlation matrix of corm, sprouting and flowering attributes (red, positive; blue, negative). CWR%, Corm weight reduction; CDR%,Corm diameter reduction; DI%, Disease incidence; DS, Days to sprout; DSE, Days to spike emergence; Days to 1st FO, Days to first floret open; RL, Rachis length; SL, Spike length; PH, Plant height; %SS, Per cent sprout in storage; ICW, Initial corm weight; FCW, Final corm weight; ICD, Initial corm diameter; FCD, Final corm diameter; % SF, Sprout in field; FL, Floret length.
Treatment details are given under Materials and Methods.

while 'Pusa Manmohak' and 'Pusa Mohini' were at par for rachis length (32.78 and 32.45 cm, respectively). Sand significantly enhanced floret longevity (4.91 days), rachis length (32.90 cm) and spike length (71.78 cm) compared to cocopeat and open conditions. The interaction (LSD = 2.950) showed that 'Creamy Green' in sand achieved the maximum spike length (79.25 cm). The superiority of sand is attributed to its excellent drainage and aeration, which prevents ethylene buildup and ensures better turgidity of vascular tissues (Sarkar *et al.* 2014). Vegetative growth followed a similar trend; 'Creamy Green' (83.77 cm), 'Pusa Shanti' (83.60 cm) and 'Pusa Manmohak' (82.52 cm) were statistically at par for maximum plant height. Sand resulted in the tallest plants (85.53 cm), significantly superior to cocopeat (77.98 cm). The interaction (LSD = 3.471) revealed that 'Creamy Green' in sand attained the absolute maximum plant height (90.75 cm). The structured aeration and high hydraulic conductivity of sand promote deep root respiration and efficient upward translocation of water, which is essential for cell elongation in taller varieties (Bhatia *et al.* 2017). This confirms that while organic media favour earliness, inert substrates often support superior structural geometry and vegetative vigour (Saleem *et al.* 2013).

Hierarchical clustering and correlation studies: Hierarchical cluster analysis of 19 standardised morpho-physiological traits classified the 15 treatment combinations into four distinct clusters (Fig. 2A), reflecting the combined influence of genotype and growing media. Cluster I grouped open-field treatments of 'Pusa Shanti' and 'Pusa Manmohak', characterised by high physiological stress (elevated corm weight reduction% and rotting%), consistent with diversity studies driven by sub-optimal environments (Sheikh and Khanday 2008). This was corroborated by correlation analysis (Fig. 2B), where corm weight reduction % showed a significant negative correlation with sprouts/corm (r= -0.67, $p \leq 0.01$), confirming that abiotic stress hampers multiplication efficiency (Lepcha *et al.* 2007). In contrast, Cluster III represented the high-yielding group ('Pusa Mohini', 'Creamy Green') across all media, recording maximum Z-scores for yield attributes. This was supported by a near-perfect correlation between initial and final corm weight (r= 0.97, $p \leq 0.001$), reinforcing planting material vigour as the primary yield determinant (Kumar *et al.* 2011). Cluster II ('Pusa Shanti', 'Pusa Manmohak' in soilless media) showed improved vegetative growth, confirmed by the strong positive association between plant height and spike length (r = 0.78, $p \leq 0.001$), indicating that vegetative vigour translates to floral quality in optimised substrates (Sankari *et al.* 2019). Cluster IV ('Jyotsna') highlighted genotypic stability. The poor performance of Cluster I was further explained by the positive correlation between days to sprout and disease incidence (r = 0.57, $p \leq 0.01$), suggesting delayed sprouting predisposes corms to biotic stress (Hussain *et al.* 2001). Furthermore, the significant association between rachis length and floret count aligns with established cut-flower quality models (Vetrivel *et al.* 2018).

This investigation concludes that gladiolus cold storage efficacy depends on the stratification medium and genotype. Cocopeat minimised physiological weight loss and hastened sprouting, favouring early markets and corm multiplication, despite higher rotting risks. Conversely, sand provided superior aeration, enhancing field establishment and floral quality. Among genotypes, 'Pusa Mohini' displayed resilience and earliness, while 'Creamy Green' excelled in cut-flower traits. Consequently, storing 'Pusa Mohini' in cocopeat is recommended for early corm production, whereas 'Creamy Green' in sand is optimal for quality cut flowers. These findings support developing variety-specific protocols to minimise post-harvest losses and enhance productivity.

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