



RESEARCH ARTICLE

Assessment of pulses storage systems and their effect on germination retention in Central Karnataka

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Abstract

Post-harvest storage losses in pulses remain a major constraint to food security in India; however, systematic assessments integrating farmers' storage practices with experimental germination data across multiple pulse species are limited. This study combined a field survey of 1200 farmers conducted across four districts of Central Karnataka (Chitradurga, Chikkamagaluru, Davanagere and Shivamogga) during 2023–24 with standardised germination testing of seven pulse crops (black gram, chickpea, cowpea, green gram, horse gram, hyacinth bean and moth bean). Seeds were evaluated under five farmer-level storage treatments (sun-dried without treatment, Nilagiri leaves, neem leaves, chemical tablets and chemical powder) and three commercial storages environments (APMC, cold storage and vendor storage). Germination was assessed monthly from the seventh to the tenth month of storage using the International Seed Testing Association (ISTA) standard paper towel method. Data were analysed using two-way analysis of variance (ANOVA) followed by Tukey's HSD post-hoc test. The survey revealed a substantial shift from traditional storage structures to polythene bags (regional mean 88.9 %) and drums (21.1 %), accompanied by continued reliance on sun drying, increased use of chemical fumigants and a decline in traditional botanical storage practices. Germination results showed that chemical seed treatments and cold storage consistently maintained higher germination percentages across all pulse crops. Two-way ANOVA demonstrated that storage method and storage duration significantly affect germination (mostly $p < 0.001$), with significant storage method $\times$ storage duration interactions observed in several pulse crops. These findings provide region-specific evidence that post-harvest germination losses in pulse seeds can be reduced through the adoption of appropriate chemical seed treatments and improved access to cold storage facilities during storage.

Keywords: botanical protectants; Central Karnataka; chemical treatments; cold storage; pulse storage; seed germination

Introduction

Pulses are a major source of high-quality proteins, minerals and dietary fibre and play a vital role in global food and nutritional security (1, 2). India is the world's largest producer, consumer and importer of pulses (3, 4). However, post-harvest losses, ranging from 10 % to 25 % depending on the region, substantially reduce the availability of these crops (5, 6). Storage is the most crucial stage in the post-harvest system because of insect infestations, moisture changes and subsequent microbiological contamination, contributes to significant quantitative and qualitative losses (7, 8).

Smallholder farmers in India typically store small quantities of pulses for domestic consumption and seeds for the following cropping season, primarily using conventional storage methods (9, 10). To meet household expenses and purchase agricultural inputs for the next season, farmers often sell the most of their harvested produce soon after harvest (11, 12). Indigenous storage practices rely on locally available, locally sourced and low-cost materials. However, their effectiveness in preserving seed quality during storage varies considerably depending on the treatment used and storage environment (13, 14). Importantly, although traditional storage practices have been widely documented, relatively few studies have scientifically assessed their efficacy in preserving seed germination capacity using standardised seed quality parameters under storage conditions relevant to the farmers (15, 14).

Modern storage systems regulate the temperature and the internal storage atmosphere to reduce seed deterioration (16, 17). For long-term seed preservation, controlled low temperature storage (5–10 °C) is an effective method. It helps to maintain seed viability and membrane structure by reducing the metabolic and respiration rates of both seeds and associated mycoflora. It also prevents sporulation and inhibits the reproductive activity of microorganisms (18, 19). A sustainable, chemical-free alternative for preserving grain quality is the use of hermetic storage techniques. Hermetic storage maintains good quality grain and seed for extended storage periods without the use of insecticides (20). It is especially suitable for pulses since it creates airtight conditions, which produce a low-oxygen environment that suppresses bruchid infestation and reduces grain deterioration, thereby preserving seed quality. However, the potential of hermetic storage systems is still not fully explored by smallholder farmers due to limited awareness to farmers, poor availability in rural market and downstream distribution issues (20).

Despite pulses being considered secondary crops in the Central Karnataka region, which has distinct agroclimatic environment (temperatures of 25–35 °C and relative humidity of 44–87 %), it depends disproportionately on them for household nutrition, crop diversification and seed-based cultivation (21). However, systematic comparisons of farmer storage practices,

commercial storage systems and their effects on seed germination in pulses remain limited. Therefore, the present study aimed to evaluate the effectiveness of farmer storage treatments and commercial storage condition on the germination of seven pulse crops in Central Karnataka, thereby addressing an important regional knowledge gap in storage-induced changes in seed viability.

Materials and Methodology

Study area and survey design

A field survey was carried out during two consecutive cropping years (2023 and 2024) in 4 districts of Central Karnataka: Chitradurga, Chikkamagaluru, Davanagere and Shivamogga. These districts were selected because they represent the major-agro-climatic zones of Central Karnataka and exhibit diverse farming systems and pulse storage practices. The survey was conducted during the kharif and rabi seasons of each year and the data collected from both seasons were pooled and analysed on an annual basis. Each year, a total of 1200 farmers were surveyed, with 300 respondents being interviewed in each district. The same respondents were interviewed during both cropping years to collect information on pulse cultivation and storage practices. Respondents were selected using the stratified random sampling technique (22). To ensure representation of diverse pulse-based farming systems, only farmers cultivating two or more pulse crops were included in the survey.

Survey questionnaire development and administration

A structured questionnaire was developed based on an extensive review of published research papers relevant to pulse storage systems and practices. Following a preliminary survey, additional locally relevant information was identified and incorporated into the final questionnaire to ensure comprehensive data capture across diverse farming contexts. The survey instrument systematically recorded the following: 1) pulse varieties cultivated on individual farms, 2) storage structures employed for post-harvest grain management and 3) post-harvest storage and preservation practices (23, 24). The data were collected through direct interviews with farmer across all four districts.

Sample collection and classification based on storage methods

The study focused on seven pulse species of regional significance: Black gram (*Vigna mungo* (L.) Hepper), chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), green gram (*Vigna radiata* (L.) R.Wilczek), hyacinth bean (*Lablab purpureus* (L.) Sweet), horse gram (*Macrotyloma uniflorum* (Lam.) Verdc.) and moth bean (*Vigna aconitifolia* (Jacq.) Maréchal). Although pigeonpea (*Cajanus cajan* Harms) was included in the field survey, it was excluded from the germination test because of its limitations in obtaining comparable storage environment seed samples across all storage categories. Seed samples were obtained after approximately 6 months of storage under different environment identified through the field survey. These environments were broadly categorised into farmer-level storage practices and comparative storage environments. Moisture content of seed samples at the time of collection was measured using oven-dry method and expressed on a percentage basis.

Farmer-level storage practices included:

- Sun dried (Untreated) storage
- Botanical treatments using neem (*Azadirachta indica* A.Juss.) and Nilgiri leaves (*Eucalyptus globulus* Labill.)
- Chemical treatments using aluminium phosphide tablets and malathion powder.
- Comparative storage environments included:
 - Cold storage (controlled environment)
 - Storage in Agricultural Produce Market Committee (APMC) market yards
- Vendor-level storage systems

All samples were collected from approximately 50 kg capacity polythene storage bags. Each sample represented an independent seed lot stored under its respective condition. All seed samples, irrespective of source, had undergone an initial six-month storage period prior to collection. After the initial storage period, germination testing was conducted at monthly intervals (7th, 8th, 9th and 10th month). At each interval, different seeds were drawn from the same original seed lot evaluate changes in germination over time.

Germination testing protocol and quality assessment

Germination test was conducted using the “Paper towel method” prescribed by International Seed Testing Association (ISTA) standards (25). For each pulse species and storage condition, 8 replicates of 50 seeds were incubated at 25 ± 1 °C. The final germination percentage was calculated based on the number of normal seedlings on the 8th day (26, 27).

$$\text{Germination (\%)} = \frac{\text{Number of normal seedlings}}{\text{Total seeds tested}} \times 100$$

Statistical analysis

Survey data were analysed using descriptive statistics and expressed as percentage for the year 2024. Year-to-year change ($\Delta\%$) was calculated as the difference between values recorded in 2023 and 2024. Germination data were analysed using analysis of variance (ANOVA) in Jamovi (Version 2.7.16). For farmer storage practices, a two-way ANOVA was performed to evaluate the effects of storage method and storage duration (7th–10th month), as well as their interaction. Similarly, germination data from comparative storage environments (cold storage, APMC and vendor storage) were analysed using two-way analysis of variance (ANOVA) considering storage environments and storage duration as factors. Since different seeds from the same seed lot were used at each sampling interval, observations were treated as independent. Prior to analysis, data were checked for normality and homogeneity of variance. Statistical significance was assessed at $p \leq 0.05$ and Tukey's honestly significant difference (HSD) test was used for post hoc comparisons where appropriate.

Results

A shifting movement in farmer interest across the districts of Chitradurga, Chikkamagaluru, Davanagere and Shivamogga was observed in pulse cultivation patterns from 2023 to 2024 (Table 1; Supplementary Table 1). Cowpea showed the greatest regional increase in cultivation, with notable expansion across districts. Green gram and black gram also exhibited regional increases, whereas chickpea cultivation remained relatively stable (Table 1; Supplementary Table 1). Horse gram and hyacinth bean displayed mixed district-level trends, resulting in only marginal regional increases. In contrast, pigeon pea showed a regional decline, largely driven by reduced cultivation in Davanagere. Moth bean remained a minor pulse crop with only a marginal increase in cultivation across the region (Table 1; Supplementary Table 1).

Table 2 shows that in Central Karnataka farmers in 2024 relied almost exclusively on simple on-farm storage systems, with no reported use of cold storage, warehouse, or traditional storage systems such as Hagevu, kanaja, kothi or sanduka for storing pulses, despite their historical prevalence in Karnataka and elsewhere in India (24, 13). Polythene bags emerged as the primary storage system across all four districts and showed a positive year-on-year increase (Table 2; Supplementary Table 2). Similarly, the use of plastic drums increased across the study area. In contrast, gunny bags, although still widely used, showed a marked decline, while cloth bags remained marginal and continued to decline (28). Earthen pots were not reported 2024 (Table 2; Supplementary Table 2).

In Central Karnataka, like other developing regions, all surveyed farmers reported employing sun- drying techniques for

their prior to storage, resulting in complete adoption across the four districts (Table 3; Supplementary Table 3). Red soil coating was commonly practiced for pigeon pea and hyacinth beans, whereas wood ash, Common salt, turmeric powder and lime powder were used by only a small proportion of farmers. Sand, matchbox and soap were not reported by any respondents in the study area (Table 3; Supplementary Table 3). Neem leaves were widely adopted, whereas neem oil and castor oil were rarely used and showed declining trends.

The use of Nilgiri (*Eucalyptus*) leaves increased during the study period. Dried chillies, tulasi leaves and camphor were used by only small proportions of farmers. In contrast to these traditional practices, chemical fumigants were used by most of the farmers, with both “Tablet” formulations (aluminum phosphide) and “powder” formulations showing increased adoption, particularly in Chitradurga and Chikkamagaluru (Table 3; Supplementary Table 3).

The analysis of variance showed that germination percentage differed significantly among storage methods for all pulse crops under farmer storage practices (Table 4). Storage duration was also significant for every crop, indicating a consistent decline in germination from the 7th to 10th month. The interaction between storage method and storage duration was significant for black gram, chickpea and moth bean but was not significant for cowpea, green gram, horse gram and hyacinth bean. This indicates that, for most crops, the effect of storage method remained consistent throughout storage duration, whereas the pattern of gedeclineson declined over time differed in black gram, chickpea and moth bean (Table 4).

Table 1. District-wise prevalence (%) and year-to-year change (Δ%) in pulse cultivation in Central Karnataka

Pulse crop cultivated	Chitradurga	Chikkamagaluru	Davanagere	Shivamogga	Regional mean (Central Karnataka)
	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)
Black gram	3.66 (2.33)	5.66 (0.33)	5.33 (4.33)	35 (3.34)	12.41 (2.58)
Chickpea	57.33 (2)	41.66 (1)	16.66 (1.33)	0 (0)	28.91 (1.08)
Cowpea	19 (1.34)	36.66 (8.66)	72.33 (9.33)	58 (9.34)	47.49 (7.16)
Green gram	9 (-2.66)	21.33 (1.67)	24.66 (12)	16 (3)	17.74 (3.50)
Horse gram	26.66 (-1)	36.33 (8)	21.33 (-0.33)	74.66 (-2.34)	39.74 (1.08)
Hyacinth bean	48.66 (0)	66.33 (11.67)	79.33 (-2)	22.66 (-4.34)	54.24 (1.33)
Moth bean	3.66 (-0.34)	0 (0)	2.33 (1)	2.33 (1)	2.08 (0.41)
Pigeonpea	57.66 (1.33)	19 (2.67)	52 (-7.66)	26.33 (1)	38.74 (-0.66)

Values represent the percentage of surveyed farmers (N = 300 per district per year) reporting cultivation of each pulse crop in 2024. Values in parentheses (Δ %) indicate the percentage change relative to 2023. Regional mean values represent the average percentage across the four study districts.

Table 2. Use of storage systems by farmers across districts of Central Karnataka

Storage systems	Chitradurga	Chikkamagaluru	Davanagere	Shivamogga	Regional mean (Central Karnataka)
	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)	% (2024) (Δ%)
Cloth bag	9 (-6)	0 (0)	0.33 (-1)	0 (0)	2.33 (-1.75)
Cold storage	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Drum	5 (-1.66)	9 (1)	27.66 (1)	42.66 (6.66)	21.08 (7)
Earthen pot	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Gunny bag	40 (-10)	36.66/-11.34	49.33 (-10)	35.66 (-8.67)	40.41 (-10)
Hagevu	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Kanaja	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Kothi	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Polythene bag	96.66 (3.33)	87.66 (5.33)	85.33 (4.33)	85.66 (17.33)	46.16 (7.58)
Sanduka	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Warehouse	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

Values represent the percentage of surveyed farmers (N = 300 per district per year) using each storage system in 2024. Regional mean values represent the average percentage across the four study districts.

Table 3. Use of storage practices by farmers across districts of Central Karnataka

Category	Practices	Chitradurga	Chikkamagaluru	Davanagere	Shivamogga	Regional mean (Central Karnataka)
		% (2024) ($\Delta\%$)	% (2024) ($\Delta\%$)	% (2024) ($\Delta\%$)	% (2024) ($\Delta\%$)	% (2024) ($\Delta\%$)
Physical and Environmental	Sun drying	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)
Mineral	Wood ash	3 (-0.66)	7.66 (-1.33)	1 (-1.33)	1.33 (-1.33)	3.24 (-1.16)
	Red soil	44.33 (10.67)	34.33 (5.66)	56.66 (5.66)	28.66 (-3.67)	40.99 (6.41)
	Common Salt	19.66 (4.66)	2.33 (-2.67)	2.33 (1.33)	0 (0)	6.08 (0.83)
	Turmeric powder	3.33 (0.33)	1.33 (1.33)	2.33 (0)	0 (0)	1.74 (0.41)
	Lime powder	0 (0)	0 (0)	6 (0.34)	0 (0)	1.5 (0.08)
	Sand	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Matchbox	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Botanical and oil based	Neem leaves (<i>Azadirachta indica</i> A. Juss.)	47.33 (20.33)	30.66 (1.33)	43 (3.67)	32.33 (-1.67)	38.33 (6.75)
	Neem oil	6.66 (-1)	0 (0)	0 (0)	0 (0)	1.66 (-0.25)
	Camphor	3.66 (0)	0 (0)	0 (0)	0 (0)	0.91 (0)
	Castor oil	1.33 (-0.33)	2.33 (-1)	0 (0)	0 (0)	0.91 (-0.33)
	Dried chillies	0 (0)	1.33 (-2)	6.66 (-1)	0 (0)	1.99 (-0.75)
	Tulasi leaves	0 (0)	2 (0)	4.66 (-0.67)	0 (0)	1.66 (-0.16)
	Nilagiri leaves (<i>Eucalyptus globulus</i> Labill)	22 (5.34)	30 (2.34)	41.33 (7)	50.66 (2.66)	35.99 (4.33)
Chemical	Soap	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Use of tablet (aluminium phosphide)	74 (8.34)	69 (14.34)	49.66 (5.66)	46 (9.34)	59.66 (9.42)
	Use of powder (malathion)	56.33 (1)	57.33 (2.33)	68.33 (5.67)	48.33 (7.76)	57.58 (4.17)

Values represent the percentage of surveyed farmers (N = 300 per district per year) using each storage system in 2024. Regional mean values represent the average percentage across the four study districts.

Table 4. Analysis of variance (ANOVA) for germination percentage of pulse crops under farmer storage methods

Pulse	Source	Df	F value	p value
Black gram	Storage method	4	195.70	< 0.001
	Storage duration (month)	3	45.28	< 0.001
	Storage method $\times$ duration	12	2.24	0.013
	Error	140		
Chickpea	Storage method	4	58.47	< 0.001
	Storage duration (month)	3	57.51	< 0.001
	Storage method $\times$ duration	12	3.41	< 0.001
	Error	140		
Cow pea	Storage method	4	403.58	< 0.001
	Storage duration (month)	3	46.35	< 0.001
	Storage method $\times$ duration	12	1.29	0.232
	Error	140		
Green gram	Storage method	4	173.56	< 0.001
	Storage duration (month)	3	42.78	< 0.001
	Storage method $\times$ duration	12	0.08	1.00
	Error	140		
Horse gram	Storage method	4	43.96	< 0.001
	Storage duration (month)	3	17.12	< 0.001
	Storage method $\times$ duration	12	0.54	0.881
	Error	140		< 0.001
Hyacinth bean	Storage method	4	389.87	< 0.001
	Storage duration (month)	3	29.21	< 0.001
	Storage method $\times$ duration	12	0.19	0.998
	Error	140		
Moth bean	Storage method	4	82.99	< 0.001
	Storage duration (month)	3	49.78	< 0.001
	Storage method $\times$ duration	12	4.25	< 0.001
	Error	140		

ANOVA was performed separately for each crop. Storage methods included sun dried, nilagiri treatment, neem treatment, chemical tablet treatment and chemical powder treatment. Storage duration represents months 7–10. Statistical significance was assessed at $p \leq 0.05$.

Similar pattern was observed under different storage environments (Table 5). Storage environment had a significant effect on germination for all pulse crops. Storage duration was also significant for all crops, confirming progressive changes in germination during storage. The interaction between storage environment and duration was significant for black gram, chickpea, horse gram and hyacinth bean, whereas it was not significant for cowpea, green gram and moth bean. Overall, these results show that both storage method and storage environment strongly influenced seed germination.

The detailed germination responses of individual pulse crops under different storage treatments and storage environments during the 7th to 10th months of storage are presented in Supplementary Tables 4–15. Seed germination declined

progressively from the 7th to 10th month in all pulse crops under both storage treatments and storage environment. The extent of decline varied with crop and storage option, indicating that germination retention was strongly influenced by the storage treatments used. Under storage treatments (Tables 6; Supplementary Table 4, 6, 8, 10, 12 and 14), tablet and powder treatments generally maintained the highest germination percentages throughout the storage period, whereas sun-dried seeds consistently recorded the lowest values. Similar trends were observed across all pulse crops. Tablet and powder treatments consistently maintained higher germination throughout the storage period, whereas sun-dried seeds showed the greatest decline. In green gram and horse gram, Nilgiri leaf treatment also maintained higher germination than sun drying, while hyacinth bean and moth exhibited the greatest differences among storage treatments.

Table 5. Analysis of variance (ANOVA) for germination percentage of pulse crops under different storage environments

Pulses	Source	df	F-value	p-value
Black gram	Storage method	2	152.0	< 0.001
	Storage duration (month)	3	48.5	< 0.001
	Storage method × duration	6	10.3	< 0.001
	Error	84		
Chickpea	Storage method	2	136.36	< 0.001
	Storage duration (month)	3	58.30	< 0.001
	Storage method × duration	6	6.68	< 0.001
	Error	84		< 0.001
Cow pea	Storage method	2	255.08	< 0.001
	Storage duration (month)	3	11.08	< 0.001
	Storage method × duration	6	1.14	0.347
	Error	84		
Green gram	Storage method	2	5.725	0.005
	Storage duration (month)	3	33.40	< 0.001
	Storage method × duration	6	0.812	0.563
	Error	84		
Horse gram	Storage method	2	58.86	< 0.001
	Storage duration (month)	3	23.20	< 0.001
	Storage method × duration	6	3.60	0.003
	Error	84		
Hyacinth bean	Storage method	2	35.26	< 0.001
	Storage duration (month)	3	4.90	0.003
	Storage method × duration	6	10.55	< 0.001
	Error	84		
Moth bean	Storage method	2	6.195	0.003
	Storage duration (month)	3	6.054	< 0.001
	Storage method × duration	6	0.738	0.620
	Error	84		

ANOVA was performed separately for each pulse crop. Storage environments included APMC, cold storage and vendor storage. Storage duration represents months 7–10. Statistical significance was assessed at $p \leq 0.05$.

Table 6. Effect of storage duration and storage treatments on germination (%) of black gram (*Vigna mungo*), during storage (estimated marginal means $\pm$ SE)

Storage condition	7 th month	8 th month	9 th month	10 th month
Sun dry	69.3 $\pm$ 1.91c	65.8 $\pm$ 1.91d	51.0 $\pm$ 1.91e	48.8 $\pm$ 1.91 e
Nilgiri leaves	81.5 $\pm$ 1.91b	77.3 $\pm$ 1.91b	72.5 $\pm$ 1.91 c	67.3 $\pm$ 1.91 c
Neem leaves	86.5 $\pm$ 1.91a	83.5 $\pm$ 1.91 b	80.0 $\pm$ 1.91 b	76.5 $\pm$ 1.91 b
Tablet	96.3 $\pm$ 1.91a	94.0 $\pm$ 1.91 a	91.5 $\pm$ 1.91 a	86.8 $\pm$ 1.91 a
Powder	94.0 $\pm$ 1.91a	91.0 $\pm$ 1.91a	88.2 $\pm$ 1.91 a	83.7 $\pm$ 1.91 b

Values represent estimated marginal means $\pm$ standard error obtained from two-way ANOVA. Means within a column followed by the same lowercase letter are not significantly different according to Tukey's HSD test ($p < 0.05$). Storage duration and storage treatment and well their interaction had a significant effect on germination ($p < 0.05$).

Under different storage environments (Tables 7; Supplementary Table 5, 7, 9, 11, 13 and 15), cold storage generally maintained the highest germination in most pulse crops, whereas APMC storage performed best for cowpea. Vendor-storage consistently recorded the lowest germination values. Vendor storage consistently recorded the lowest germination values. Similar trends were observed across all pulse crops, with cold storage and APMC storage maintaining higher germination than vendor storage throughout the storage period. Hyacinth bean and moth bean were more sensitive to storage environments, but cold and APMC storage still supported better germination retention than vendor storage.

Discussion

The observed changes in pulse cultivation patterns across Central Karnataka between 2023 and 2024 suggest that farmers are adapting their cropping decisions in response to agronomic and economic factors affecting pulse production. The increasing preference for cowpea and the reduced cultivation of pigeon pea likely reflect differences in crop adaptability, production risks and economic returns under local farming conditions (Table 1; Supplementary Table 1). Farmers continue to struggle with the high cost of quality seeds, which has been documented nationally through low seed-replacement rates and uneven access to improved varieties (29, 30). In addition, major biotic stresses can cause severe yield losses and many smallholders underuse pesticides or rely on less effective products because of cost and limited technical knowledge (31, 32). Farmers also reported that high labour costs for weeding, harvesting and threshing increase production costs, which may discourage continued pulse cultivation, particularly on marginal lands (Table 1; Supplementary Table 1) (1, 11, 33).

The disappearance of structures such as hagevu, kanaja, kothi and sanduka, together with the absence of cold storage and warehouse use, mirrors national patterns in which 60–70 % of grain is still stored at home for family consumption and seed, while scientific storage remains largely limited to speculative sellers (Table 2; Supplementary Table 2) (13, 28). The dominance of reused fertilised-grade polythene bag and simple drums reflects farmers' preference for low-cost, readily available and easy-to-handle options. However, these containers are permeable to air and moisture and offer limited protection against storage insects (9, 28). Evidence from on-farm trials in Africa and Asia demonstrated that hermetic drums and multilayer hermetic bags can maintain grain at near-constant moisture content and reduce insect damage and weight loss to below about 1–3 % over 6–12 months, compared with 10–30 % losses in jute or polypropylene bags under farmer storage conditions (28, 34). The increasing adoption of polythene bag and drums therefore represents only a partial modernisation of storage.

Without the adoption of improved storage technologies and better storage hygiene, pulse producers are likely to continue experiencing substantial storage-related productivity and income losses (9, 28).

The 100 % adoption of sun-drying confirms its continued use as the primary pre-storage practice for reducing seed moisture to the safe range of 9–12 % (5). The application of Indigenous Technical Knowledge (ITK) exhibits considerable variability. The red-soil coating was consistent with earlier reports from Tamil Nadu, where red earth (1 : 1 with pulses) was traditionally used (35) and previous researchers reported its adoption by farmers in Karnataka (23). Wood ash, recognised as a cheap, silica-rich desiccant and acts as a physical barrier against storage pests, was retained by only a small proportion of farmers, indicating a markedly decline compared with earlier reports from Karnataka and Rajasthan (23). Farmers reported that this decline was likely associated with the reduced availability of ash following the transition from traditional fuelwood stoves to LPG-based cooking, which has become widely adopted in rural India. Common salt and turmeric powder continued to be used by some households; supporting earlier reports these materials help repel storage insects and maintain grain dryness (23, 36). Lime powder reported only in Davanagere district, suggesting it remains a marginal practice. The absence of sand, matchbox and soap indicates that these methods are no longer practiced in Central Karnataka, with farmers reporting that they were unfamiliar with these techniques. Neem leaves remained the predominant botanical protectant, consistent with extensive evidence that neem foliage and seed derivatives act as repellents, oviposition deterrents and growth regulators against storage beetles (23, 33, 35). Botanical and oil-based storage practices showed mixed trends. The decline in the use of neem oil and castor oil may be attributed to limited awareness among farmers despite experimental evidence supporting their effectiveness (36). The increasing adoption of Nialgiri leaves points to a regional shift towards alternative botanical protectants, whereas the low adoption of dried chillies, Tulasi leaves and camphor indicates a decline in the broader range of plant-based practices previously recorded in Karnataka (23). The widespread use of chemical fumigants (aluminium phosphide tablets) and insecticidal dusts formulations (malathion) closely mirrors patterns reported from Nepal, where limited access to improved storage structures has encouraged greater reliance on chemical treatments (37, 38). Although these products effectively reduce insect populations in the short term, repeated and unsupervised use may contribute to insect resistance, acute poisoning and pesticide risks (10, 38).

The significant effects of storage method and storage duration on germination indicate that seed deterioration progressed throughout the storage period and was strongly influenced by storage conditions. The significant interaction effects observed for some pulse crops further suggest that the rate of deterioration

Table 7. Effect of storage duration and storage environments on germination (%) of black gram (*Vigna mungo*), during storage (estimated marginal means $\pm$ SE)

Storage condition	7 th month	8 th month	9 th month	10 th month
APMC storage	95.8 $\pm$ 1.77 a	88.8 $\pm$ 1.77 a	82.3 $\pm$ 1.77 a	76.0 $\pm$ 1.77 a
Cold storage	97.8 $\pm$ 1.77 a	97.3 $\pm$ 1.77 b	96.3 $\pm$ 1.77 b	95.8 $\pm$ 1.77 c
Vendor storage	87.8 $\pm$ 1.77 b	81.5 $\pm$ 1.77 b	69.5 $\pm$ 1.77 c	61.0 $\pm$ 1.77 d

Values represent estimated marginal means $\pm$ standard error obtained from two-way ANOVA. Means within a column followed by the same lowercase letter are not significantly different according to Tukey's HSD test ($p < 0.05$). Storage duration and storage environment and their interaction had a significant effect on germination ($p < 0.05$).

differed among species, reflecting differences in their response to storage conditions. These findings demonstrate that storage management influences not only the final level of germination but also the rate at which seed viability declines during storage.

The superior performance of botanical and chemical protectants compared with untreated sun-dried seeds suggests that these treatments effectively reduced seed deterioration during storage. Botanical protectants may help minimise insect infestation and fungal infection, whereas chemical protectants provide rapid and effective control of storage pests, thereby preserving seed viability. Similar observations have been observed in black gram where neem oil and thiram prevented deterioration of germination and vigour as compared to the untreated seeds during storage (39) and seed treated with protectants had lower seed mycoflora and high germination rate as compared to untreated seeds (40). Also, in chickpea, the use of botanical protectants like neem oil decreased damage during storage along with prolonged germination (41).

The progressive decline in germination during storage indicates that seed deterioration increased with storage duration and exposure to ambient conditions. This observation agrees with previous studies reduced germination and vigour during storage. Germination and vigour index declined with increasing storage duration under ambient condition, whereas fungicidal seed treatment prolonged seed longevity in chickpea and pigeonpea (1). Similar, studies on green gram, black gram, chickpea, pea and pigeon pea, have shown that increased seed-borne fungal population during storage are associated with reduced seed germination, suggesting that biological deterioration is a major factor contributing to seed quality degradation (28).

The superior performance of cold storage indicated that low temperature and stable humidity effectively preserve seed viability by reducing respiration, delaying seed ageing, suppressing fungi growth and insect reproduction during storage. Similar findings have been reported in chickpea, where storage temperatures and appropriate packaging low maintained higher germination than traditional storage methods (42, 43). Likewise, studies on cowpea and faba bean have shown that hermetic storage restricts moisture exchange, suppresses insect reproduction and maintains seed germination and vigour more effectively than non-hermetic storage (44, 45). These findings confirm that cold storage provides the most favorable environment for preserving seed germination among the storage environments evaluated. The presence of interaction effects between the significant crops in Table 4 and 5 demonstrates that storability was not consistent between the pulse species. This was to be anticipated considering that seed life span would be influenced by temperature, relative humidity and moisture content (45). It explains the presence of interaction effects for certain crops while others only exhibited main effects for their treatments.

The significant effects of storage treatment, storage duration and their interaction indicate that storage method influenced not only germination percentage but also the rate at which seed viability declined over time. These findings suggest that the effectiveness of storage treatments varied among pulse crops under different storage environment.

Untreated sun-dried seeds showed more rapid deterioration than seeds treated with chemical and botanical protectants,

indicating the importance of seed protection during storage. Synthetic chemical protectants and fumigants provide rapid and effective control of stored-product insects, whereas botanical products act as grain protectants by reducing seed damage, suppressing adult emergence and inhibiting oviposition in stored grains (46). Similar effects of botanical protectants have been reported in mungbean and chickpea, where higher germination was maintained during extended storage (47).

The superior performance of cold storage indicated that low temperature and low relative humidity play a critical role in preserving seed viability during storage. This observation agrees with previous findings showing that pea seeds stored at 4 °C and 8 % relative humidity maintained the highest germination, whereas increasing storage duration, temperature and humidity resulted in reduced germination and vigour (48). Similar results have been reported for *Melanoxylon brauna* Schott seeds, which retained viability significantly longer under freezer and refrigerator storage than at ambient temperature (49). These findings are further supported by Millennium Seed Bank, where long-term storage of Orthodox seeds at -20 °C substantially prolonged seed longevity, although some collections exhibited gradual age-related declines in germination over extended storage period (50).

Limitations of the study

The research utilised seed samples gathered from both farm and market settings to examine existing on-farm and commercial storage systems. Initial germination rates before storage were not available and factors like temperature and humidity were not controlled experimentally. Despite these constraints, the study offers valuable insights into the pulse storage practices commonly employed in Central Karnataka and evaluates the relative effectiveness of various storage methods in real-world scenarios.

Conclusion

A field survey of 1200 farmers in four districts of Central Karnataka showed a clear shift from traditional storage structures to polythene bags; widespread reliance on sun drying; increased use of chemical fumigants and variable adoption of indigenous botanical practices. Germination assessments demonstrated that improved storage treatments and storage environments maintained higher seed viability than untreated and vendor-stored seeds during storage. These findings highlight the need to promote affordable and effective storage technologies for smallholder farmers and to strengthen community and market-level storage infrastructure to improve pulse seed quality during storage.

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Authors' contributions

PR, RN and RBHN contributed to the laboratory work and manuscript preparation. All authors read and approved of the final manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used QuillBot application to check grammar of the text and ChatGPT to create a reference. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of publication.

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