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Thota Rambabu
Department of Seed Science and Technology, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

Olivya SR
Division of Seed Science and Technology, Indian Agricultural Research Institute, New Delhi, India

Gouthami A
Division of Seed Science and Technology, Indian Agricultural Research Institute, New Delhi, India

Kagita Navya
Division of Seed Science and Technology, Indian Agricultural Research Institute, New Delhi, India

Sujatha Patta
Department of Seed Science and Technology, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

Kaparthi Jhansi Rani
Department of Genetics and Plant Breeding, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

Angala Padma Sri
Department of Entomology, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

Corresponding Author:
Kagita Navya
Division of Seed Science and Technology, Indian Agricultural Research Institute, New Delhi, India

Storability assessment of polymer coated and biologically treated maize seeds in different packaging systems

Thota Rambabu, Olivya SR, Gouthami A, Kagita Navya, Sujatha Patta, Kaparthi Jhansi Rani and Angala Padma Sri

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Abstract
This study evaluated the impact of storage methodologies on seed quality and longevity of maize inbred and hybrid lines under ambient conditions at Department of Seed Science and Technology, Seed Research and Technology Centre, PJTAU, Hyderabad. Four maize genotypes (BML 7, PFSR 3, KNMH 4010131, KNMH 4010141) were treated with chemical protectants (Thiamethoxam, Metalaxyl), biocontrol agents (*Trichoderma viride*, *Bacillus megaterium*), and biofriendly polymers (adjuvant), and stored in jute and polypropylene bags. Seed quality parameters such as germination (%), seedling length (cm), seedling dry weight (mg), seedling vigour index I and II, field emergence (%), insect infestation (%), and seed infection (%) were evaluated bi monthly. Seed quality gradually declined during storage however, seeds treated with the combination of chemical protectants, biocontrol agents, biofriendly polymer, and stored in polypropylene woven bags showed highest retention of seed quality and storability in both inbreds and hybrids. Across eight months of storage, the mean germination percentage declined from 87% to 69%. Hybrid KNMH 4010131 exhibited superior storability, maintaining 81% germination, compared with 56% in KNMH 4010141. In inbreds, treatment T_9 - (PFSR 3 + chemical + biological + polymer + colourant in polypropylene bags) retained 76% germination, while untreated seeds dropped to 65%. The combined treatment resulted in a 13.3% improvement, compared to 4.41% with chemical treatment alone. The best-performing hybrid treatment (T_3) recorded 88% germination, followed by 84% in T_4. Seedling length decreased from 30.38 cm to 23.15 cm, but treated hybrids maintained higher values (23.95 cm in KNMH 4010131 and 22.22 cm in KNMH 4010141). Seedling dry weight declined from 865 mg to 418 mg, with treated seeds in polypropylene bags showing the highest retention (526 mg in KNMH 4010131). Field emergence declined from 79% to 51%, but integrated treatment improved emergence by 16.4% in inbreds and by 17.1 - 48.3% in hybrids. Insect infestation increased to 2.39% in untreated seeds, while treated seeds stored in polypropylene bags achieved 100% reduction in both insect infestation and seed infection in inbreds, and substantial reduction in hybrids (29.5% in KNMH 4010141; 19.4% in KNMH 4010131). Overall, integrating seed treatments with polypropylene packaging proved to be the most effective strategy for maintaining seed quality and storability during ambient storage.

Keywords: Maize inbreds, plant growth promoting microorganisms, seed coating, seed health, seed longevity, seed vigour

Introduction
Maize (*Zea mays* L.), is widely recognized as the "queen of cereals", is one the most adaptable and versatile cereal crops cultivated worldwide. Its high productivity, diverse end uses, and economic importance make it indispensable global food and feed. In India, maize ranks third among cereal crops after wheat and rice. It is cultivated year-round in multiple forms such as sweet corn, baby corn, green cobs, and popcorn. In India maize production reached 42.28 million tonnes, the government has set up long term target to increase maize production to 86 million tonnes by 2047 (IBEF, 2024) [25]. Despite this, the national productivity (~3.5 t ha^{-1}) still trails behind the global average, although states like West Bengal, Telangana, and Andhra Pradesh reports near-optimal yields (Livemint, 2024) [33].
Ensuring sustained high quality seed supply is essential for meeting this growing demand. As seed longevity of maize is influenced by several factors like moisture content, temperature,

relative humidity, storage conditions, fungal growth, and insect pests. Proper seed storage methodologies, as controlling temperature, relative humidity, and seed moisture, can significantly slows the seed deterioration. The proper storage practices like maintaining low seed moisture, using effective packaging materials and minimizing thermal fluctuations can significantly delay seed deterioration.

Seed coating has emerged as an important strategy to enhance seed performance during storage by forming a protective barrier and enabling the controlled delivery of active agents. Chemical seed coatings containing fungicides and insecticides are widely used to suppress seed and soil borne pathogens and reduce early seedling mortality (Dhiman *et al*., 2023) [20]. In recent years, biological seed coating an eco-friendly approach has gained attention. It involves applying a thin film of biodegradable polymer embedded with biological agents on the seed surface, thereby reducing chemical inputs and promoting sustainable agriculture. Biological coatings typically encapsulate plant growth-promoting microorganisms within biodegradable polymers to form a uniform and stable layer. Beneficial microbes such as *Trichoderma* spp., *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Rhizobium* spp. exhibit strong antagonistic activity against pathogens, enhance nutrient availability, improve seedling vigour, and increase tolerance to abiotic stresses (Mastouri *et al*., 2010; Zhang *et al*., 2023) [36, 59].

Polymer coatings also contribute to seed longevity by regulating moisture absorption, stabilizing applied chemicals or biological agents, and providing a physical barrier against environmental stress. Recent studies indicate that polymer-coated maize seeds maintain higher germination, vigour, and seedling biomass during extended ambient storage compared with uncoated seeds (Moharana *et al*., 2020; Badiger *et al*., 2024) [37, 11]. Furthermore, research on natural polymers such as chitosan, super absorbent polymers (SAPs), and nano-biopolymer blends demonstrates improved seedling performance and stress tolerance, highlighting emerging opportunities for climate-resilient seed-coating technologies (Behboud *et al*., 2024; Ondreickova *et al*., 2023) [16, 40]. Recent studies have shown that biological and polymer-based coatings effectively maintain microbial viability, promote early crop establishment (Priyadharshini *et al*., 2022; Artemyeva *et al*., 2023) [43, 9]. Importantly, commercial polymers used in the seed industry have demonstrated high compatibility (96 -100%) with beneficial microbes, confirming their suitability for biological seed coating applications (Arpitha *et al*., 2024) [8].

In addition to seed treatments, packaging materials also play a crucial role in extending seed longevity by preventing insect infestation. Conventional packaging materials such as jute and polypropylene woven bags are widely used for storing the seeds. Although they are used for grain storage the combined use with polymer or biological seed coatings remains insufficiently evaluated for maize seeds.

Despite substantial progress, limited research has focused on integrating biological and chemical seed coatings with different packaging systems to evaluate their combined influence on seed storability, particularly in both inbred and hybrid maize lines under tropical ambient conditions. Such information is essential for developing comprehensive storage strategies that ensure high seed quality, reduce post-harvest losses, and support India's expanding maize seed industry. Therefore, the present study was undertaken to assess the effect of chemical, biological, and untreated seed coatings in combination with different packaging materials on seed longevity, vigour, health, and overall storability of maize inbred and hybrid lines under ambient storage conditions.

Materials and Methods

Freshly harvested seeds of maize genotypes two inbreds (BML 7, PFSR 3) and two hybrids KNMH 4010131, KNMH 4010141) were collected from the Agricultural Research Station (ARS) at PJTAU, Karimnagar. The seeds were stored under ambient conditions with initially recorded germination rate of 94%.

Seed coating: Biological agents like *Trichoderma viride* and *Bacillus megaterium* were applied at 2g kg^{-1} of seed, along with a bio-friendly polymer at 6g kg^{-1}, fungicide metalaxyl at 2g kg^{-1}, and insecticide thiamethoxam at 3g kg^{-1} and colourants. The required quantities of each coating material were weighed and mixed into a slurry in a glass beaker. This slurry was then uniformly applied to the 2000g maize seeds per treatment by thorough mixing in a polythene cover. The coated seeds were shade dried for 2 hours, after drying the treated seeds were divided into two replications of 1000g each and packed into jute bags and polypropylene woven sac bags.

Treatment details

Experiment 1

Treatment details					
Factor 1	Inbred lines (2)	IL 1	BML 7		
		IL 2	PFSR 3		
Factor 2	Seed coatings (3)	C1	Thiamethoxam (3g kg^{-1}seed) + Metalaxyl (2g kg^{-1}seed) + Biofriendly polymer + Colourant of CI (6 g kg^{-1} seed)		
		C2	Thiamethoxam (3g kg^{-1}seed) + *Trichoderma viride* (2g kg^{-1}seed) + *Bacillus megaterium* (2g kg^{-1} seed) + Biofriendly polymer + Colourant of CI (6 g kg^{-1} seed)		
		C3	Untreated Control		
Factor 3	Packaging material (2)	P1	Jute bag		
		P2	Polypropylene woven sack bag		
Treatments	**12 12**				
T_1	:	IL 1 + C1 + P1	T_7	:	IL 2 + C1 + P1
T_2	:	IL 1 + C1 + P2	T_8	:	IL 2 + C1 + P2
T_3	:	IL 1 + C2 + P1	T_9	:	IL 2 + C2 + P1
T_4	:	IL 1 + C2 + P2	T_{10}	:	IL 2 + C2 + P2
T_5	:	IL 1 + C3 + P1	T_{11}	:	IL 2 + C3 + P1
T_6	:	IL 1 + C3 + P2	T_{12}	:	IL 2 + C3 + P2

Experiment 2

<table>
<tr><th colspan="6">Treatment details</th></tr>
<tr><td rowspan="2">Factor 1</td><td rowspan="2">Hybrids (2)</td><td>H 1</td><td colspan="3">KNMH 4010131</td></tr>
<tr><td>H 2</td><td colspan="3">KNMH 4010141</td></tr>
<tr><td rowspan="4">Factor 2</td><td rowspan="4">Seed coatings (4)</td><td>C1</td><td colspan="3">Thiamethoxam (3g kg^{-1}seed) + Metalaxyl (2g kg^{-1}seed) + Biofriendly polymer + Colourant of CI (6 g kg^{-1} seed)</td></tr>
<tr><td>C2</td><td colspan="3">Thiamethoxam (3g kg^{-1}seed) + <i>Trichoderma viride</i> (2g kg^{-1}seed) + <i>Bacillus megaterium</i> (2g kg^{-1} seed) + Biofriendly polymer + Colourant of CI (6 g kg^{-1} seed)</td></tr>
<tr><td>C3</td><td colspan="3">Trichoderma viride (2g kg^{-1}seed) + <i>Bacillus megaterium</i> (2g kg^{-1} seed) + Biofriendly polymer + Colourant of CI (6 g kg^{-1} seed)</td></tr>
<tr><td>C4</td><td colspan="3">Untreated Control</td></tr>
<tr><td rowspan="2">Factor 3</td><td rowspan="2">Packaging material (2)</td><td>P1</td><td colspan="3">Jute bag</td></tr>
<tr><td>P2</td><td colspan="3">Polypropylene woven sack bag</td></tr>
<tr><td>Treatments</td><td colspan="5">12 16</td></tr>
<tr><td>T_1</td><td>:</td><td>H1 + C1 + P1</td><td>T_9</td><td>:</td><td>H2 + C1 + P1</td></tr>
<tr><td>T_2</td><td>:</td><td>H1 + C1 + P2</td><td>T_{10}</td><td>:</td><td>H2 + C1 + P2</td></tr>
<tr><td>T_3</td><td>:</td><td>H1 + C2 + P1</td><td>T_{11}</td><td>:</td><td>H2 + C2 + P1</td></tr>
<tr><td>T_4</td><td>:</td><td>H1 + C2 + P2</td><td>T_{12}</td><td>:</td><td>H2 + C2 + P2</td></tr>
<tr><td>T_5</td><td>:</td><td>H1 + C3 + P1</td><td>T_{13}</td><td>:</td><td>H2 + C3 + P1</td></tr>
<tr><td>T_6</td><td>:</td><td>H1 + C3 + P2</td><td>T_{14}</td><td>:</td><td>H2 + C3 + P2</td></tr>
<tr><td>T_7</td><td>:</td><td>H1 + C4 + P1</td><td>T_{15}</td><td>:</td><td>H2 + C4 + P1</td></tr>
<tr><td>T_8</td><td>:</td><td>H1 + C4 + P2</td><td>T_{16}</td><td>:</td><td>H2 + C4 + P2</td></tr>
</table>

The seed quality parameters were assessed bi-monthly for the coated inbred and hybrid maize seeds are as follows:
The germinated seedlings were evaluated for seedling parameters,

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

Seedling length (cm): Ten normal seedlings of 7th day old were selected the shoot and root length was measured from the cotyledon to the tip of the primary root and shoot, the respective values were recorded in cm.

Seedling dry weight: The seedlings measured for length were kept in an oven at 60ºC for 48 hrs. Then the seedling dry weight was measured, and the mean values were expressed in grams (g).

Vigour index I & II: It was calculated as per the formula given by (Abdul- Baki & Anderson, 1973) [3].

Vigour index I =
$\text{Germination \%} \times \text{total seedling length (cm)}.$

Vigour index II = Germination% × Seedling dry weight (g).

Field Emergence (%): Field emergence percentage was recorded to assess the establishment potential of maize seeds under field conditions. Seeds from each treatment/replication were sown in rows at a uniform depth and spacing. The field was maintained under recommended agronomic practices. The number of seedlings that successfully emerged was counted at a specified interval (usually 10-14 days after sowing).
Field Emergence (%) was calculated using the formula:

$$\text{Field Emergence(\%)} = \frac{\text{Number of emerged seedlings}}{\text{Total weight of seeds}} \times 100.$$

Insect infestation (%): Insect infestation was assessed using a representative 20 g seed sample from each replication. The sample was carefully examined, and insect-damaged, bored, or perforated kernels were separated from the healthy ones. The number or weight of infested kernels was recorded.
Insect Infestation (%) was then calculated using:

$$\text{Insect Infestation (\%)} = \frac{\text{Weight of infected kernels}}{\text{Total weight of kernels}} \times 100.$$

Seed Infection (%): Seed health status was assessed using the Standard Blotter technique as described by ISTA (2023) [26]. For each treatment, 400 seeds (100 seeds per replication) were placed equidistantly on moistened, three-layer blotter paper inside sterile Petri plates. The plates were incubated at 22 ± 2°C under alternating 12 h light and 12 h dark cycles for 7 days.
After incubation, seeds were examined under a stereobinocular microscope for the presence of fungal pathogens. Infected seeds showing mycelial growth, sporulation, or characteristic pathogen structures were counted. Seed Infection (%) was calculated as:

$$\text{Seed Infection (\%)} = \frac{\text{Number of infeccted seeds}}{\text{Total number of seeds}} \times 100.$$

Statistical analysis: The experiment was conducted in a Completely Randomized Design (Factorial) with three replications. Data were analysed using ANOVA as described by Gomez and Gomez (1984) [23]. Standard Error of Difference (SED) and Critical Difference (CD) at 5% probability were calculated for comparison of means. Percentage data were transformed to arcsine values before analysis (Snedecor & Cochran, 1956) [53].

Results

Combined effect of seed storage methodologies on the quality parameters and storability of maize inbred lines and hybrids

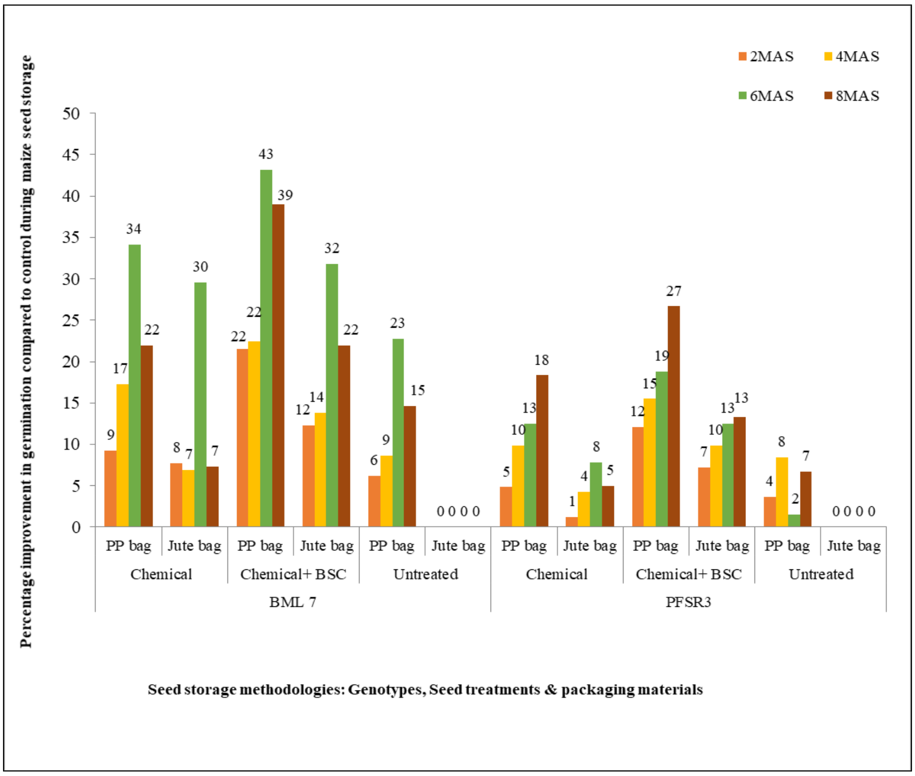
Germination (%)

The study evaluated the longevity of maize inbred lines and hybrid seeds using seeds with 95% germination rate initially (Table 1 and Table 2). Among the hybrids, KNMH 4010131 showed better storability, with 81% germination rate compared to 56% in KNMH 4010141. Seeds treated with combined formulation of Thiamethoxam + *Trichoderma viride* + *Bacillus megaterium* + biofriendly polymer + colourant of CI recorded a germination percentage of 75%. In inbred lines, treatment T_9 (PFSR 3 seeds treated with Thiamethoxam, *Trichoderma viride*, *Bacillus megaterium*, biofriendly polymer, and colourant of CI, and stored in polypropylene woven sacs) recorded germination rate of 76%, followed by T_7 with 71%, compared to 65% for untreated seeds (Figure 1and Figure 2). This treatment resulted in a 13.3% improvement in germination, compared to a 4.41% improvement with chemical treatment alone. The best treatment, labelled T_3, involved KNMH 4010131 seeds treated with Thiamethoxam, *Trichoderma viride*, *Bacillus megaterium*, biofriendly polymer, and colourant of CI, and stored in polypropylene woven sacks. This treatment achieved an 88% germination rate, followed by T_4 with 84%.

Table 1: Analysis of variance for seed quality parameters of maize influenced by type of genotypes, seed treatment, packaging material.

Sources of variance	Df	Germination (%)	Seedling length (cm)	Seedling dry weight (mg)	Field emergence (%)	Insect infestation (%)	Seed infection (%)	SVI-I	SVI-II
A	1	2128.17***	61.312***	84966.0***	590.04***	17.661***	1828.76***	1970879.4***	1323372610***
B	2	329.33***	7.425*	1121.58**	303.25***	124.046***	478.896***	288611.66***	94721346***
A*B	2	41.33	0.731	4352.25***	3.583**	62.027***	46.896	33695.05	39136446**
C	1	4.17***	0.018**	5104.17**	2.042***	8.204***	178.760**	4804.774***	38294160***
A*C	1	60.17	0.784817	5828.17	15.04***	11.409**	162.760	48220.94	73038726
B*C	2	17.33	2.850	2745.08	21.58	1.196***	3.646	35334.722	25436976
A*B*C	2	201.33	5.274	3383.08	308.58	5.283***	150.146	203232.38	80579703
Error	12	44.00	6.017	3815.00	38.50	0.060	90.125	55209.082	27925206
Total	23	2825.83	84.411	111315.33	1282.63	229.887	2939.99	2639988.06	1702505175

*, **, *** represent significance at 0.05, 0.01, 0.001 probability levels
Genotypes (A) Seed Treatment (B) Packaging material (C)



Note: MAS- Months After Storage; BSC-Biological Seed Coating

Fig 1: Effect of storage methodologies (seed treatment and packaging material) on the percentage improvement in seed germination over control (untreated seed stored in jute bag) during storage of maize inbred lines

Seedling length (cm)

Similarly, seed coating with biological agents was found to improve seedling length. Over an eight-month storage period, the seedling length of maize hybrids decreased from 30.38 cm to 23.15 cm. However, among the hybrids, KNMH 4010131 exhibited highest seedling length of 23.95 cm compared to 22.22 cm for KNMH 4010141. Treating seeds with a combination of chemicals, biological agents, biofriendly polymer, and colourant of CI resulted in7.82% improvement in seedling length, while chemical treatment alone resulted in a 5% improvement with storage in polypropylene woven sac bags.

Seedling dry weight (mg)

The mean seedling dry weight decreased from 865 mg to 418 mg over the storage period. After eight months, seeds stored in polypropylene woven sack bags recorded the highest improvement in seedling dry weight (5.35%) compared to those stored in jute bags. Among the hybrids, KNMH 4010131 demonstrated superior storability, maintaining a higher seedling dry weight of 526 mg compared to 332 mg for KNMH 4010141.

Field emergence (%)

Field emergence (%) declined from 79% to 51% over the storage period in inbreds and hybrids. At the end of ageing the seed treatment with chemical and biological agents, biofriendly polymer, and colourant recorded the highest improvement in field emergence (16.4%) of maize inbred lines, followed by chemical seed treatment (11.5%) while, among the hybrids, KNMH 4010131 showed better storability, achieving a 70% field emergence rate, compared to 46% for KNMH 4010141 compared to untreated control. The combination of chemical and biological seed treatments, along with biofriendly polymers and polypropylene woven sac bags, was the best method for maintaining seed quality and improving field emergence in maize hybrid lines. This approach led to field emergence improvements of 48.3% for KNMH 4010141 and 17.1% for KNMH 4010131.

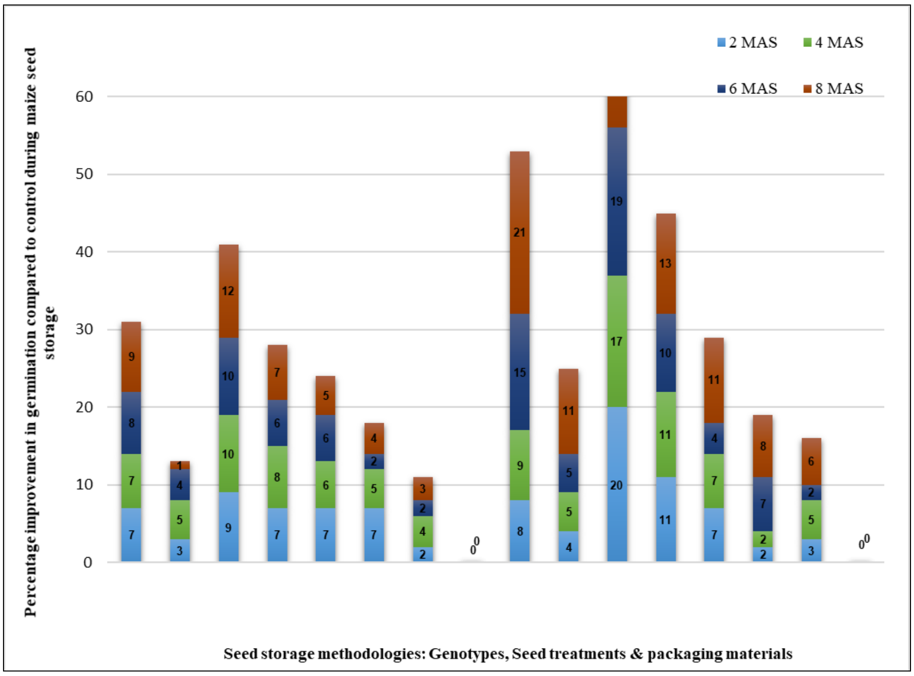
Insect infestation (%)

The mean insect infestation (%) increased gradually from 0% to 2.39% over the storage period. After eight months, maize inbred lines stored in polypropylene woven sack bags showed the highest percentage reduction in seed infection (5.75%) compared to seeds stored in jute bags. Among hybrids treatments T_1 to T_{14} maintained high storage potential and recorded the lowest infestation rate of 0%, while treatment T_{15} had an infestation rate of 13.98%. Seed treatment with a combination of chemicals, biological agents, biofriendly polymer, and colourant of CI stored in polypropylene woven sac bags showed the highest reduction in insect infestation at the eighth month, achieving 100% effectiveness for both KNMH 4010141 and KNMH 4010131, making it the best storage method for maize hybrid lines.

Table 2: Analysis of variance for seed quality parameters of maize influenced by type of genotypes, seed treatment, packaging material

Sources of variance	Df	Germination (%)	Seedling length (cm)	Seedling dry weight (mg)	Field emergence (%)	Insect infestation (%)	Seed infection (%)	SVI-I	SVI-II
A	1	5151.125 ***	6.845 **	300797 ***	4418.00 ***	149.13 ***	255.945 ***	191630822 ***	4695677140***
B	3	479.375 ***	12.567 **	2466.34 **	917.00 ***	447.37***	1032.46***	7604857 ***	148748098 ***
A*B	3	39.375*	4.636	464.961	149.00 ***	447.37***	180.336 **	2102189	2375309
C	1	45.125**	1.990	765.383*	312.50 ***	5.412***	155.320 **	1382816*	21859272 ***
A*C	1	0.125	1.14005	146.633	60.5**	5.412***	6.57031	310627	11100.5
B*C	3	3.375	2.937	1109.148	40.50	16.24***	83.586	2318912*	11657974
A*B*C	3	12.375	1.129	932.898	74.50**	16.24***	240.461**	1479816	10095085
Error	16	54.000	8.580	1984.125	74.00	0.180	172.875	3485795	21284924
Total		5784.875	39.82405	308665.488	6045.00	1087.354	2127.553	210315834	4912708803.5

*, **, *** represent significance at 0.05, 0.01, 0.001 probability levels



Note: MAS- Months After Storage; BSC-Biological Seed Coating

Fig 2: Effect of storage methodologies (seed treatment and packaging material) on the percentage improvement in seed germination over control (untreated seed stored in jute bag) during storage of maize hybrid lines

Discussion

Seed quality deterioration during storage is a natural and inevitable process driven by multiple physiological, biochemical, and environmental factors. In the present study, a progressive decline in germination, seedling vigour, seedling biomass, and field emergence was observed across maize hybrids and inbred lines over eight months of ambient storage, consistent with earlier reports in maize and other field crops (Shobha *et al*., 2015; Ozturk *et al*., 2006; Singh *et al*., 2020) [50, 41, 52]. However, the magnitude of deterioration differed significantly among genotypes, seed treatments, and packaging materials.

Germination declined from an initial mean of 87% to 69% after eight months, reflecting typical ageing-induced reductions reported in soybean, groundnut, sunflower, and maize (Rasheed *et al*., 2020; Davila-Olivas *et al*., 2021) [44, 18]. The hybrid KNMH 4010131 showed superior storability compared to KNMH 4010141, highlighting genotype-dependent seed longevity a feature widely documented in maize and rice (Ghosh *et al*., 2018; Prasanna *et al*., 2021) [22, 42]. Seeds treated with a combination of chemical protectants (Thiamethoxam, Metalaxyl), biological agents (*Trichoderma viride*, *Bacillus megaterium*), biofriendly polymer, and colourant of CI retained significantly higher germination percentage than untreated or chemically treated seeds. These improvements was similar with earlier findings where integrated seed coating formulations reduced deterioration by minimizing fungal infection, oxidative damage, and insect activity (Arantes *et al*., 2000; Manjunatha, 2007; Sharma *et al*., 2019; Abbas *et al*., 2022) [6, 35, 49, 1]. Recent studies further confirmed the role of polymer-enhanced seed coatings in maintaining hydration balance and reducing membrane damage, thereby prolonging seed viability (Waqas *et al*., 2023; Moreno-Perez *et al*., 2022) [56, 38].

Polypropylene woven sacks were consistently superior to jute bags, likely due to their semi-permeable nature that restricts moisture ingress, maintains lower equilibrated moisture content, and prevents insect movement these findings are in agreement with Mutige *et al*. (2013) [39], Sastry *et al*. (2007) [47], and more recent reports by Singh and Kaur (2021) [51] and Teklu *et al.* (2022) [54]. Thus, packaging material significantly influenced germination and longevity. Seedling length showed a steady decline during ageing, aligning with earlier studies linking reduced early growth to DNA degradation, chromosomal aberrations, and failure of enzyme activation during germination (Kapoor *et al*., 2010; Kibinza *et al*., 2020) [28, 31]. Ageing-induced impairment in enzymatic pathways required for early seedling development is well documented, and recent evidence suggests that oxidative stress accelerates mitochondrial disfunction during storage (Bailly, 2020) [12].

Treatments involving integrated seed coatings (chemical + biological + polymer) significantly improved seedling length during storage. *Trichoderma viride* and *Bacillus megaterium* are known to promote early root - shoot growth by producing phytohormones, solubilizing nutrients, and mitigating oxidative stress, explaining the superior performance of treated seeds (Ameen *et al*., 2019; Tiwari *et al*., 2022) [5, 55]. Comparable improvements have been reported in maize, wheat, and soybean seedling growth when coated with beneficial microbes and polymers (Bargaz *et al*., 2021; Zhang *et al*., 2020) [14, 57]. A marked decline in seedling dry weight from 865 mg initially to 418 mg after eight months was observed in untreated and jute-stored seeds. This reduction agrees with earlier reports that attribute seedling dry matter loss to restricted nutrient mobilization, weakening of endosperm reserves, and exhaustion of metabolic substrates during ageing (Khatun *et al*., 2009; Bedi *et al*., 2020) [30, 15]. Recent studies confirm that oxidative injury to membranes and storage proteins accelerates reserve depletion during storage (Chen *et al*., 2021; Hasan *et al*., 2023) [17, 24].

In contrast, seeds treated with combined biological and chemical agents, along with polymer coatings, maintained higher dry weights due to reduced deterioration, improved enzyme activity, and enhanced seed metabolism. Similar enhancements in seedling biomass have been documented in crops such as beans (with Trichoderma and Pseudomonas), sunflower, and rice (Ashwini & Giri, 2014; Zhou *et al*., 2022; Elshazly *et al*., 2024) [10, 60, 21].

Field emergence declined more sharply than laboratory germination, a common phenomenon attributed to environmental stress, soil pathogens, and fluctuating moisture and temperature (Maheshwar *et al*., 2012; Mutige *et al*., 2013) [34, 39]. The integrated seed treatment significantly improved field emergence in both inbred lines and hybrids, aligning with similar findings in okra, sunflower, sorghum, and rice where polymer-based coatings with bioagents improved emergence under field conditions (Khan *et al*., 2019; Abeysiriwardena *et al*., 2021; Barad *et al*., 2023) [29, 4, 13]. The hybrid KNMH 4010131 again showed superior storability, confirming genetic influences on emergence potential and seed vigour under stress (Prasanna *et al*., 2021) [42]. Untreated seeds and those stored in jute bags recorded the highest insect infestation, primarily by rice moth consistent with reports from pigeon pea, chickpea, maize, and stored pulses (Rathod *et al*., 2018; Devi & Mohan, 2020) [45, 46, 19]. Polypropylene bags and integrated seed treatments completely eliminated infestation in hybrid seeds and substantially reduced seed infection in inbreds.

Chemical protectants (Thiamethoxam, Metalaxyl) combined with polymer coatings create a physical barrier and biochemical protection, significantly reducing pest entry and fungal invasion. Similar reductions in seed infection have been reported in cotton, chilli, black gram, and green gram (Arantes *et al*., 2000; Shailbala & Tripathi, 2004; Ashwini & Giri, 2014) [7, 48, 10]. Recent studies further demonstrate that polymer-fungicide combinations enhance long-term protection by controlling storage pathogens and sealing micro fissures on the seed coat (Zhang *et al*., 2021; Abdelhamid *et al*., 2023) [58, 2].

The present study highlights that integrating chemical protectants + biological agents + biofriendly polymer + Colourant of CI, combined with polypropylene woven sack storage, provides the most effective strategy for maintaining maize seed quality during ambient storage. This integrated approach minimized deterioration, controlled insect infestation and seed infection, and maximized germination, vigour, biomass, and field emergence in both hybrid and inbred lines. Genotypes differed in storage potential, with KNMH 4010131 consistently displaying higher storability across all parameters, implying inherent physiological resilience a trend supported by recent genetic and physiological studies on maize seed longevity (Li *et al*., 2022; Jha & Singh, 2023) [32, 27]. Overall, the findings reinforce that integrated seed coating technologies combined with appropriate packaging are critical for ensuring seed longevity under ambient storage conditions, especially in tropical environments.

Conclusion

The seed storage methodology involving treatment with a combination of chemicals, biological agents, biofriendly polymer, colourant of CI, and storage in polypropylene woven sac bags, showed the highest improvement in field emergence, seedling vigour index I, and seedling vigour index II in maize hybrid lines. Among all treatments, the integrated seed coating consisting of chemical protectants (Thiamethoxam, Metalaxyl), biological agents (*Trichoderma viride*, *Bacillus megaterium*), biofriendly polymer, and Colourant of CI combined with polypropylene woven sack packaging proved most effective in maintaining seed viability and vigour during the eight-month storage period. This treatment significantly improved germination, seedling growth, seedling dry weight, field emergence, and seed health while achieving complete control of insect infestation and substantial reduction in seed infection.Hybrid KNMH 4010131 consistently exhibited superior storability compared to KNMH 4010141, indicating inherent genetic advantages. In inbred lines, PFSR 3 seeds treated with the integrated coating and stored in polypropylene sacks recorded the highest retention of seed quality. Overall, the findings highlight that integrated seed treatment technologies combined with suitable semi-permeable packaging materials are essential for safeguarding seed quality under ambient storage, particularly in tropical and subtropical climates. The approach offers a practical, scalable, and cost-effective solution for enhancing seed longevity, improving field performance, and ensuring high-quality seed supply for maize growers.

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