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Interactive Effect of Seed Pelleting Treatments and Storage Duration on Seed Quality and Vigour in Tomato

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ABSTRACT: High-quality seed is a critical input for achieving uniform crop establishment, vigorous plant growth and higher productivity. The present investigation was undertaken to evaluate the effect of different seed pelleting treatments on seed quality and storability of tomato (*Solanum lycopersicum* L.) cv. Punjab Ratta under different storage durations. The experiment was conducted in a factorial completely randomized design comprising eleven seed pelleting treatments and five storage durations (0, 3, 6, 9 and 12 months). Significant variations were observed among pelleting treatments and storage durations for most of the seed quality parameters studied. Seeds treated with Captan/Thiram (2 g kg^{-1} seed) (T_{11}) recorded the highest mean germination percentage (84.51%), seedling length (17.27 cm), seed vigour index I (1462.08), seed vigour index II (17.57) and field emergence (86.50%) throughout the storage period. Among microbial pelleting treatments, Azotobacter (200–300 g kg^{-1} seed) (T_6) and Pseudomonas (200–300 g kg^{-1} seed) (T_8) showed better performance compared with non-pelleted seeds (T_1). Seed quality parameters, including germination percentage, seedling vigour indices and field emergence, declined progressively with increase in storage duration, indicating gradual deterioration associated with seed ageing. However, moisture content and 100 seed weight exhibited relatively stable trends during storage. The study demonstrated that seed pelleting, particularly with fungicidal and microbial formulations, effectively delayed seed deterioration and helped maintain seed viability, vigour and field performance during storage. Thus, seed pelleting can be recommended as an effective seed enhancement technique for improving storability and establishment potential of tomato seeds.

Keywords: Tomato seeds, Seed pelleting, Storage duration, Seed vigour, Microbial pelleting

INTRODUCTION

Tomato (*Solanum lycopersicum* L.), a member of the Solanaceae family having chromosome number 2n=2x=24, is believed to have originated in the Peru–Ecuador region. It is one of the most widely cultivated vegetable crops owing to its adaptability across diverse agro-climatic conditions and its importance in both fresh consumption and processed forms such as sauce, ketchup, puree, paste and soup, contributing significantly to its economic value [1]. In addition to its versatility, tomato is highly valued for its nutritional composition, particularly being rich in lycopene, vitamin A and antioxidant compounds, which enhance its dietary and health significance [2]. Globally, tomato occupies a prominent position among horticultural crops, being cultivated on over 5.2 million hectares with an annual production exceeding 187 million tonnes, making it second only to potato in terms of importance [3]. Major producers include China, India, Turkey and the United States, with India ranking second and contributing over 20 million metric tonnes from approximately 0.8 million hectares of cultivated land to global output [4]. In India, tomato cultivation has expanded considerably due to its high market demand and economic returns. In regions like Punjab, traditionally dominated by cereal-based systems, diversification towards vegetable crops, including tomato, has gained momentum in recent years [5]. The crop now occupies a notable area and contributes significantly to the state's horticultural production, reflecting its growing importance in enhancing farm income and supporting agricultural sustainability [6].

Seed is a fundamental input in agriculture and the use of high-quality seed is essential for achieving successful crop establishment and better crop productivity. The planting value of seed is influenced by several management practices that affect its viability and vigour during cultivation and storage. Among various seed quality enhancement techniques, seed pelleting has emerged as an effective approach for improving seed performance [7]. Seed pelleting involves coating seeds with a measured quantity of inert materials to produce a uniform, spherical unit of standard size, which may also serve as a carrier for nutrients that support early seedling growth [8,9,10]. It is considered a key approach in improving seed handling and precision sowing. One of the critical requirements in modern planting systems is the accurate placement of individual seeds at a predetermined depth and spacing, ensuring uniform coverage at an efficient planting speed. However, this process becomes difficult with seeds that are small, irregular in shape or low in density, as successful establishment of a crop largely depends on achieving an optimum plant population, which in turn requires a high probability of successful germination and establishment of each individual seed.

Seed pelleting helps overcome these limitations by improving seed size, weight and uniformity, thereby facilitating better singulation and placement [11,12]. Furthermore, rapid seed deterioration during storage remains a major challenge, particularly under uncontrolled environmental conditions where seed quality declines at an accelerated rate. Seed deterioration during storage is an unavoidable process; however, the use of chemical and botanical seed pelleting materials can help slow this decline. Botanicals contain growth-promoting substances that enhance seedling growth, while chemicals protect seeds from seed-borne diseases, thereby improving seed germination percentage, seedling vigour and seed storability [13]. In tomato, seed pelleting offers additional advantages, including the possibility of direct seeding in the main field, thereby eliminating the need for transplanting. This not only reduces labour requirement and seed rate per unit area but also aids in early-stage disease management when seeds are pelleted with appropriate protective agents [14].

Despite these benefits, information on the combined effect of pelleting treatments and storage duration under ambient conditions on tomato seed quality remains limited. Therefore, the present study is aimed at evaluating these factors and identifying the best treatment combination for seed storability and field performance in pelleted seeds of tomato.

MATERIALS AND METHODS

Experimental material and site: The present investigation was conducted at the Research Farm of the Office of Director (Seeds), Punjab Agricultural University, Ludhiana during the year 2022-2023. Seeds of tomato cultivar ‘Punjab Ratta’ were harvested during second fortnight of April, 2023 produced under recommended agronomic practices as per the Package of Practices of Punjab Agricultural University, Ludhiana [15] were used for seed pelleting treatments followed by storage of pelleted seeds under ambient conditions at 9p C temperature and 45-50% relative humidity.

Experimental Design and Treatment details: The experiment was laid out in a factorial completely randomized design (FCRD) with two factors and 55 treatment combinations with each treatment replicated three times. The details of both the factors and various seed pelleting treatments is provided in Table 1.

Parameters recorded and statistical analysis: The observations were recorded for all the treatments at each storage interval (0, 3, 6, 9, 12 MAS) using standardized protocol for moisture content (%), seed germination

Table 1. Details of storage durations (Factor A) and seed pelleting treatments (Factor B) used under present study

Factors	Description	Treatment details
I	Storage duration (S)	0 MAS: 0 months after storage
		3 MAS: 3 months after storage
		6 MAS: 6 months after storage
		9 MAS: 9 months after storage
		12 MAS: 12 months after storage
II	Treatments (T)	T_1: Control (Non-pelleted seeds)
		T_2: Seed pelleting with *Albizia amara* leaf powder (250g/kg of seeds)
		T_3: Seed pelleting with neem leaf powder (250g/kg of seeds)
		T_4: Seed pelleting with *Trichoderma* (200-300g/kg of seeds)
		T_5: Seed pelleting with *Rhizobacteria* (200-300g/kg of seeds)
		T_6: Seed pelleting with *Azotobacter* (200-300g/kg of seeds)
		T_7: Seed pelleting with *Azospirillum* (200-300g/kg of seeds)
		T_8: Seed pelleting with *Pseudomonas* (200-300g/kg of seeds)
		T_9: Seed pelleting with *Bacillus* consortia (200-300g/kg of seeds)
		T_{10}: Seed pelleting with *Bacillus* + *Pseudomonas* + *Trichoderma* + *Azotobacter* (50-100g/kg of seeds of each agent)
		T_{11}: Seed treatment with Captan/Thiram (2g/kg of seeds)

*Guar gum powder was used as an adhesive in all seed treatments execpt T_1 (non-pelleted seeds) and T_{11} (Seed treatment with Captan/ Thiram (2g/kg of seeds)) percentage, first count (%) which was recorded on the 4th day of germination, seedling length (cm), seedling dry weight (g), seed vigour indices (SVI I and SVI II), calculated, field emergence (%) and 100 seed weight (g). The data obtained were subjected to analysis of variance (ANOVA) for factorial completely randomized design. Treatment means were compared using the Least Significance Difference (LSD) test at 5% level of significance ($p \leq 0.05$) and statistical analysis was carried out using R software.

RESULTS AND DISCUSSION

Moisture content (%)

Moisture content of pelleted tomato seeds was significantly influenced by seed pelleting treatments as well as storage duration, whereas the interaction effect between storage duration and treatments was non-significant (Table 2). In freshly pelleted seeds, moisture content ranged from 8.16% in the control (T_1) to 9.56% in *Rhizobacteria* pelleted seeds (T_5) with pelleted seeds recording significantly higher moisture content than the non-pelleted seeds which indicates that the pelleting material increase seed moisture content. A progressive increase in moisture content was observed upto 9 months, followed by slight reduction at 12 months after storage. The highest mean moisture content was recorded at 9 MAS (9.56%), while the lowest was observed at 12 MAS (9.21%). Among various treatments, significantly higher mean moisture content was recorded in *Rhizobacteria* pelleted seeds (T_5; 9.71%), followed by *Azotobacter* pelleted seeds (T_6; 9.61%), likely due to the hygroscopic nature of coating material, which can absorb and retain moisture during storage, whereas the lowest moisture content was observed in non-pelleted seeds (T_1; 8.31%). Similar observations were recorded by [16] in carrot, lettuce, chicory and endive seeds, where pelleting material significantly influenced moisture content (%) and increased water retention capacity in pelleted seeds. The gradual increase in moisture content during storage may be associated with equilibration of seeds with ambient relative humidity under storage conditions. The relatively stable moisture levels throughout the storage period indicate that the pelleting material remained structurally stable with limited fluctuations. The lower moisture content recorded in non-pelleted seeds further suggests the role of pelleting material in modifying physical properties of seed and moisture absorption behaviour during storage. Also, seed pelleting with various treatments enhanced moisture content as compared to the non-pelleted seed but the moisture levels remained within the safe storage range (8-10%), indicating that seed pelleting did not affect storability.

Seed germination (%)

Seed germination (%) was significantly influenced by storage duration and pelleting treatments, while the interaction between them was found to be non-significant (Table 3). Germination percentage declined progressively with advancement in storage period, with the highest mean germination recorded at 0 MAS (86.01%) and the lowest at 12 MAS (79.53%). Initially at 0 MAS, seed germination ranged from 83.46% (T_5) to 89.93% (T_6, T_{11}), with a gradual decline observed with increasing storage duration for all the treatments, which may be due to the natural ageing process of seed leading to progressive

Table 2. Effect of various seed pelleting materials on moisture content (%) of pelleted tomato seeds under different storage durations

Storage (S)/	Moisture content (%)					
Treatment (T)	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	8.16±0.56^{j}	8.23±0.24^{j}	8.37±0.18^{j}	8.56±0.46^{ij}	8.22±0.33^{j}	8.31^{e}
T_2	9±0.1^{hi}	9.37±0.16^{abcdefgh}	9.31±0.06^{bcdefgh}	9.52±0.41^{abcdefgh}	9.25±0.05^{defgh}	9.29^{d}
T_3	9.41±0.03^{abcdefgh}	9.53±0.28^{abcdefgh}	9.21±0.03^{efgh}	9.42±0.11^{abcdefgh}	9.14±0.12^{fghi}	9.34^{bcd}
T_4	9.26±0.15^{defgh}	9.21±0.31^{efgh}	9.36±0.14^{abcdefgh}	9.57±0.07^{abcdefgh}	9.22±0.15^{defgh}	9.32^{cd}
T_5	9.56±0.09^{abcdefgh}	9.94±0.17^{a}	9.66±0.18^{abcdefg}	9.88±0.06^{ab}	9.5±0.01^{abcdefgh}	9.71^{a}
T_6	9.45±0.07^{abcdefgh}	9.68±0.28^{abcdefg}	9.65±0.53^{abcdefg}	9.87±0.15^{abc}	9.41±0.23^{abcdefgh}	9.61^{ab}
T_7	9.33±0.01^{bcdefgh}	9.64±0.28^{abcdefg}	9.52±0.16^{abcdefgh}	9.74±0.05^{abcdef}	9.38±0.24^{abcdefgh}	9.52^{abcd}
T_8	9.27±0.13^{cdefgh}	9.63±0.16^{abcdefg}	9.33±0.11^{abcdefgh}	9.54±0.09^{abcdefgh}	9.28±0.02^{bcdefgh}	9.41^{bcd}
T_9	9.16±0.21^{fghi}	9.37±0.27^{abcdefgh}	9.26±0.02^{defgh}	9.47±0.14^{abcdefgh}	9.12±0.11^{ghi}	9.28^{d}
T_{10}	9.34±0.23^{abcdefgh}	9.25±0.31^{defgh}	9.39±0.09^{abcdefgh}	9.61±0.05^{abcdefg}	9.55±0.17^{abcdefgh}	9.43^{bcd}
T_{11}	9.46±0.13^{abcdefgh}	9.82±0.16^{abcd}	9.56±0.17^{abcdefgh}	9.78±0.17^{abcde}	9.29±0.42^{bcdefgh}	9.58^{abc}
Mean	9.22^{c}	9.43^{ab}	9.33^{bc}	9.54^{a}	9.21^{c}	
LSD(0.05)	Storage (S) = 0.18		Treatment (T) = 0.27		S × T = NS	

Table 3. Effect of various seed pelleting materials on seed germination (%) of pelleted tomato seeds under different storage durations

Storage (S)/ Treatment (T)	Seed germination (%)					
	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	84.3±4.12^{abcd}	80.71±4.45^{abcd}	80.84±3.92^{abcd}	80.03±3.88^{bcd}	78.45±0.68^{cd}	80.86^{abc}
T_2	86.45±3.93^{abc}	81.54±3.76^{abcd}	82.51±6.39^{abcd}	81.69±6.32^{abcd}	79.24±0.37^{bcd}	82.29^{abc}
T_3	88.08±5.5^{ab}	82.85±4.55^{abcd}	82.65±5.79^{abcd}	81.82±5.73^{abcd}	79.54±0.33^{bcd}	82.99^{ab}
T_4	83.99±5.25^{abcd}	82.33±4.54^{abcd}	83.54±2.75^{abcd}	82.71±2.73^{abcd}	79.84±0.12^{bcd}	82.48^{abc}
T_5	82.46±2.06^{abcd}	78.49±3.63^{cd}	78.49±3.1^{cd}	77.71±3.07^{cd}	76.22±0.87^{d}	78.67^{c}
T_6	89.93±2.29^{a}	84.91±4.66^{abcd}	84.55±2.12^{abcd}	83.7±2.1^{abcd}	81.24±0.8^{abcd}	84.87^{a}
T_7	83.48±0.74^{abcd}	81.02±4.47^{abcd}	80.11±4.43^{bcd}	79.31±4.39^{bcd}	79.24±0.21^{bcd}	80.63^{bc}
T_8	86.55±0.85^{abc}	82.56±3.82^{abcd}	83.55±4.41^{abcd}	82.71±4.37^{abcd}	80.32±1.55^{bcd}	83.14^{ab}
T_9	84.5±1.01^{abcd}	80.71±4.43^{abcd}	82.45±4.1^{abcd}	81.63±4.06^{abcd}	79.22±0.87^{bcd}	81.7^{abc}
T_{10}	86.45±1.94^{abc}	83.32±4.6^{abcd}	83.55±2.35^{abcd}	82.72±2.33^{abcd}	80.12±1.84^{bcd}	83.23^{ab}
T_{11}	89.93±2.11^{a}	82.69±3.82^{abcd}	84.66±3.86^{abcd}	83.81±3.83^{abcd}	81.44±1.91^{abcd}	84.51^{ab}
Mean	86.01^{a}	81.92^{bc}	82.45^{b}	81.62^{bc}	79.53^{c}	
LSD(0.05)	Storage (S) = 2.84		Treatment (T) = 4.21		S × T = NS	

depletion of seed reserves and deterioration of physiological and biochemical integrity during storage. Similar declining trends in seed germination were recorded in brinjal pelleted seeds during storage [17]. Higher germination percentage in pelleted seeds has also been reported in several crops. Enhanced germination in pelleted okra seeds with different leaf powders was observed by [18]. Similarly, improved germination was reported in lettuce by comparing pelleted and non-pelleted seeds [19]. Higher germination in onion seeds pelleted with neem leaf powder was also observed [20].

Among various treatments, pelleting with Azotobacter (T_6) recorded the highest mean germination (84.87%), followed by Captan/Thiram treatment (T_{11}; 84.51%), microbial consortium (T_{10}; 83.23%) and Pseudomonas pelleting (T_8; 83.14%), which consistently recorded higher seed germination percentage values across storage durations. The comparatively better germination observed in microbial and fungicidal treatments may be attributed to their protective role against storage-associated deterioration and their ability to enhance physiological activity during germination. Similar results on better performance of seeds treated with fungicide have also been reported in brinjal seeds [17] and tomato seeds [21], where protection against fungal and insect damage contributed to better seed quality. The comparatively lower germination in untreated seeds indicates greater susceptibility to storage-induced deterioration. However, the relatively smaller decline observed in pelleted and treated seeds suggests that seed pelleting contributes to maintaining seed viability during storage by providing a protective coating around the seed surface.

First count (%)

First count (%) was done on the 4th day of germination and is an indicator of seed vigour and speed of germination. It was significantly influenced by seed pelleting treatments and storage duration, with a non-significant interaction between both the factors (Table 4). A gradual decline in first count was observed with increasing storage duration, with the highest mean recorded at 0 MAS (62.10%) and the lowest at 3 MAS (59.15%) for all the treatments, indicating progressive loss of seed vigour during storage. Among treatments, Azospirillum pelleting (T_7) recorded the highest mean first count (70.89%), followed by unpelleted seeds (T_1; 70.45%). In contrast, Bacillus consortia pelleting (T_9) and fungicidal seed treatment (T_{11}) recorded significantly lower first count values of 50.94% and 53.02%, respectively. Treatments involving Rhizobacteria (T_5) and Pseudomonas (T_8) maintained comparatively higher first count values than other pelleted treatments during storage.

The superior performance of Azospirillum pelleted seeds may be associated with enhanced physiological activity and improved metabolic efficiency during the early stages of germination. Comparable findings have been reported in tomato, where improved speed of germination was observed in pelleted seeds [22]. Similarly, better germination speed in pelleted seeds of bell pepper was reported [23]. The decline in first count with prolonged storage reflects progressive loss of seed vigour due to ageing-related deterioration. Reduction in membrane integrity, enzymatic activity and reserve mobilization during storage may delay germination speed, thereby

Table 4. Effect of various seed pelleting materials on first count (%) 4th day of pelleted tomato seeds under different storage durations

Storage (S)/	First count (%)					
Treatment (T)	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	72.56 ± 1.43^{ab}	69.22 ± 1.2^{cd}	71.25 ± 0.6^{abc}	69.82 ± 0.59^{bc}	69.42 ± 1.47^{bcd}	70.45^{a}
T_2	60.35 ± 2.2^{ghijklmn}	57.85 ± 1.53^{nopq}	58 ± 0.09^{mnopq}	56.84 ± 0.09^{opqr}	56.99 ± 0.27^{opqr}	58.01^{d}
T_3	58.15 ± 2.5^{klmnopq}	55.28 ± 0.96^{qrstu}	58.96 ± 0.06^{jklmnop}	57.78 ± 0.06^{nopq}	58.04 ± 0.67^{lmnopq}	57.64^{d}
T_4	62.22 ± 0.55^{fghi}	$59.06 \pm 1.56^{ijklmnop}$	62.54 ± 0^{fg}	61.54 ± 0.25^{fghij}	$59.22 \pm 1.05^{hijklmno}$	60.92^{c}
T_5	66.5 ± 1.6^{de}	64.09 ± 1.69^{ef}	62.44 ± 0.42^{fgh}	$61.19 \pm 0.41^{fghijklm}$	61.25 ± 0.42^{fghijkl}	63.09^{b}
T_6	56.48 ± 2.06^{opqrs}	53.04 ± 0.92^{tuvw}	55.21 ± 0.89^{qrstu}	54.11 ± 0.87^{rstuv}	55.88 ± 1.25^{pqrst}	54.94^{e}
T_7	73.92 ± 0.42^{a}	70.52 ± 1.22^{bc}	71.25 ± 1.15^{abc}	69.82 ± 1.13^{bc}	68.94 ± 0.9^{cd}	70.89^{a}
T_8	63.89 ± 1.79^{ef}	$61.17 \pm 1.62^{fghijklm}$	62.54 ± 0.88^{fg}	61.29 ± 0.86^{fghijk}	$60.22 \pm 1.44^{ghijklmn}$	61.82bc
T_9	52.62 ± 1.51^{uvw}	49.36 ± 0.85^{x}	51.22 ± 0.05^{vwx}	50.19 ± 0.05^{wx}	51.33 ± 1.31^{vwx}	50.94g
T_{10}	62.33 ± 0.87^{fgh}	58.81 ± 1.56^{jklmnop}	61.89 ± 1.39^{fghij}	$60.65 \pm 1.36^{ghijklmn}$	58.78 ± 0.34^{jklmnop}	60.49^{c}
T_{11}	54.08 ± 1.73^{rstuv}	52.24 ± 1.38^{uvwx}	53.44 ± 0.95^{stuv}	52.37 ± 0.92^{uvwx}	52.98 ± 0.03^{tuvw}	53.02^{f}
Mean	62.1^{a}	59.15^{c}	60.79^{b}	59.6^{c}	59.37^{c}	
LSD(0.05)	Storage (S) = 0.97		Treatment (T) = 1.44		S × T = NS	

Table 5. Effect of various seed pelleting materials on seedling length (cm) of pelleted tomato seeds under different storage durations

Storage (S)/	Seedling length (cm)					
Treatment (T)	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	$15.83 \pm 0.21^{ghijklmnop}$	14.59 ± 0.75^{qr}	$15.42 \pm 0.24^{klmnopqr}$	$15.27 \pm 0.24l^{mnopqr}$	14.98 ± 0.26^{nopqr}	15.22^{e}
T_2	17.16 ± 0.51^{abcdef}	$15.89 \pm 0.49^{ghijklmno}$	16.24 ± 0^{defghijklm}	16.08 ± 0^{fghijklmno}	$15.24 \pm 0.37l^{mnopqr}$	16.12^{d}
T_3	$16.17 \pm 0.52^{efghijklmn}$	14.97 ± 0.77^{nopqr}	15.09 ± 0.13^{mnopqr}	14.94 ± 0.13^{opqr}	14.65 ± 0.28^{pqr}	15.17^{e}
T_4	$16.49 \pm 0.29^{cdefghijk}$	14.61 ± 0.91^{qr}	$15.77 \pm 0.34^{hijklmnopq}$	$15.61 \pm 0.33^{jklmnopq}$	14.22 ± 0.3^{r}	15.34^{e}
T_5	17.44 ± 0.6^{abcd}	$16.41 \pm 0.5^{cdefghijkl}$	$15.84 \pm 0.37^{ghijklmnop}$	$15.68 \pm 0.36^{ijklmnopq}$	15.02 ± 0.17^{nopqr}	16.08^{d}
T_6	17.3 ± 0.34^{abcde}	$16.04 \pm 0.83^{fghijklmno}$	$16.04 \pm 0.16^{fghijklmno}$	$15.88 \pm 0.16^{ghijklmno}$	$15.68 \pm 0.14^{ijklmnopq}$	16.19^{cd}
T_7	17.01 ± 0.77^{abcdefg}	15.54 ± 0.8^{jklmnopq}	$15.98 \pm 0.33^{fghijklmno}$	$15.82 \pm 0.33^{ghijklmnop}$	15.47 ± 0.19^{klmnopq}	15.96^{d}
T_8	17.54 ± 0.4^{abc}	$16.68 \pm 0.51^{bcdefghij}$	$16.87 \pm 0.04^{bcdefghi}$	$16.7 \pm 0.04^{bcdefghij}$	$16.26 \pm 0.36^{defghijklm}$	16.81^{ab}
T_9	17.29 ± 0.31^{abcde}	$16.03 \pm 0.84^{fghijklmno}$	$15.41 \pm 0.01^{klmnopqr}$	15.26 ± 0.01^{lmnopqr}	15.47 ± 0.02^{klmnopq}	15.89^{d}
T_{10}	17.73 ± 0.25^{ab}	$15.7 \pm 0.97^{hijklmnopq}$	16.89 ± 0.02^{bcdefgh}	$16.72 \pm 0.02^{bcdefghij}$	$16.55 \pm 0.21^{bcdefghijk}$	16.72^{bc}
T_{11}	18.18 ± 0.64^{a}	17.44 ± 0.53^{abcd}	17.02 ± 0.18^{abcdefg}	$16.85 \pm 0.18^{bcdefghi}$	$16.88 \pm 0.35^{bcdefghi}$	17.27^{a}
Mean	17.1^{a}	15.81^{bc}	16.05^{b}	15.89^{b}	15.49^{c}	
LSD(0.05)	Storage (S) = 0.36		Treatment (T) = 0.54		S × T = NS	

lowering first count values. Despite this decline, several pelleted treatments maintained relatively stable performance, indicating their potential role in preserving early germination ability during storage.

Seedling length (cm)

Seedling length is closely associated with seed vigour during germination, with seeds producing longer seedlings generally regarded as more vigorous than those producing shorter ones. Seedling length was significantly influenced by storage duration and pelleting treatments, with non-significant interaction between both the factors. Mean seedling length declined progressively during storage, with the highest value recorded at 0 MAS (17.10 cm) and the lowest at 12 MAS (15.49 cm) (Table 5). Among treatments, fungicidal treatment with Captan/ Thiram (T_{11}) recorded significantly higher mean seedling length (17.27 cm), followed by Pseudomonas seed pelleting (T_8; 16.81 cm) and microbial consortium seed pelleting (T_{10}; 16.72 cm). In contrast, the lowest mean seedling length was observed in non-pelleted seeds (T_1; 15.22 cm) and neem leaf powder pelleted seeds (T_3; 15.17 cm).

The comparatively superior performance of fungicidal and microbial treatments may be associated with improved seedling vigour and efficient mobilization of seed reserves during germination. Similar observations have been reported in brinjal, where fungicidal seed treatment helped maintain seedling vigour by minimizing fungal deterioration [24]. The improved performance observed in microbial and consortium treatments (T_8 and T_{10}) may be attributed to their capacity to produce plant growth-

Table 6. Effect of various seed pelleting materials on seedling dry weight (g) of pelleted tomato seeds under different storage durations.

Storage (S)/ Treatment (T)	Seedling dry weight (g)					
	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	0.19±0^{fghij}	0.17±0.01^{jk}	0.18±0.01^{hijk}	0.18±0.01^{hijk}	0.17±0.01^{jk}	0.18^{d}
T_2	0.21±0.01^{abcde}	0.19±0^{defghi}	0.19±0^{fghij}	0.19±0^{fghij}	0.17±0^{k}	0.19^{c}
T_3	0.20±0.01^{bcdefg}	0.18±0.01^{hijk}	0.19±0.01^{efghi}	0.19±0.01^{efghi}	0.19±0^{efghi}	0.19^{c}
T_4	0.20±0^{bcdef}	0.18±0.01^{ijk}	0.20±0.02^{bcdefg}	0.20±0.02^{bcdefg}	0.19±0.01^{efghi}	0.19^{c}
T_5	0.22±0.01^{ab}	0.19±0^{defghi}	0.19±0.02^{efghi}	0.19±0.02^{efghi}	0.17±0^{jk}	0.19^{c}
T_6	0.21±0.01^{abcd}	0.19±0.01^{efghi}	0.20±0.01^{bcdefg}	0.20±0.01^{bcdefg}	0.18±0^{ghijk}	0.20^{bc}
T_7	0.21±0.01^{abcde}	0.21±0^{abcde}	0.21±0.01^{abcd}	0.21±0.01^{abcd}	0.19±0^{defghi}	0.21^{ab}
T_8	0.22±0^{ab}	0.20±0^{bcdef}	0.21±0.01^{abcd}	0.21±0.01^{abcd}	0.19±0^{defghi}	0.21^{a}
T_9	0.21±0^{abcde}	0.19±0.01^{efghi}	0.19±0^{defghi}	0.19±0^{defghi}	0.18±0^{hijk}	0.19^{c}
T_{10}	0.22±0^{a}	0.20±0.01^{cdefgh}	0.19±0.01^{efghi}	0.19±0.01^{efghi}	0.18±0.01^{hijk}	0.20^{c}
T_{11}	0.22±0.01^{a}	0.21±0^{abc}	0.21±0.01^{abcd}	0.21±0.01^{abcd}	0.19±0^{efghi}	0.21^{a}
Mean	0.21^{a}	0.19^{b}	0.20^{b}	0.20^{b}	0.18^{c}	
LSD(0.05)	Storage (S) = 0.006		Treatment (T) = 0.009		S × T = NS	

promoting substances and stimulate early seedling development, a response also documented in lettuce seeds pelleted with plant growth-promoting bacteria [25].

Seedling dry weight (g)

Seedling dry weight is a key indicator of seed vigour, as it shows a strong positive correlation with overall seed performance. Seed lots with higher seedling dry weight are considered more vigorous. Bolder seeds produce healthy seedlings and have more dry weight than smaller seeds [20]. Significant differences were recorded for seedling dry weight as influenced by various pelleting treatments and storage duration, whereas the interaction effect between both factors was non-significant (Table 6). Mean seedling dry weight decreased gradually with increase in storage duration. The highest mean seedling dry weight was recorded at 0 MAS (0.21 g), which declined to the lowest value of 0.18 g at 12 MAS.

Among treatments, Pseudomonas seed pelleting (T_8) and Captan/Thiram treatment (T_{11}) recorded significantly higher mean seedling dry weight (0.21 g), followed by Azospirillum seed pelleting (T_7; 0.21 g). In contrast, non-pelleted seeds (T_1) recorded the lowest mean seedling dry weight (0.18 g). The comparatively higher seedling dry weight observed in microbial and fungicidal treatments may be associated with improved seed reserve utilization and enhanced metabolic activity during seedling development. Similar improvements in seedling dry weight following seed pelleting have been reported in pelleted seeds of bell pepper [26]. The decline in seedling dry weight with prolonged storage may be attributed to seed deterioration processes, including reduced enzymatic efficiency, membrane damage and impaired translocation of stored reserves to the developing seedling. However, the relatively stable seedling dry weight observed in pelleted treatments indicates that seed pelleting helps maintain seedling vigour during storage.

Seed vigour indices

Both seed vigour index I (SVI I) and seed vigour index II (SVI II) were significantly influenced by storage duration and pelleting treatments, whereas the interaction effect between storage duration and treatments was non-significant (Table 7). For SVI I, the highest mean value was recorded at 0 MAS (1473.71), followed by a gradual decline with storage, reaching the lowest value at 12 MAS (1232.73). Among treatments, Captan/Thiram-treated seeds (T_{11}) recorded significantly higher mean SVI I (1462.08), followed by Pseudomonas pelleting (T_6; 1377.53). The lowest mean SVI I was observed in non-pelleted seeds (T_1; 1232.79).

Similarly, SVI II declined progressively during storage, with the highest overall mean recorded at 0 MAS (17.89) and the lowest at 12 MAS (14.51). Among treatments, T_{11} recorded the highest mean SVI II (17.57), followed by T_8 (17.04) and T_6 (16.54), whereas non-pelleted seeds (T_1) showed the lowest value (14.36). The comparatively superior seed vigour indices observed in fungicidal and microbial treatments may be associated with improved maintenance of seed viability, enhanced reserve mobilization and better seedling growth during storage. Microbial inoculants such as Pseudomonas and Azotobacter are known to stimulate early seedling development through production of growth-promoting

Table 7. Effect of various seed pelleting materials on seed vigour indices of pelleted tomato seeds under different storage durations

Storage (S)/ Treatment (T)	Seed vigour index I					
	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	1336.74±57.01^{hijklmnopq}	1183.9±49.86^{wxyz}	1246.55±10.25^{qrstuvwxyz}	1221.61±10.05^{tuvwxyz}	1175.17±30.45^{xyz}	1232.79^{e}
T_2	1485.48±57.75^{bcde}	1299.16±38.85^{lmnopqrstuv}	1339.96±26.5^{hijklmnopq}	1313.16±25.97^{jklmnopqrstu}	1207.66±20.74^{vwxyz}	1329.08^{c}
T_3	1426.42±50.36^{defghi}	1247.61±52.05^{qrstuvwxyz}	1247.19±22.72^{qrstuvwxyz}	1222.25±22.26^{stuvwxyz}	1165.26±6.06^{yz}	1261.74^{de}
T_4	1386.73±52.31^{efghijkl}	1210.17±55.76^{uvwxyz}	1317.43±1.37^{jklmnopqrst}	1291.08±1.34^{lmnopqrstuv}	1135.32±22.45	1268.15^{de}
T_5	1440.48±59.31^{cdefgh}	1290.99±38.6^{lmnopqrstuv}	1243.28±30.41^{qrstuvwxyz}	1218.41±29.8^{tuvwxyz}	1144.82±16.09^{z}	1267.6d^{e}
T_6	1558.1±61.34^{ab}	1369.56±57.31^{fghijklmno}	1356.18±11.29^{ghijklmnop}	1329.05±11.07^{ijklmnopqr}	1273.84±19.89^{nopqrstuvwx}	1377.35^{b}
T_7	1421.72±54.16^{defghi}	1265.79±53.36^{opqrstuvwxy}	1280.16±13.32^{mnopqrstuvw}	1254.55±13.06^{pqrstuvwxy}	1225.84±3.83^{rstuvwxyz}	1289.61^{cd}
T_8	1519.92±62.15^{bcd}	1381.05±41.29^{fghijklm}	1409.49±27.87^{efghijk}	1381.3±27.32^{efghijklm}	1305.87±31.26^{klmnopqrstuv}	1399.53^{b}
T_9	1463.29±59.81^{bcdef}	1300.7±54.59^{lmnopqrstuv}	1270.55±9.92^{nopqrstuvwx}	1245.14±9.72^{qrstuvwxyz}	1225.53±9.57^{rstuvwxyz}	1301.04^{cd}
T_{10}	1534.88±52.56^{abc}	1315.93±60.55^{jklmnopqrst}	1410.99±24.96^{efghij}	1382.77±24.47^{efghijklm}	1325.99±13.11^{ijklmnopqrs}	1394.11^{b}
T_{11}	1637.01±57.53^{a}	1445.67±43.08^{cdefg}	1440.91±8.25^{cdefgh}	1412.09±8.08^{efghij}	1374.71±30.76^{fghijklmn}	1462.08^{a}
Mean	1473.71^{a}	1300.96^{b}	1323.88^{b}	1297.4^{b}	1232.73^{c}	
LSD(0.05)	Storage (S) = 0.006		Treatment (T) = 0.009		S × T = NS	

Storage (S)/ Treatment (T)	Seed vigour index II					
	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	15.8±0.09^{ghijklmnopqrst}	13.75±0.19^{uvwx}	14.55±0.2^{rstuvwx}	14.12±0.19^{tuvwx}	13.57±0.32^{vwx}	14.36^{g}
T_2	17.63±0.62^{bcdef}	15.66±0.47^{hijklmnopqrst}	15.68±0.48^{hijklmnopqrst}	15.21±0.47^{mnopqrstuvw}	13.47±0.59^{wx}	15.53^{ef}
T_3	17.6±0.55^{cdef}	14.94±0.47^{opqrstuvw}	15.7±0.49^{hijklmnopqrst}	15.23±0.47^{lmnopqrstuvw}	15.1±0.15^{nopqrstuvw}	15.72^{def}
T_4	17.04±0.67^{cdefghijk}	14.7±0.27^{qrstuvw}	16.71±0.28^{efghijklmno}	16.21±0.27^{efghijklmnopqrs}	15.2±0.82^{mnopqrstuvw}	15.97^{cde}
T_5	17.67±1.01^{bcde}	15.07±0.55^{nopqrstuvw}	14.91±0.57^{pqrstuvw}	14.46±0.55^{stuvwx}	12.9±0.29^{x}	15^{fg}
T_6	18.62±0.79^{abcd}	16.16±0.31^{efghijklmnopqrs}	16.91±0.32^{cdefghijklm}	16.4±0.31^{efghijklmnopq}	14.63±0.03^{qrstuvwx}	16.54^{bc}
T_7	17.11±1.63^{cdefghij}	16.23±0.71^{efghijklmnopqrs}	16.82±0.73^{defghijklmn}	16.32±0.71^{efghijklmnopqr}	15.07±1.01^{nopqrstuvw}	16.31^{bcde}
T_8	18.63±0.63^{abc}	16.69±0.36^{efghijklmnop}	17.55±0.37^{cdefg}	17.03±0.36^{cdefghijkl}	15.3±0.78^{klmnopqrstuv}	17.04^{ab}
T_9	17.41±0.53^{cdefgh}	15.36±0.29^{jklmnopqrstuv}	15.67±0.3^{hijklmnopqrst}	15.2±0.29^{mnopqrstuvw}	14.27±1.18^{tuvwx}	15.58^{def}
T_{10}	19.41±0.51^{ab}	16.53±0.23^{efghijklmnop}	15.87±0.24^{fghijklmnopqrst}	15.39±0.23^{jklmnopqrstu}	14.63±1.27^{qrstuvwx}	16.37^{bcd}
T_{11}	19.82±1.49^{a}	17.55±0.59^{cdefg}	17.78±0.61^{bcde}	17.25±0.59^{cdefghi}	15.47±1.23^{ijklmnopqrstu}	17.57^{a}
Mean	17.89^{a}	15.69^{b}	16.2^{b}	15.71^{b}	14.51^{c}	
LSD(0.05)	Storage (S) = 0.54		Treatment (T) = 0.80		S × T = NS	

metabolites, while fungicidal treatments help minimize storage-associated deterioration.

The progressive reduction in seed vigour indices with storage duration reflects natural seed ageing and associated physiological deterioration. Since SVI I integrates germination percentage and seedling length, while SVI II combines germination percentage with seedling dry weight, reduction in these parameters during storage directly contributed to lower seed vigour index values. However, the relatively smaller decline observed in pelleted and treated seeds suggests that seed pelleting contributes to better preservation of seed vigour during storage. Similar decline in SVI I with storage has been reported in pelleted cowpea seeds [27]. The results are in close agreement with the earlier findings of [28], who reported reduction in SVI II in pelleted tomato (*Solanum lycopersicum* L.) seeds after five months of storage duration.

Field emergence (%)

Field emergence was significantly influenced by storage duration and various pelleting treatments, with a non-significant interaction between the two factors. Mean field emergence declined gradually with increasing storage duration, with the highest emergence recorded at 0 MAS (84.47%) and the lowest at 12 MAS (80.42%) (Table 8). Among treatments, Captan/Thiram treatment (T_{11}) recorded significantly higher mean field emergence (86.50%), followed by Azotobacter seed pelleting (T_6; 85.15%) and neem leaf powder pelleting (T_3; 84.42%). The non-pelleted seeds (T_1) recorded the lowest mean field emergence (73.64%).

Better field emergence (%) in pelleted seeds of onion compared with non-pelleted seeds has also been reported [28]. Similarly, higher field emergence in pelleted tomato (*Solanum lycopersicum* L.) seeds was observed by [22]. The comparatively higher field emergence

Table 8. Effect of various seed pelleting materials on field emergence (%) of pelleted tomato seeds under different storage durations

Storage (S)/	Field emergence (%)					
Treatment (T)	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	76.89±2.06^{efgh}	76.1±0.99^{fgh}	72.84±0.9^{gh}	71.38±2.06^{h}	70.96±1.96^{h}	73.64^{d}
T_2	85.39±5.01^{abcde}	82.54±2.42^{abcdef}	83.55±1.74^{abcdef}	81.88±2.36^{abcdef}	81.4±4.77^{abcdefg}	82.95^{abc}
T_3	88.81±5.09^{ab}	82.11±2.46^{abcdef}	85.14±0.89^{abcde}	83.44±2.41^{abcdef}	82.58±4.85^{abcdef}	84.42^{ab}
T_4	83.32±2.87^{abcdef}	84.18±1.39^{abcdef}	82.24±1.07^{abcdef}	80.6±2.33^{bcdefg}	80.84±2.73^{abcdefg}	82.24^{bc}
T_5	82.69±5.89^{abcdef}	78.12±2.85^{defgh}	81.22±0.72^{abcdefg}	79.59±2.3^{cdefgh}	79.44±5.61^{cdefgh}	80.21^{c}
T_6	89.53±3.33^{a}	82.02±1.61^{abcdef}	86.54±0^{abcd}	84.81±2.45^{abcdef}	82.87±3.17^{abcdef}	85.15^{ab}
T_7	83.83±7.59^{abcdef}	84.48±3.67^{abcdef}	83.22±0.13^{abcdef}	81.61±2.35^{abcdefg}	81.89±7.22^{abcdef}	83.01^{abc}
T_8	83.32±3.9^{abcdef}	81.05±1.88^{abcdefg}	83.14±1.95^{abcdef}	81.47±2.35^{abcdefg}	81.68±3.72^{abcdef}	82.13^{bc}
T_9	81.24±3.11^{abcdefg}	77.03±1.51^{efgh}	81.24±1.1^{abcdefg}	79.61±2.3^{cdefgh}	79.41±2.97^{cdefgh}	79.71^{c}
T_{10}	84.66±2.46^{abcdef}	84.27±1.19^{abcdef}	81.39±0.21^{abcdefg}	79.76±2.3^{cdefgh}	79.65±2.35^{cdefgh}	81.95^{bc}
T_{11}	89.53±6.32^{a}	86.32±3.06^{abcd}	87.24±1.09^{abc}	85.5±2.47^{abcde}	83.9±6.02^{abcdef}	86.5^{a}
Mean	84.47^{a}	81.66^{b}	82.52^{ab}	80.88^{b}	80.42^{b}	
LSD(0.05)	Storage (S) = 2.66		Treatment (T) = 3.95		S × T = NS	

Table 9. Effect of various seed pelleting materials on 100 seed weight (g) of pelleted tomato seeds under different storage durations

Storage (S)/	100 seed weight (g)					
Treatment (T)	0 MAS	3 MAS	6 MAS	9 MAS	12 MAS	Mean
T_1	0.3±0.01^{y}	0.32±0.01^{y}	0.33±0^{y}	0.33±0^{y}	0.32±0.01^{y}	0.32^{h}
T_2	1.54±0.03^{efgh}	1.57±0.02^{cdefg}	1.58±0.01^{cde}	1.56±0.01^{defg}	1.52±0.04^{ghi}	1.55^{c}
T_3	1.56±0.04^{defg}	1.58±0.03^{cde}	1.62±0.02^{c}	1.6±0.02^{cd}	1.58±0.01^{cdef}	1.59^{b}
T_4	1.4±0.01^{lmnop}	1.43±0.03^{kl}m	1.54±0.03^{efgh}	1.52±0.02^{fghi}	1.5±0.04^{hi}	1.48^{d}
T_5	1.42±0.01^{klmno}	1.5±0.02^{hi}	1.87±0^{a}	1.85±0^{ab}	1.81±0^{b}	1.69^{a}
T_6	1.44±0.02^{jkl}	1.47±0.03^{ijk}	1.52±0.04^{ghi}	1.5±0.04^{hi}	1.49±0.01^{hij}	1.48^{d}
T_7	1.26±0.01^{u}	1.3±0.03^{tu}	1.35±0.03^{pqrst}	1.34±0.03^{qrst}	1.31±0.01^{stu}	1.31^{f}
T_8	1.34±0.02^{qrst}	1.38±0.02^{nopqr}	1.39±0.01^{lmnopq}	1.38±0.01^{mnopqr}	1.33±0.01^{rst}	1.36^{e}
T_9	1.41±0.02l^{mno}	1.43±0.03^{klmn}	1.38±0.01^{nopqr}	1.37±0.01^{opqrs}	1.34±0.02^{qrst}	1.39^{e}
T_{10}	1.17±0.01^{v}	1.18±0.03^{v}	1.39±0.02l^{mnopq}	1.38±0.02^{mnopqr}	1.33±0.01^{rst}	1.29^{f}
T_{11}	0.5±0.01^{x}	0.53±0.01^{x}	0.59±0.01^{w}	0.58±0.01^{w}	0.58±0.01^{w}	0.56^{g}
Mean	1.21^{d}	1.24^{c}	1.32^{a}	1.31^{a}	1.28^{b}	
LSD(0.05)	Storage (S) = 0.01		Treatment (T) = 0.02		S × T = NS	

observed in fungicidal and microbial treatments may be attributed to improved protection against seed- and soil-borne pathogens along with better maintenance of seed vigour during storage. Beneficial microorganisms such as Azotobacter may also enhance early root growth and nutrient uptake, thereby supporting better field establishment.

The decline in field emergence during storage reflects progressive deterioration of seed physiological quality with ageing. Compared with laboratory germination, field emergence is more sensitive to environmental stresses, and therefore even slight reductions in seed vigour can adversely affect crop stand establishment under field conditions. However, several pelleting treatments showed relatively stable field emergence, suggesting that seed pelleting helps preserve field performance during storage.

100 seed weight (g)

The data presented in Table 9 indicate that 100 seed weight was significantly influenced by storage duration and seed pelleting treatments, whereas the interaction between both factors was found to be non-significant. Across storage duration, mean 100 seed weight increased gradually from 1.21 g at 0 MAS to a maximum of 1.32 g at 6 MAS, followed by a slight decline to 1.28 g at 12 MAS.

Among treatments, T_5 recorded the highest mean 100 seed weight (1.69 g), followed by T_3 (1.59 g) and T_2 (1.55 g), whereas the lowest mean value was observed in non-pelleted seeds (T_1; 0.32 g). T_5 showed a marked increase in seed weight from 1.42 g at 0 MAS to 1.87 g at 6 MAS and remained comparatively higher even after 12 MAS (1.81 g). Similarly, T3 maintained relatively stable and higher seed weight values throughout the storage period. The non-pelleted seeds (T_1) and T_{11} recorded significantly lower seed weight compared with pelleted seeds.

The higher seed weight in pelleted seeds is attributed to the addition of coating materials, which increase seed mass and improve physical integrity during storage. T_5 exhibited the highest 100 seed weight throughout the storage duration, suggesting superior coating retention and stability of the pelleting material. Similar observations of higher seed weight in pelleted seeds compared with non-pelleted seeds in bell pepper (*Capsicum annuum* L.) were reported (26).

CONCLUSION

The study clearly demonstrates that seed pelleting can be used as an effective technology to improve the handling, physical properties and quality of pelleted tomato seeds without affecting the storability. Although pelleted seeds showed slightly higher moisture content and seed weight due to the presence of coating materials, but the values remained within the acceptable limits and did not adversely affect seed quality during storage period. Seed germination percentage remained largely stable across treatments, with only a gradual decline over time, reflecting natural seed ageing process. In contrast, vigour related parameters such as first count (%), seedling length (cm), seedling dry weight (g) and seed vigour indices, were more affected during storage period. Despite this decline, seeds treated with fungicide (T_{11}: Seed treatment with Captan/Thiram (2g/kg of seeds) and certain beneficial microorganisms such as *Azotobacter* (T_6: Seed pelleting with *Azotobacter* (200-300g/kg of seeds), *Pseudomonas* (T_8: Seed pelleting with *Pseudomonas* (200-300g/kg of seeds) and their consortium (T_9: Seed pelleting with *Bacillus* consortia (200-300g/kg of seeds) consistently maintained better seed vigour over the storage period. *Rhizobacteria* seed pelleting (T_5: 200-300g/kg of seeds) recorded the highest 100 seed weight, indicating the influence of coating material on physical properties of seed. Field emergence (%) further supported these findings, as pelleted seeds showed improved establishment as compared to non-pelleted seeds, particularly at later stages of storage. This suggests that pelleting not only preserves seed quality under storage conditions but also provides better field emergence. Hence, in conclusion, storage duration leads to loss of seed quality, but appropriate seed pelleting treatments *viz.*, fungicide treatment and biologically active components can slow this decline and help sustain seed performance. Seed pelleting proves to be a simple yet effective technique for enhancing seed longevity, maintaining seed vigour and ensuring better crop establishment in tomato.

CONFLICT OF INTREST

It is to be certified that there is no conflict of intrest among the authors / institutes.

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