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Research Article

Effect of Packaging Materials and Storage Duration on Tef Seed Quality and Related Traits

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Abstract

The experiment was conducted from 2021 to 2023 at Bishoftu Agricultural Research Center, utilized tef variety Dagim and employed a factorial combination of a completely randomized design with four replications. The factors considered were four packaging materials (Polypropylene bag, Polypropylene bag with polyethylene sheet, PICS bag, and Grain super Pro bag) and four storage periods (6, 12, 18, and 24 months), with data recorded every six months throughout the storage periods. Results indicated significant effects of packaging materials and storage time on seedling shoot and root lengths, standard germination, seedling vigor indexes, seedling dry weight, and germination speed. Polypropylene bag with polyethylene sheet and PICS bags consistently yielded the highest mean values across parameters. While standard germination exhibited a decreasing trend from 95.5% to 92.16% over the storage period (though still within acceptable standards), other physiological parameters like moisture content, germination rate, seedling Vigor and emergence showed an increasing trend as storage time extended. Two-way interaction effects were not significant for standard germination and germination speed but were significant for seedling lengths and vigor indexes. All packaging materials met the standard germination requirement for pre-basic seed (90%) at all storage times. Additionally, no live insects or clumped tef seeds were found in any storage container throughout the storage durations tested, underscoring the effectiveness of storing clean tef grain in managing storage insect pests. The study concluded that hermetic bags had no adverse impact on tef seed quality, suggesting their suitability as an alternative storage method. These findings provide valuable insights for tef storage practices and emphasize the importance of cleanliness in preventing infestation.

Keywords

Packaging Materials, Storage Duration, Tef

1. Introduction

Tef [*Eragrostis tef* (Zucc) Trotter] is a crucial cereal crop in Ethiopia and Eritrea, serving as a staple food for most people. Outside Ethiopia, it is grown to a limited extent in the USA, South Africa, the Netherlands, and Australia for forage and grain. Ethiopia is the world's largest tef producer, with the crop covering about 28% of the total cereal acreage (2.93 million ha), involving over 6.87 million farmers, and an average yield of 1.88 t/ha [4].

It is staple food in Ethiopia, cultivated by millions of smallholder farmers, but its productivity lags behind other cereal crops due to limited access to technology [18, 3, 10]. Efforts to improve tef production have led to the release of 58 new varieties since 1950, aiming to enhance productivity and sustainability [2, 14].

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Tef, known for its tolerance to extreme climatic and soil conditions, is a favored crop in semi-arid areas with moisture limitations [22]. Recently, tef has gained global attention for its nutritional and health benefits, particularly due to its gluten-free nature, making it suitable for people with celiac disease [20, 21].

Despite its adaptability and importance as a staple food for over 60 million Ethiopians, tef yields remain low. The national average yield is around 1.9 t/ha, compared to 3.1 t/ha for wheat, 4.2 t/ha for maize, and 2.5 t/ha for barley [14, 5]. There is also a notable yield gap, with on-station research achieving 2.8 t/ha, while the national average remains 1.9 t/ha [5]. The low productivity is primarily due to farmers' limited access to improved varieties and advanced agronomic practices [12, 4].

Tef grains are very small in size, which ranges from 0.9 to 1.7 mm in length and 0.7 to 1.0 mm in diameter [13]. It is speculated that the small grain size is the factor that contributes most to tef resistance to storage insect pests. To prove this supposition [16], Artificially infested tef grain with eight species and confirmed that only the red flour beetle (*Tribolium castaneum* (Hurbst)), dark flour beetle (*T. destructor* Uyttenb.) and warehouse moth (*Cadra cautella* (Walker) (Synonym *Ephestia cautella* (Walker)) infest and produce fertile progeny on stored tef grain, although the latter two species have low rate of multiplication than the former one. [24] first reported natural infestation of tef grain by the lesser grain borer (*Rhyzopetha dominica* (F.)) in southern Ethiopia. Moreover, reported natural infestation of stored grains by the cigarette beetle (*Lasioderma serricorne* F.) and confused flour beetle (*T. confusum* J du Val.). All the aforementioned storage insect pests feed only on the embryo of tef grain [16, 23]. Consequently, insect-infested tef seed has significantly reduced germination capacity than un-infested seeds. For instance, according to [23] the germination capacity of infested tef seed was 40%, compared to 98% for un-infested tef seed. Tef seed is relatively less affected by storage diseases and insect pests, as a result, the seed could be stored for prolonged period with very minor deterioration. However adequate information on the effect of different packaging materials and storage duration on tef seed deterioration dynamics in storage and the resulting losses of seed qualities is not well studied. Therefore, this study was aimed to assess the effect of packaging materials and storage duration on tef seed quality.

Moreover, [23] reported that cigarette beetles (*Lasioderma serricorne*) and confused flour beetles (*Tribolium confusum*) infest stored tef grain, feeding on its embryo and reducing germination capacity from 98% to 40% [16, 23]. Despite being less prone to storage pests and diseases, the impact of packaging materials and storage duration on tef seed quality remains understudied. This study aims to evaluate how these factors affect tef seed quality over time.

Seed packaging plays a critical role in both storing and distributing seeds in safe and manageable quantities. Its primary purpose during storage, transportation, and distribution is to shield seeds from environmental factors, physical damage, and mechanical hazards [9]. High-quality seeds are fundamental for boosting agricultural yields. While a seed's genetic makeup determines its inherent quality, proper storage and maintaining viability are crucial for seed vigor [6]. Standardizing appropriate seed treatments and packaging materials is paramount to preserving seed quality during storage, because seed treatments and packaging materials serves as the first line of defense, ensuring healthy crop emergence and subsequent plant. [25]. Accordingly, some of the relationships of packaging materials and factors for seed quality losses are: *Moisture Content*: Moisture-proof packaging is critical because *high seed moisture* accelerates seed aging, promotes fungal growth, and reduces viability. Dry environments and proper packaging materials (e.g., hermetically sealed bags) can mitigate these risks.

Seed packaging is essential for safe storage, transport, and distribution, protecting seeds from environmental factors, physical damage, and mechanical hazards (Harrington and Douglas, 1970) [9]. High-quality seeds are vital for agricultural productivity, with genetic makeup, proper storage, and viability maintenance influencing seed vigor [6]. Effective seed treatments and packaging materials serve as the first defense against quality loss, supporting healthy crop emergence [25]. Moisture-proof packaging is crucial, as high seed moisture accelerates aging, promotes fungal growth, and reduces viability, while dry conditions and hermetically sealed bags help mitigate these risks.

Temperature: Packaging that insulates seeds from extreme temperatures can prevent heat-induced deterioration, which is particularly important in regions with high temperatures or fluctuating climates. *Heat-sensitive packaging* (like thin plastics) can increase seed respiration, aging, and deterioration.

Oxygen Levels: Reducing oxygen through vacuum-sealing or using materials with low permeability can prevent oxidative damage, thus preserving seed vigor and extending shelf life. *Permeable materials* can exacerbate oxygen exposure and degrade seed quality.

Storage Pests: Properly sealed containers and packaging materials that are impermeable to pests prevent infestation. *Weak packaging materials* such as paper or cloth bags can be penetrated by insects or rodents, leading to seed destruction.

Fungal and Microbial Contamination: Moisture and air-permeable materials promote microbial growth if stored in humid conditions.

Moisture-proof and airtight materials help protect seeds from fungal spores and bacteria, ensuring better seed health.

Seed Aging and Vigor Loss: Seeds stored in *high-quality packaging* that limits moisture, light, and oxygen have slower aging rates and retain higher vigor for a longer time. Poor packaging can accelerate seed aging, reducing vigor and the overall ability of seeds to establish successfully when planted.

In general, choosing the right packaging material is vital to preserving seed quality. High-quality packaging prevents the key factors responsible for seed deterioration moisture, temperature fluctuations, oxygen, physical damage, and pest infestations. Proper packaging not only extends seed longevity but also helps maintain high seed germination rates, vigor, and field performance over time.

The quality of seeds can deteriorate during storage due to various internal and external factors. This decline, often referred to as poor storability, is a major concern. Hermetic storage, a controlled atmospheric technology, has emerged as a promising solution to extend the shelf life of grains. By creating a near-anaerobic environment, it eliminates insects, mites, and the growth of aerobic fungi. However, research on the impact of such technologies on the physiological quality of seeds remains limited. To address this gap in knowledge, conducting such research experiment which investigate the effects of different packaging materials over various storage durations for tef seed quality is crucial.

2. Materials and Methods

The experiment was conducted from 2021 and 2023 at the Bishoftu Agricultural Research Center, utilizing approximately 25 kg of homogenized pre-basic seed of tef variety Dagim harvested during the 2021 main cropping season. Employing a factorial combination, the experiment employed a completely randomized design with four replications. The study investigated four packaging materials: Polypropylene bag, Polypropylene bag with polyethylene sheet lining, PICS bag, and Grain super Pro bag, alongside four storage periods (6, 12, 18, and 24 months). Initial data was collected prior to packaging and storage, while subsequent data for the stored samples was recorded every six months over the two-year duration of the experiment. This design aimed to assess the impact of packaging materials and storage duration on various parameters related to tef seed quality and longevity, providing insights into optimal storage practices for tef seeds.

2.1. Data Collected

2.1.1. Thousand Seed Weight

To Determine the Thousand Seed Weight, the Following Procedure Was Followed.

After storage, seeds were counted and ten replicates of 100 seeds each were randomly selected. The weight of each set of 100 seeds was measured and the mean weight of the ten replicates was calculated. The mean weight was then multiplied by 10 to obtain the thousand seed weight. This method ensures a representative sample of seeds is weighed to determine the average weight of 100 seeds, which is then extrapolated to estimate the weight of a thousand seeds.

2.1.2. Speed of Germination

measures the time taken for seeds to germinate under optimal conditions or it refers to the rate at which seeds germinate over a specified period. It is often quantified by calculating the mean germination time (MGT) or germination index (GI). A faster speed of germination indicates higher seed vigor and potential for rapid establishment in the field. It is a key parameter in assessing both seed germination and seed vigor, as it provides insights into how quickly seeds are capable of germinating and helps determine how viable and strong those seedlings will be under favourable conditions.

As proposed by [17] a method for calculating) based on the rate of germination over a specific period. The formula for calculating germination speed of germination (SG) is as follows:

$$\text{Speed of germination} = (N1/D1) + (N2/D2) + \cdots + (Nf/Df)$$

Where:

N1, N2,…, Nk = Number of seeds germinated on days 1, 2,..., k, respectively.

D1, D2,…, Dk = Number of days taken for germination on days 1, 2,..., k, respectively.

This formula calculates the average germination speed over the observed period, taking into account the number of seeds that germinated each day and the time it took for them to germinate. In the provided context, 100 seeds were taken from each sample and divided into four replicates. These seeds were then subjected to germination conditions at 20 ℃ for 8 days in a seed germinator since the standard temperature range for tef seed germination in the laboratory is 20 ℃ to 30 ℃, often tested at a constant 25 ℃. Normal seedlings were removed each day, and the number of seeds germinated on each day (n1, n2, nk) and the corresponding number of days taken for germination (t1, t2, tk) were recorded. Using the collected data, the speed of germination (SPG) can be calculated using the formula mentioned above, providing insight into the vigor of the seeds based on their speed of germination.

2.1.3. Standard Germination Test

The standard germination test was conducted by randomly selecting four hundred (400) seeds from a mixed pure seed batch. These seeds were then divided into four replicates, each containing 100 seeds. The seeds were sown on standardized germination paper and maintained at room temperature throughout the germination period. The first seed count was conducted on the 3rd day after planting for tef seeds, while the final count was performed on the 10th day. During the evaluation process, seedlings were categorized as either normal, abnormal, or dead seedlings based on predetermined criteria. The standard germination percentage was calculated according to the guidelines outlined by the International Seed Testing Association [11]. This calculation involves determining the percentage of seeds that successfully germinated within the specified time frame, considering both the initial and final counts based on the following procedure.

$$\text{Germination (\%)} = \frac{\text{Total number of normal seedling}}{\text{Total number of seeds planted}} \times 100$$

Shoot and root lengths: were measured after the final count of the standard germination test. Ten normal seedlings were randomly selected from each replicate. Shoot length was measured from the cotyledon attachment to the seedling tip, while root length was measured from the cotyledon attachment to the root tip. Average lengths were calculated by dividing the total shoot or root length by the number of seedlings measured [8]. By assessing both shoot and root lengths, insights into the overall growth and development of the seedlings can be obtained. These measurements help evaluate the vigor and health of the seedlings, providing valuable information for further analysis and decision-making in agricultural practices which ensures systematic and standardized procedures for assessing seedling characteristics, contributing to the reliability and reproducibility of the results.

2.1.4. Seedling Dry Weight

The seedling dry weight was measured after the final count in the standard germination test. Ten seedlings randomly selected from each replicate were cut free from their cotyledons and placed in envelopes and dried in an oven at 80 ±1 ℃ for 24 hours. The dried seedlings were weighed to the nearest milli-gram and the average seedling dry weight was calculated by dividing the total dry weight by the total number of seedlings measured. This calculation provides an average measure of seedling dry weight across the sample. By assessing seedling dry weight, insights into the biomass accumulation and growth potential of the seedlings can be obtained. This measurement is crucial for evaluating the vigor and health of the seedlings, as it reflects their ability to accumulate biomass and sustain growth under the given conditions. This methodology ensures systematic and standardized procedures for assessing seedling characteristics, contributing to the reliability and reproducibility of the results.

Seedling dry weight was measured after the final count of the germination test. Ten randomly selected seedlings from each replicate were detached from their cotyledons, dried at 80 ±1 ℃ for 24 hours, and weighed to the nearest milligram. The average dry weight was calculated by dividing the total dry weight by the number of seedlings. This measurement reflects seedling vigor, biomass accumulation, and growth potential, providing a standardized approach for assessing seedling health and ensuring reliable results.

2.1.5. Vigor Index Test

The seedling vigor index was calculated for each sample as per Abdul Baki and Anderson [1] and expressed in number by using formula below. Seedling vigor index 1 was calculated by multiplying the standard germination with the average sum of shoot length and root length after 10 days of germination and vigor index 2 was again calculated by multiplying the standard germination with mean seedling dry weight (drying at temperature of 80 ℃ for 24 hours).

Vigor index provides a comprehensive assessment of seed vigor, taking into account both germination performance and seedling vigor. These mean values provide valuable insights into the physiological quality of the seed samples tested in the laboratory. They serve as indicators of seed viability, vigor, and overall performance, helping seed producers and users make informed decisions regarding seed storage, handling, and planting.

Seedling vigor index was calculated following the method of [1]. Vigor index 1 was obtained by multiplying standard germination by the average of shoot and root lengths after 10 days of germination. Vigor index 2 was calculated by multiplying standard germination by the mean seedling dry weight after drying at 80 ℃ for 24 hours.

The vigor index offers a comprehensive measure of seed quality, reflecting both germination capacity and seedling vigor. These values provide critical insights into seed viability, vigor, and overall performance, supporting informed decisions on seed storage, handling, and planting.

The formula for these parameters:

$$\text{SVI1} = \text{Standard germination} \times \text{mean seedling length (Roots +Shoots length)}.$$

$$\text{SVI2} = \text{Standard germination} \times \text{mean seedling dry weight}$$

These indices provide a comprehensive measure of seedling vigor, taking into account both germination performance and subsequent seedling growth or biomass accumulation. By calculating SVI1 and SVI2 for each sample, one can assess the overall vigor of the seeds based on their germination rate and subsequent growth or biomass characteristics.

2.1.6. The Assessment for Infestation of Tef Seeds by Storage Insect Pests Involved Two Criteria

1. Presence of Live or Dead Insects (Adults and Larvae).

This criterion involves examining the grain samples for the presence or absence of live or dead insects, including both adults and larvae. Live insects suggest an active infestation, while dead insects may indicate a previous infestation or recent control measures. The presence of either live or dead insects is an indication of potential infestation and warrants further investigation or pest management measures.

2. Presence of Aggregated/Clumped Tef Seed

This criterion involves observing the grain samples for the presence of aggregated or clumped seeds, which may indicate the existence of the pupal stage of storage insect pests. Aggregated or clumped seeds often result from the presence of pupae, which form clusters during their development. The presence of aggregated or clumped seeds serves as an indirect indicator of infestation by storage insect pests, particularly during the pupal stage. By examining grain samples for the presence of live or dead insects and observing the aggregation or clumping of seeds, one can assess the extent of infestation by storage insect pests in tef seeds. These criteria help in identifying potential infestation problems and implementing appropriate pest management strategies to mitigate losses and preserve seed quality during storage.

2.2. Data Analysis

In the provided information, the Tukey test was employed to compare all treatments at a 5% level of significance. SAS software was utilized for laboratory data analysis.

3. Results and Discussion

3.1. Initial Seed Quality of Tef Seed Before Storage

Physiological seed quality test was conducted in seed laboratory for all seed samples before storage. The mean values for the speed of germination, standard germination, seedling shoot and root length, seedling dry weight, vigor index-I and II were indicated in Table 1 below.

Table 1. *Mean values of seed physiological quality before storage.*

Crop	Rep	SDG	SHL	RL	SFW	SDW	VI	VII	SPG
Tef	1	96	1.8	0.56	0.17	0.09	226.56	8.64	11.86071
Tef	2	98	2.4	0.4	0.39	0.29	274.4	28.42	11.85119
Tef	3	86	1.2	0.88	0.3	0.22	178.88	18.92	10.36667
Tef	4	96	1.5	0.6	0.33	0.24	201.6	23.04	10.24762
.	Mean	94	1.725	0.61	0.298	0.21	220.4	19.76	11.08

SDG=Standard germination percent, SHL= shoot length. RL= root length. SDW= seedling dry weight. VI=vigor index-I, VII=vigor index-II, SPG = speed of germination

3.2. Effect of Packaging Material and Storage Duration on Standard Germination

The main effect of packaging materials and storage duration significantly ($P \leq 0.01$) influenced tef seed germination, although there was no significant effect for the interaction effect of packaging material and storage duration on tef seed germination. Before packaging and storage, the initial standard germination of the seed was recorded at 94 percent. Maximum germination percentage was observed in seeds stored in Polypropylene bags with polyethylene sheets (94.5%), followed by PICs bags (94.3%), while the lowest result was obtained from Grain Super Pro bags (93%) and regular Polypropylene bags (91%). The effect of packaging materials on germination remained significant across different storage periods. in line with the present study result [15] stated that the decline in germination percentage over the storage period was due to ageing effect leading to depletion of food reserves, seed deterioration, fluctuating temperature, relative humidity and grain moisture content as influenced by storage packaging materials.

Table 2. *Mean values of physiological seed quality of tef under different packaging materials.*

Treatment	Parameters								
Packging Materials	**ASD**	**DS**	**SDG**	**SHL**	**RL**	**SDW**	**VI**	**VII**	**SG**
Grain super pro bag	3.8a	3.1ab	93ab	2.35b	1.58b	0.1a	364.99d	9.69a	15.23a
Pics bag	2.8a	3ab	94.3a	2.55a	1.6b	0.094ab	392.36b	8.9ab	15.29a
Plypropylne bag	4.3a	4.5a	91b	2.42b	1.8a	0.085b	382.91c	7.74c	14.26b
Polypropylene bag with polyethylene sheet	2.9a	2.41b	94.5a	2.45ab	1.84a	0.087b	405.85a	8.32bc	15.69a
CV	40.3	49	2.8	4.3	6.2	11.4	1.07	11.2	5.6

Treatment	Parameters								
Packging Materials	ASD	DS	SDG	SHL	RL	SDW	VI	VII	SG
Tukey	1.55	1.79	2.94	0.118	0.117	0.118	4.59	1.08	0.95

ABS=Abnormal seeds, DS=dead seeds SDG=Standard germination percent, SHL= shoot length. RL= root length. SDW= seedling dry weight. VI=vigor index-I, VII=vigor index-II,. SPG = speed of germination. Means followed by the same letter in the column are not significantly different from each other at 5% probability level.

3.3. Effect of Packaging Material and Storage Duration on Seedling Shoot and Root Length

The highest mean germination value was recorded for seeds stored for six months (94.66%), followed by twelve months (92.0%), eighteen months (93.6%), and twenty-four months (92.16%). Notably, the germination results obtained across all storage periods met the standard set for tef seed (90%) [7]. Shoot and root lengths of tef seedlings were significantly influenced by both the main effect and the interaction effect of packaging materials and storage durations. The highest shoot length was recorded when seeds were stored in PICs bags (2.55) (Table 2) with the peak mean value of shoot length (2.69) (Table 3) observed at eighteen months of storage.

***Table 3.** Mean values of seed physiological quality parameters under different storage duration.*

Storage Duration	Parameters								
	ASD	DS	SDG	SHL	RL	SDW	VI	VII	SG
6month	2.5b	1.83b	95.5a	1.98c	1.33d	0.07b	317.3d	6.68b	15.09
12month	4.08a	3.58ab	92.5b	2.43b	1.47c	0.1a	361.3c	9.25a	14.83
18month	3.5ab	3.66a	92.66ab	2.69a	1.89b	0.1a	424.3b	9.63a	15.16
24month	3.83ab	4a	92.16b	2.66a	2.14a	0.09a	443.03a	9.10a	15.39
CV	40.3	49	2.8	4.3	6.2	11.4	1.07	11.2	5.6
Tukey	1.55	1.79	2.94	0.118	0.117	0.0118	4.59	1.08	0.95

ABS=Abnormal seeds, DS=dead seeds SDG=Standard germination percent, SHL= shoot length. RL= root length. SDW= seedling dry weight. VI=vigor index-I, VII=vigor index-II. SPG = speed of germination. Means followed by the same letter in the column are not significantly different from each other at 5% probability level

3.4. Effect of Packaging Material and Storage Duration on Seedling Dry Weight

The study found that seedling dry weight was notably affected by the two experimental factors: storage duration and type of packaging material. However, the analysis showed that seeds stored in PICs (Purdue Improved Crop Storage) bags and those in polypropylene bags with or without polyethylene sheets did not display significant differences in seedling dry weight. This suggests that these packaging types provided a similar level of protection for the seeds, preventing major moisture loss or damage that could impact seedling growth.

Interestingly, a significant difference was observed with seeds stored in Grain Super Pro bags. These bags yielded the lowest seedling dry weight, particularly by the sixth month of storage, with an average of 0.06 grams, indicating that the material or structure of the Grain Super Pro bag may not have provided adequate conditions to maintain seed quality for optimal growth. In contrast, polypropylene bags seemed to offer better protection, with seeds stored in them achieving the highest mean seedling dry weight (0.13 grams) at the six-month storage mark. This may reflect that polypropylene's properties whether its material density or moisture barrier effectiveness better preserved the seeds' viability, resulting in more robust seedlings.

Overall, it underscores the importance of selecting appropriate storage materials to maintain seed quality over time. The prolonged storage period can lead to declines in seed quality, but the right storage solution can mitigate these effects, supporting healthier seedlings even after several months. This is crucial for agricultural practices where storage duration may impact crop productivity, and selecting suitable storage materials could thus enhance germination success and seedling vigor. Regarding the interaction effect, the highest value for shoot length was recorded for seeds stored in Polypropylene bags (2.83) at six months of storage, while the lowest mean value for shoot length was recorded at six months from Grain Super Pro bags (1.67). As for root length, the highest mean value was obtained from seeds stored in Polypropylene bags after twenty-four months, while the lowest value was observed in seeds stored in Grain Super Pro bags after six months of storage (Table 4). These findings suggest that seedlings with well-developed shoot and root systems are better equipped to withstand adverse conditions and achieve better seedling emergence and establishment in the field [26]. Similar observations have been made by previous studies, indicating a decrease in shoot and root length of rice varieties as the storage period progresses [19]. This reduction in the rate of seedling development over prolonged storage periods may be attributed to the depletion of seed food reserves.

Table 4. *Mean values for Two-way interaction effects of Packaging materials and storage durations on physiological seed quality of tef.*

Packaging Materials	Storage Duration	ADS	DS	SDG	SHL	RL	SDW	VI	VII	SPG
Grain superpro bag	6 months	3.3ab	2ab	94.66	1.67g	1.26c	0.06c	278.2j	6.3ed	15
Pics bag	6 months	4ab	3.3ab	92.66	2.2df	1.4bc	0.1ab	333gh	9.2ad	15
Plypropylne bag	6 months	3.3ab	3.3ab	93.33	2.83a	1.56bc	0.13a	410d	12.1a	15.2
Fertilizer bag	6 months	4.66ab	4ab	91.33	2.7ab	2.1a	0.12a	438.2c	11.1ab	15.5
Grain Super pro bag	12 months	2b	2ab	96	2.3ce	1.32bc	0.06c	349.12ef	6e	15.5
Pics bag	12 months	4ab	4ab	92	2.5ac	1.36bc	0.1ab	358.66e	9.2ad	14.6
Plypropylne bag	12 months	3.3ab	3.3ab	94	2.73a	1.56bc	0.1ab	404d	10.1ac	15.2
Fertilizer bag	12 months	2b	2.66ab	95.33	2.63ac	2.16a	0.1ab	457.6a	10.1ac	15.7
Grain superpro bag	18 months	2b	1.3ab	96.66	1.95gf	1.38bc	0.06c	322.8hi	6.4de	13.8
Pics bag	18 months	6.66a	6a	87.33	2.4bd	1.53bc	0.1ab	342gf	8.7be	13.6
Plypropylne bag	18 months	4ab	5.3ab	90	2.6ac	2.2a	0.08bc	431.8c	8ce	15
Fertilizer bag	18 months	4.66ab	5.3ab	90	2.73a	2.1a	0.8bc	434.8c	7.7ce	14.5
Grain superpro bag	24 months	2.6ab	2ab	94.66	2ef	1.36bc	0.08bc	319.2i	7.8ce	15.9
Pics bag	24 months	1.66ab	1b	98	2.6ac	1.6b	0.1ab	411.6d	9.8ac	15.9
Plypropylne bag	24 months	3.3ab	2.66ab	93.33	2.6ac	2.23a	0.08bc	451ab	8.2be	15.2
Fertilizer bag	24 months	4ab	4ab	92	2.6ac	2.2a	0.08bc	441.46bc	7.3ce	15.7
CV		40	49	2.8	4.3	6.2	11.4	1.07	11.2	5.6
Tukey		4.2	4.9	8	0.32	0.32	0.03	12.61	2.97	2.61

ABS=Abnormal seeds, DS=dead seeds SDG=Standard germination percent, SHL= shoot length. RL= root length. SDW= seedling dry weight. VI=vigor index-I, VII=vigor index-II, SPG = speed of germination. Means followed by the same letter in the column are not significantly different from each other at 5% probability level

3.5. Effect of Packaging Material and Storage Duration on Vigor Indexes

The main limitation of the germination test is its inability to detect quality differences among seed samples at high germination percentages and its failure to predict field emergence under adverse field conditions. To address this limitation, several physiological tests were considered to assess the vigor of tef seeds stored in different packaging materials under various storage periods. The study results revealed that both the main and interaction effects of packaging materials and storage duration significantly affected vigor index-I and II (p

< 0.01). The highest mean values of vigor index I and II were observed in seeds stored in Polypropylene bags with polyethylene sheets and Grain Super Pro bags, respectively. Notably, the maximum values were attained after 24 months of storage for both the main and interaction effects. In terms of the interaction effect, the highest mean value of vigor index-I was observed in seeds stored in fertilizer bags (457) for 12 months of storage, while the lowest value was recorded in Grain Super Pro bags after six months of storage (278.2). Regarding vigor index-II, the maximum mean value for the interaction effect was recorded in Polypropylene bag after 6 months of storage (12.1), while the lowest value was recorded in Grain super pro bag (6.0) after 6 months of storage.

Insect infestation:

No live insects or clumped tef seeds were found in any of the storage containers tested after 6, 12, 18, and 24 months. This suggests that the likelihood of field infestation of tef grain by storage insect pests is low, although [24] reported accidental infestation of tef by lesser grain borer before harvest. Additionally, it's recommended to store tef grain cleanly as a practice for managing storage insect pests [23] Thus, the absence of infestation in any of the packaging materials tested could be attributed to the cleanliness of the stored tef.

4. Conclusion and Recommendations

The study findings underscore the significant influence of packaging materials and storage duration on various parameters related to tef seedling growth and vitality. Notably, Polypropylene bags with polyethylene sheet and PICs bags emerged as the most effective, yielding the highest mean values across key parameters such as seedling shoots and root lengths, standard germination, seedling vigor indexes, seedling dry weight, and germination speed. While standard germination rates displayed a downward trend with prolonged storage (from six to twenty-four months), they remained within acceptable limits. Conversely, other vital parameters like shoot and root lengths, vigor indexes, and seedling dry weight exhibited an upward trajectory with extended storage durations. Crucially, all packaging materials consistently met the prescribed standard germination rate of 90% for pre-basic seed throughout the testing periods. Moreover, the absence of live insects and clumped tef seeds in storage containers after 6, 12, 18, and 24 months suggests that maintaining cleanliness in stored tef grain effectively manages storage insect pests. This observation highlights the importance of cleanliness in preventing infestation across all packaging materials examined.

Furthermore, the study indicates that hermetic bags did not compromise tef seed quality, suggesting their viability as an alternative storage solution. This insight offers valuable guidance for agricultural practices aimed at preserving tef seed integrity during storage.

Abbreviations

SG	Standard Germination
ABS	Abnormal Seeds
DS	Dead Seeds
SHL	Shoot Length
RL	Root Length.
SDW	Seedling Dry Weight
VI	Vigor Index-I
VII	Vigor Index-II
SPG	Speed of Germination

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Author Contributions

Bekele Gemechu is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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