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Effect of Green Tea Extract Coating on Viability and Vigor of Recalcitrant Cocoa (Theobroma cacao L.) Seeds during Ambient Storage

Hajar Setyaji[1]*, Mukhsin[2], Suryanto[3]
Department of Agrotechnology, Faculty of Agriculture, Universitas Jambi
Corresponding Author: Hajar Setyaji hajarsetyaji@unja.ac.id

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A B S T R A C T
This study evaluated green tea (*Camellia sinensis*) extract as a natural coating to improve the storability of recalcitrant cocoa (*Theobroma cacao* L.) seeds under ambient conditions. Seeds were coated with green tea extract at 0, 5, 10, and 20 g/100 mL and stored for up to six weeks. Seed moisture content, germination, germination rate, germination uniformity, and seedling dry weight were evaluated. Storage duration caused a rapid decline in seed quality, particularly after four weeks of storage. Although green tea extract provided slight protection during storage, its overall effect was limited, and higher concentrations tended to reduce germination performance. Overall, green tea extract coating could not substantially extend cocoa seed storability under ambient tropical conditions.

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INTRODUCTION

Theobroma cacao L. constitutes a cornerstone of the agricultural economy in many tropical developing countries and serves as a primary source of income for millions of smallholder farmers. Indonesia ranks among the world's leading cocoa producers, with national production reaching approximately 720,660 metric tons in 2020 (Pirade et al., 2022). Despite its economic importance, farm-level productivity in many regions remains below national averages, largely due to the dominance of aging plantations, inferior planting materials, and chronic shortages of high-vigor seeds for large-scale replanting programs (Duriat et al., 2023; Shahruddin et al., 2025).

High-quality seeds are fundamental for successful cocoa cultivation. However, the recalcitrant nature of cocoa seeds severely constrains their handling and distribution. Recalcitrant seeds are shed at high moisture content (typically 40–60%) and are extremely sensitive to desiccation. Unlike orthodox seeds, they cannot be stored for extended periods because dehydration triggers membrane disintegration, accelerated respiration, excessive production of reactive oxygen species (ROS) and reactive nitrogen species (RNS), and lipid peroxidation, ultimately causing rapid viability loss (Berjak & Pammenter, 2013; Lah et al., 2023).

Under ambient conditions, extracted cocoa seeds generally remain viable for less than three weeks. Storage inside intact pods offers only marginal improvement but is impractical due to large volume requirements and increased risks of fungal and pest damage. These limitations highlight the urgent need for practical storage technologies.

Oxidative stress is a primary driver of deterioration in recalcitrant seeds. Cocoa seeds contain approximately 50% lipids, predominantly unsaturated fatty acids that are highly prone to peroxidation. ROS and RNS, such as H_2O_2, $O_2{\bullet}^-$, $\bullet OH$, $NO\bullet$, and $ONOO^-$, play dual roles as signaling molecules and damaging agents (Kumar et al., 2021; Prasad et al., 2020). High initial moisture content sustains high respiration rates, leading to ROS overproduction and disruption of the prooxidant-antioxidant balance (Bonvisutto & Busso, 2007).

Green tea (*Camellia sinensis*) is rich in polyphenols, particularly catechins and epigallocatechin gallate (EGCG), which possess strong antioxidant and membrane-stabilizing activities (Jin et al., 2018). Seed coating technology using natural antioxidants can provide dual protection through physical barriers and biochemical mechanisms. However, limited information is available regarding its efficacy on recalcitrant cocoa seeds.

Therefore, this study aimed to evaluate the effect of various concentrations of green tea extract as a seed coating material on the viability and vigor of cocoa seeds during ambient storage. The findings are expected to contribute to the development of low-cost, natural technologies for improving cocoa seed handling in tropical countries.

LITERATURE REVIEW

Recalcitrant Seed Storage Theory

Recalcitrant seeds, such as cocoa seeds, are shed with high moisture content and are highly sensitive to desiccation. They cannot be stored for long periods because they remain metabolically active, leading to rapid viability loss due to increased respiration and oxidative stress (Berjak & Pammenter, 2013; Lah et al., 2023; Corbineau et al., 2024). Previous studies consistently show that storage duration has a strong negative effect on seed quality in recalcitrant species.

$H0_1$: Storage duration has no significant effect on moisture content, germination percentage, germination rate, germination uniformity, and seedling dry weight of cocoa seeds. **$H1_1$**: Storage duration has a significant negative effect on moisture content, germination percentage, germination rate, germination uniformity, and seedling dry weight of cocoa seeds.

Antioxidant Protection and Seed Coating Theory

Green tea (*Camellia sinensis*) extract is rich in polyphenols, particularly catechins and epigallocatechin gallate (EGCG), which act as potent antioxidants capable of scavenging reactive oxygen species (ROS) and stabilizing cell membranes (Jin et al., 2018; Paparella et al., 2025). Seed coating with natural antioxidants is expected to provide both physical protection (semi-permeable barrier) and biochemical protection against oxidative deterioration.

Several studies have reported positive effects of polyphenol-based coatings on seed storability, although results on recalcitrant seeds remain inconsistent. This study tests whether green tea extract coating can improve cocoa seed quality during storage.

$H0_2$: Green tea extract concentration as a seed coating has no significant effect on the viability and vigor of cocoa seeds during storage. **$H1_2$**: Green tea extract concentration as a seed coating has a significant positive effect on the viability and vigor of cocoa seeds during storage.

$H0_3$: There is no significant interaction between green tea extract concentration and storage duration on cocoa seed quality parameters. **$H1_3$**: There is a significant interaction between green tea extract concentration and storage duration on moisture content, germination percentage, germination rate, germination uniformity, and seedling dry weight of cocoa seeds.

Contextual Framework

This study integrates the Recalcitrant Seed Storage Theory and the Antioxidant Protection via Seed Coating Theory within the context of tropical seed technology. Recalcitrant cocoa seeds face rapid deterioration due to high initial moisture content (≈38%), which sustains high respiration rates and excessive ROS production. This oxidative imbalance leads to lipid peroxidation and loss of membrane integrity, resulting in fast viability decline.

The present research tests whether green tea extract coating can serve as a practical, low-cost intervention to slow this deterioration process under ambient conditions. By applying different concentrations of green tea extract and observing seed quality over six weeks of storage, this study examines the main effects of storage duration and coating concentration, as well as their interaction.

The research is particularly relevant to Indonesia, where the national seed certification standard requires a minimum of 80% germination for cocoa seeds (BPTP, 2011; BSN, 2024). However, the short storage life of cocoa seeds creates major logistical problems for replanting programs. This study therefore contributes empirical evidence on whether a simple natural coating technology can help bridge the gap between seed harvest and planting time, while also providing scientific insight into the effectiveness of antioxidant intervention on highly recalcitrant tropical seeds.

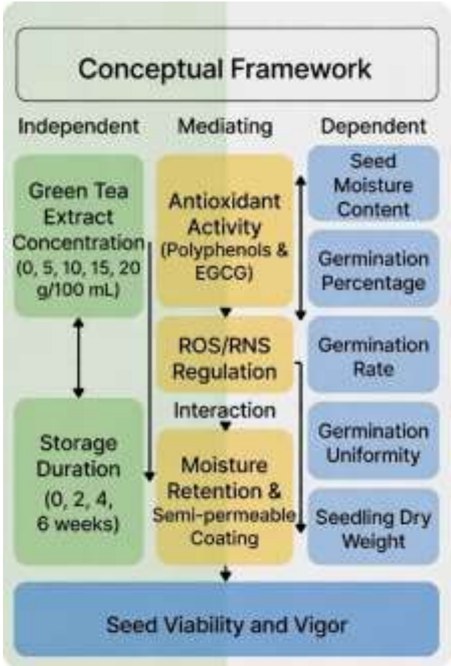

Figure 1. Conceptual Framework of the Study

METHODOLOGY

Experimental Site

The experiment was carried out in the Seed Technology Laboratory, Faculty of Agriculture, under ambient room conditions. The average temperature during the study ranged from 25 to 28 °C with relative humidity fluctuating between 70–85 %.

Plant Materials

Mature and fully ripened cocoa pods of a local cultivar were harvested from smallholder plantations. The pods were immediately transported to the laboratory. Seeds were manually extracted, washed thoroughly to remove the mucilage, and surface-dried with absorbent paper. Only healthy, uniform-sized seeds free from visible mechanical damage, insect injury, or fungal infection were selected for the experiment.

Preparation of Green Tea Extract

Dried green tea leaves (*Camellia sinensis*) were finely ground into powder. The extract was prepared using a hot-water extraction method. Briefly, the powdered green tea was mixed with distilled water at various ratio depending on the treatment and incubated in a water bath at 80 °C for 30 minutes. The mixture was then filtered through Whatman No. 1 filter paper. The resulting filtrate was collected and diluted with distilled water to obtain the desired concentrations for each treatment.

Seed Coating Application

The coating solution was prepared by combining the green tea extract with a CMC as adhesive. Seeds were immersed in the respective coating solutions for 10 minutes, then removed and air-dried at room temperature until the seed surface appeared dry and non-sticky.

Experimental Design

The study was arranged in a factorial completely randomized design (CRD) with two factors and three replications. The factors were:

- Factor A: Storage duration A0 = 0 weeks (initial) A1 = 2 weeks A2 = 4 weeks A3 = 6 weeks
- Factor B: Green tea extract concentration: 0 g/100 mL (control), 5 g/100 mL, 10 g/100 mL, 20 g/100 mL

Each treatment combination consisted of three replications.

Storage Conditions

Coated seeds were placed in perforated plastic containers to allow gas exchange and stored under ambient laboratory conditions (25–28 °C) with high relative humidity.

Observed Parameters

1 Seed Moisture Content Seed moisture content was determined using the oven-drying method. Approximately 5 g of seeds were weighed (W_i) and dried in an oven at 105 °C for 24 hours until constant weight was achieved (W_d). Moisture content was calculated as:

$$\text{MC (\%)} = \frac{(W_i - W_d)}{W_i} \times 100$$

2 Germination Percentage Germination percentage was recorded according to the method of Sutariati et al. (2014). Seeds showing normal radicle emergence (≥ 2 mm) were considered germinated. The percentage was calculated as:

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

3 Germination Rate Germination rate was calculated daily for 14 days after sowing following the formula of Kartika et al. (2015):

$$\text{Germination Rate} = \frac{\sum_{i=1}^{n} (n_i / h_i)}{N}$$

where $n_i$is the number of seeds germinated on day i, $h_i$is the number of days from sowing, and $N$is the total number of germinated seeds.

4 Germination Uniformity Germination uniformity was determined as the percentage of strong, normal seedlings at 11 days after sowing (Debtisari et al., 2018). Seedlings were classified as normal if they possessed a well-developed radicle, intact hypocotyl, and healthy cotyledons.

5 Seedling Dry Weight At the end of the germination test, ten normal seedlings per replication were randomly selected, oven-dried at 70 °C for 48 hours until constant weight, and weighed using a digital analytical balance.

Statistical Analysis

All data were subjected to two-way analysis of variance (ANOVA) using SPSS software version 11. Significant differences among treatments were compared using Duncan's Multiple Range Test (DMRT) at the 5% probability level ($p < 0.05$).

RESEARCH RESULT

Moisture Content

Analysis of variance revealed that storage duration significantly influenced the moisture content of cocoa seeds ($p < 0.05$). In contrast, green tea extract concentration and its interaction with storage duration did not show any significant effects.

The moisture content of cocoa seeds throughout the storage period is presented in Table 1.

Table 1. Moisture content (%) of cocoa seeds coated with different concentrations of green tea extract during storage

Storage duration	green tea extract g/100mL			
	0	5	10	20
A0 (0 weeks)	37.60 ± 0.36 aA	38.37 ± 1.14 aA	37.90 ± 1.65 aA	38.80 ± 0.40 aA
A1 (2 weeks)	30.60 ± 1.44 bB	30.75 ± 1.11 bB	29.25 ± 1.62 bB	31.70 ± 0.16 bB
A2 (4 weeks)	27.50 ± 0.40 cC	26.63 ± 0.43 cC	26.18 ± 1.31 cC	24.79 ± 0.77 cdC
A3 (6 weeks)	21.45 ± 1.49 dD	21.15 ± 0.68 dD	20.45 ± 0.30 dD	20.28 ± 0.82 dD

Values are means ± standard error of three replicates. Means followed by the same lowercase letter in the same column and the same uppercase letter in the same row are not significantly different according to Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

Moisture content decreased steadily over the storage period, which is typical of recalcitrant cocoa seeds that are highly sensitive to desiccation. The highest moisture level was observed at the beginning of storage (38.17%), declining sharply to the lowest level of 20.83% after 6 weeks. The DMRT test at 5% level further confirmed that moisture content differed significantly across storage durations.

Interestingly, the application of green tea extract coating had no significant effect on moisture loss. This suggests that the coating primarily acts as a biochemical protectant rather than a physical barrier to moisture migration during storage.

The decline in seed moisture content during storage is characteristic of recalcitrant seeds such as cocoa. Recalcitrant seeds possess high initial moisture content and remain metabolically active after harvest, resulting in continuous respiration and gradual water loss during storage. Excessive moisture reduction may disrupt membrane integrity, accelerate lipid peroxidation, and decrease seed viability.

The significant effect of storage duration indicates that prolonged storage intensified physiological deterioration processes. Similar findings have been reported in recalcitrant seed systems where moisture decline is closely associated with rapid viability loss.

Green tea extract concentration did not significantly affect moisture content, suggesting that the coating layer was insufficient to substantially modify seed water exchange. Nevertheless, the coating may still provide antioxidant protection against oxidative stress without directly influencing moisture retention.

Germination percentage (%)

Table 2. Germination percentage (%) of cocoa seeds treated with green tea extract coating during storage

Storage duration (weeks)	Green tea extract g/100mL			
	0	5	10	20
A0 (0 weeks)	93.53 ± 2.31 aA	93.33 ± 2.07 aA	88.67 ± 3.01 aA	85.33 ± 5.31 aA
A1 (2 weeks)	81.33 ± 4.62 bA	87.33 ± 4.07 bA	82.00 ± 4.55 bA	54.67 ± 7.42 bB
A2 (4 weeks)	56.00 ± 10.07 cA	60.00 ± 15.02 cA	52.00 ± 8.04 cA	5.33 ± 3.27 dB
A3 (6 weeks)	5.33 ± 6.93 dB	11.33 ± 2.62 dB	12.00 ± 5.76 dB	14.00 ± 3.50 cA

Values are means ± standard error of three replicates. Means followed by the same lowercase letter in the same column and the same uppercase letter in the same row are not significantly different according to Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

Germination percentage of cocoa seeds was significantly affected by storage duration, green tea extract concentration, and their interaction ($P < 0.05$). Seed viability declined progressively and sharply with increasing storage time, indicating rapid deterioration of seed quality.

Freshly harvested seeds (0 weeks) exhibited high germination percentages ranging from 85.33% to 93.53%, and green tea extract coating did not significantly affect germination at the initial stage. After two weeks of storage, germination remained relatively high (81.33–87.33%) in seeds coated with 0–5% green tea extract, while the 10% concentration resulted in a lower germination rate (54.67%).

A substantial decline occurred after four weeks of storage, particularly in seeds treated with 10% green tea extract (5.33%). By the end of six weeks, germination percentage in all treatments had dropped below 15%. At this stage, seeds coated with 10% green tea extract still showed a slightly better germination rate (14.00%) compared to the untreated control (5.33%).

These results suggest that green tea extract coating provided only limited protection to cocoa seed viability, mainly during the early storage period. The rapid loss of seed germinability observed in this study is typical for recalcitrant seeds such as cocoa, which are highly sensitive to storage duration due to their high moisture content and active metabolism.

Germination Rate

Table 3. Germination rate of cocoa seeds treated with green tea extract coating during storage

Storage duration (weeks)	Green tea extract g/100mL			
	0	5	10	20
A0 (0 weeks)	5.72 ± 0.66 aA	5.87 ± 0.87 aA	6.10 ± 0.23 aA	4.91 ± 0.35 aA
A1 (2 weeks)	5.31 ± 0.49 bA	5.22 ± 0.34 bA	5.61 ± 0.24 bA	3.05 ± 0.05 bA
A2 (4 weeks)	3.10 ± 0.42 cA	3.50 ± 0.46 cA	3.12 ± 0.40 cA	1.00 ± 0.11 cB
A3 (6 weeks)	1.00 ± 0.65 dA	0.85 ± 0.52 dA	0.98 ± 1.29 dA	0.68 ± 0.57 dA

Values are means ± standard error of three replicates. Means followed by the same lowercase letter in the same column and the same uppercase letter in the same row are not significantly different according to Duncan's Multiple Range Test (DMRT) at P < 0.05.

Germination rate of cocoa seeds was significantly influenced by storage duration, green tea extract concentration, and their interaction ($P < 0.05$). The germination rate decreased consistently with increasing storage duration, indicating progressive loss of seed vigor.

At the initial stage (0 weeks), germination rates were highest across all treatments, ranging from 4.91 to 6.10, with no significant differences observed among green tea extract concentrations. After two weeks of storage, germination rates began to decline, particularly in seeds coated with 10% green tea extract (3.05). A more pronounced reduction occurred after four weeks of storage, where the 10% extract treatment showed a significantly lower germination rate (1.00) compared to the other treatments (3.10–3.50). By six weeks, germination rates had dropped sharply in all treatments (0.68–1.00), reflecting severe deterioration of seed physiological quality.

These results demonstrate that while lower concentrations of green tea extract (0–5%) maintained relatively better germination rates during the first four weeks, the application of 10% extract tended to accelerate the decline in germination speed. This pattern suggests that high concentrations of green tea extract may impose mild phytotoxic effects on cocoa seeds under prolonged storage conditions.

Germination Uniformity

Table 4. Germination uniformity (%) of cocoa seeds treated with green tea extract coating during storage

Storage duration (weeks)	Green tea extract (g/100 ml)			
	0	**5**	**10**	**20**
A0 (0 weeks)	77.33 ± 12.22 aA	68.00 ± 14.42 aA	76.67 ± 3.06 aA	74.67 ± 9.64 aA
A1 (2 weeks)	76.00 ± 6.11 aA	77.33 ± 4.00 aA	81.33 ± 8.72 aA	32.00 ± 8.72 aB
A2 (4 weeks)	47.33 ± 6.93 bA	46.67 ± 7.21 bA	52.00 ± 4.00 bA	4.00 ± 3.09 bB
A3 (6 weeks)	4.00 ± 0.15 cB	6.67 ± 2.31 cAB	6.00 ± 8.72 cAB	9.33 ± 8.72 cA

Values are means ± standard error of three replicates. Means followed by the same lowercase letter in the same column and the same uppercase letter in the same row are not significantly different according to Duncan's Multiple Range Test (DMRT) at $P < 0.05$

Germination uniformity of cocoa seeds was significantly affected by storage duration, green tea extract concentration, and their interaction ($P < 0.05$). Germination uniformity decreased markedly with prolonged storage, reflecting progressive loss of seed vigor and synchronization.

At the initial stage (0 weeks), germination uniformity was relatively high across all treatments (68.00–77.33%), with no significant effect of green tea extract coating. Uniformity remained stable after two weeks of storage in seeds treated with 0–5% extract (76.00–81.33%). However, the 10% concentration caused a sharp decline to 32.00%. After four weeks, uniformity dropped to approximately 46.67–52.00% in lower concentrations, while seeds coated with 10% extract showed extremely low uniformity (4.00%). By six weeks of storage, germination uniformity had fallen below 10% in all treatments, indicating severe loss of seed quality.

These results suggest that high concentrations of green tea extract (10%) negatively affected germination uniformity, particularly after two weeks of storage. This may indicate a concentration-dependent phytotoxic effect on cocoa seeds during storage.

Seedling Dry Weight

Table 5. Seedling dry weight (g) of cocoa seedlings treated with green tea extract coating during storage

Storage duration (weeks)	Green tea extract (g/100 ml)			
	0	5	10	20
A0 (0 weeks)	2.15±1.12 aA	2.30±1.01 aA	2.61±0.71 aA	2.25±0.40 aA
A1 (2 weeks)	1.88±1.22 bB	1.90±0.95 bB	1.92±1.07 bB	2.50±0.92 aA
A2 (4 weeks)	1.75±1.04 bA	1.51±0.90 bcA	1.25±0.34 cA	1.75±0.67 bA
A3 (6 weeks)	0.25±0.13 dB	0.40±0.25 dAB	0.50±0.30 dAB	0.55±0.31 cA

Values are means ± standard error of three replicates. Means followed by the same lowercase letter in the same column and the same uppercase letter in the same row are not significantly different according to Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

Seedling dry weight was significantly affected by storage duration, green tea extract concentration, and their interaction ($P < 0.05$). Seedling biomass decreased sharply with increasing storage duration, indicating progressive loss of seed vigor and reserves.

At the initial stage (0 weeks), seedling dry weight ranged from 2.15 to 2.61 g with no significant differences among treatments. After two weeks of storage, seedlings from seeds coated with 20 g/100 ml green tea extract maintained significantly higher dry weight (2.50 g) compared to other treatments (1.88–1.92 g). However, after four weeks of storage, dry weight began to decline across all treatments, with the lowest value recorded in the 10 g/100 ml treatment (1.25 g). By six weeks of storage, seedling dry weight had dropped drastically in all treatments (0.25–0.55 g), although seeds treated with higher extract concentrations (10 and 20 g/100 ml) produced slightly heavier seedlings than the control.

These results indicate that while high concentrations of green tea extract (particularly 20 g/100 ml) provided some protective effect on seedling growth during the early storage period, this benefit disappeared under extended storage. The substantial reduction in seedling dry weight after four to six weeks confirms the limited storability of cocoa seeds and the rapid depletion of seed reserves.

DISCUSSION

The results of this study clearly demonstrate that storage duration is the dominant factor affecting the quality of recalcitrant cocoa seeds under ambient tropical conditions. Seed moisture content decreased progressively from an average of 38.17% at harvest to 20.83% after six weeks of storage. This steady moisture loss was accompanied by sharp declines in germination percentage, germination rate, germination uniformity, and seedling dry weight.

Such a pattern is typical for recalcitrant seeds like cocoa. Freshly harvested cocoa seeds generally have high moisture content ranging from 35–50%. During ambient storage, moisture content declines gradually due to continued respiration and transpiration, especially when relative humidity is not fully controlled. When moisture falls below the critical level (generally 20–30%), irreversible cellular damage occurs, including loss of membrane integrity, increased electrolyte leakage, and accelerated oxidative stress (Anita-Sari et al., 2018; Lahay et al., 2018; Toruan-Mathius et al., 2000). In the present study, the most drastic reduction in seed viability occurred between the fourth and sixth weeks, coinciding with moisture content approaching 20–21%, which is consistent with previous reports indicating that cocoa seeds become highly vulnerable once moisture drops below 25–30% (Li et al., 1999; Shahruddin et al., 2025).

In recalcitrant seeds such as cocoa, a decline in moisture content below the critical threshold leads to uncontrolled generation of reactive oxygen species (ROS) and reactive nitrogen species (RNS). Cocoa seeds contain high lipid content (approximately 50%), predominantly unsaturated fatty acids that are highly susceptible to peroxidation. Excessive ROS accumulation triggers lipid peroxidation, protein carbonylation, and DNA fragmentation, ultimately causing loss of membrane integrity and seed death (Bailly, 2019; Kumar et al., 2021; Berjak & Pammenter, 2013). The present findings strongly support this mechanism.

Application of green tea extract as a coating material provided only limited protective effects. Although higher concentrations (10 and 20 g/100 mL) slightly improved germination percentage and seedling dry weight at the end of the six-week period, the overall benefit was modest and insufficient to meet the national seed certification standard of 80% germination. This limited efficacy may be attributed to the coating's primary role as a biochemical (antioxidant) protectant rather than a physical moisture barrier, as shown by the non-significant effect on moisture retention. Green tea polyphenols, particularly epigallocatechin gallate (EGCG) and catechins, are potent ROS scavengers and membrane stabilizers (Jin et al., 2018). However, under high humidity ambient conditions (70–85% RH), their protective capacity appears limited.

Interestingly, higher concentrations of green tea extract tended to reduce germination rate and uniformity during the intermediate storage period (2–4 weeks), suggesting possible mild phytotoxic effects at elevated levels. Similar concentration-dependent responses have been observed in other studies using natural polyphenols on metabolically active recalcitrant seeds.

Compared with previous research, the current results align with findings that simple antioxidant treatments alone are often inadequate for extending the storage life of highly recalcitrant tropical seeds (Anita-Sari et al., 2018; Lahay et al., 2018; Corbineau et al., 2024). Integrated approaches combining antioxidant coatings with better moisture and temperature management (e.g., modified atmosphere or hydrated storage) show greater potential.

In conclusion, while green tea extract coating offers modest short-term antioxidant protection, it cannot overcome the inherent physiological constraints of recalcitrant cocoa seeds — particularly the rapid moisture loss and associated oxidative damage — under uncontrolled ambient conditions. These findings emphasize the need for multi-layered storage technologies to support the cocoa seed supply chain in tropical smallholder farming systems.

CONCLUSIONS AND RECOMMENDATIONS

This study confirms that cocoa seeds exhibit typical recalcitrant characteristics, showing rapid deterioration during ambient storage. Storage duration was the most dominant factor affecting seed quality. Moisture content decreased significantly from approximately 38% to 21% within six weeks, followed by sharp declines in germination percentage, germination rate, germination uniformity, and seedling dry weight. Seed quality remained relatively good for up to two weeks of storage, but declined drastically afterward. Green tea extract coating provided only limited protective effects. Although higher concentrations (10–20%) slightly improved germination percentage at the end of storage, they tended to reduce germination speed and uniformity during the intermediate period. Overall, the extract offered modest antioxidant benefits but could not substantially extend the storage life of cocoa seeds beyond two weeks.

In conclusion, under ambient tropical conditions, cocoa seeds coated with green tea extract can maintain acceptable quality for a maximum of two weeks after harvest.

ADVANCED RESEARCH

Although this study offers valuable insights, it was conducted under uncontrolled ambient conditions. Further research could explore the effectiveness of green tea extract under controlled temperature and humidity, test better formulations, and examine how its polyphenols interact with ROS and RNS at the molecular level. Field trials evaluating actual seedling performance in real farming conditions would also be very useful

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