

Comparative Analysis of Finger Millet Varieties across Formal and Informal Seed Systems in the Amhara Region, Ethiopia

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ABSTRACT

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*Finger millet (*Eleusine coracana*) is a staple crop in Africa and India, contributing significantly to food security in Ethiopia. However, the effectiveness of its seed system remains a challenge, particularly regarding seed quality and availability. This study aimed to evaluate and compare the physical, physiological, and vigour quality of finger millet seeds obtained from formal and informal sources in the Amhara Region. Seed samples were collected from the Adet Agricultural Research Center (formal) and from local farmers using various traditional storage methods (informal). Data analysis using independent t-tests (SPSS) and ANOVA (SAS) revealed that formal seed sources consistently exhibited superior quality, including higher physical purity (99.98% vs. 63.55%), greater thousand seed weight (3.21 g vs. 1.93 g), and improved standard seedling emergence (97.3% vs. 84.6%). Despite the widespread reliance on informal seed sources among smallholder farmers, the results underscore the benefits of formal seeds and the need to strengthen formal seed systems. Recommendations include enhancing farmer awareness, promoting proper seed selection and handling, and facilitating access to high-quality seeds to improve finger millet productivity and support regional food security.*

1. INTRODUCTION

Finger millet (*Eleusine coracana*) is one of the most important staple crops in Ethiopia, particularly in the Amhara region, where it serves as a primary food source for many rural communities. Its drought tolerance and adaptability to marginal soils make it a key crop in areas with erratic rainfall and challenging agro-ecological conditions (Yitayew et al., 2023). Despite these advantages, the productivity of finger millet in Ethiopia remains well below its potential. The national average yield is approximately 1 t/ha, whereas the crop can potentially yield 2.5–3 t/ha under optimal management practices (Tadele, 2007). Globally, average yields range from 1.5–3.5 t/ha, depending on the region and cultivation practices. This yield gap is influenced by several factors, among which low seed quality is a critical determinant, affecting crop establishment, vigor, and ultimate yield (Gebreyohannes et al., 2021).

In Amhara, farmers obtain finger millet seeds from diverse sources, including farmer-saved seeds, local markets, and certified seed producers. Farmer-saved seeds, while readily accessible and cost-effective, often exhibit lower germination rates, reduced vigor, and contamination with weed seeds and diseases (Tsegaye et al., 2019). In contrast, certified seeds produced under controlled conditions generally demonstrate higher germination rates, greater vigor, and lower disease incidence. However, despite the recognized benefits of certified seeds, many smallholder farmers face constraints in accessing them due to high costs and logistical challenges (Mohammednur & Megersa, 2021).

Seed quality is a fundamental determinant of successful finger millet cultivation and is typically assessed through parameters such as germination rate, seed vigor, disease resistance, seed purity, and thousand seed weight. Understanding how these parameters vary across seed sources is essential for designing effective interventions that enhance productivity. While formal and informal seed systems have been extensively studied in crops such as maize, wheat, and sorghum—consistently showing superior performance of formal seeds (Ali et al., 2021) empirical evidence for finger millet remains limited. This knowledge gap is particularly pronounced regarding the variability within informal seed systems, including differences across districts, storage practices, and the potential role of community-based “intermediate” seed systems such as cooperatives and seed banks.

Addressing this gap is critical for supporting smallholder farmers and improving the productivity of finger millet. Therefore, this study was conducted to evaluate the quality of finger millet seeds from formal and informal sources in the Amhara region. Specifically, the study assesses seed purity, thousand seed weight, germination, and vigor to provide evidence on the comparative performance of seed sources, highlight variability and weaknesses within informal systems, and explore opportunities for strengthening intermediate/community-based seed systems.

2. MATERIALS AND METHODS

2.1. Description of the Study Areas

A finger millet seed system study was conducted in Dera, Mecha, and Sekota districts during the 2023/24 cropping season, focusing on major finger millet-producing areas in the Amhara Region. Dera, located in the South Gondar Zone, experiences bimodal rainfall and is known for maize, tef, and wheat production. Mecha, in the North Gojjam Zone, has plateaus and high rainfall from June to September, with a population of over 331,000 people and significant irrigation from the Koga Dam. Sekota, in the Waghimera Zone, has unimodal rainfall, with sorghum and tef as the main crops, and more than 98% of the population is engaged in agriculture.

2.2. Seed Sampling

Farmers for informal seed sampling were selected in consultation with agricultural development agents and district-level agricultural experts, based on their active engagement in finger millet production. The laboratory treatments consisted of seed samples collected from both formal and informal seed sources.

The seed sample collected from Adet Agricultural Research Center (AARC) represents the formal seed source. Approximate geographic coordinates of the districts have also been included. Farmer-saved seed samples of different finger millet varieties were purposively collected from the seed lots of ten model farmers in each peasant association. A sample of 1 kg of seed was drawn from the farmers' seed harvested in the 2023/24 cropping season and correctly labeled (Ali et al., 2021). Composite samples were prepared by mixing primary samples collected from farmers growing the same finger millet variety within each peasant association, ensuring genetic uniformity; samples from different varieties were kept separate throughout the analysis. Collected composite samples were subdivided to get working samples for subsequent seed quality tests. Half of the collected composite seed samples were used for seed health tests, while the remaining half was used to test seed quality in the laboratory (ISTA, 2014). The farmer saved seed samples, but the seed class is unknown.

2.3. Treatments and Design of Laboratory Experiment

The laboratory investigation was conducted at the Amhara Regional Agricultural Research Institute (ARARI) Seed Laboratory, adhering strictly to the protocols established by the International Seed Testing Association (ISTA, 2014). The study employed a Completely Randomized Design (CRD) with three replications for each seed sample to ensure statistical reliability and repeatability. To eliminate potential experimental bias, laboratory tests were randomized by both seed source and district, and certified seeds were included as controls to maintain standardized environmental conditions.

The experimental treatments comprised 27 total seed samples of finger millet (*Eleusine coracana*), representing both formal and informal seed systems (Table 1). The informal seed source consisted of 24 samples collected from model farmers across three purposively selected districts, encompassing varied seed storage practices and local grain color classifications (black, red, and white). The formal seed system was represented by three varieties obtained from the Adet Agricultural Research Center (AARC). Before laboratory analysis, all samples were cleaned to analytical purity, following standardized procedures to ensure consistency in the determination of thousand-seed weight (TSW).

Varietal identity was rigorously verified using a multi-methodological approach, including national crop variety records and standard morphological descriptors. This confirmation process integrated farmer interviews and field observations of panicle structure before harvest, supplemented by visual assessment of grain color post-threshing. The experimental scope covered two critical dimensions of seed quality: physical purity, analyzing crop seed fractions, other crop seeds, weed seeds, and inert matter, and physiological quality, specifically moisture content and germination capacity.

2.4. Data Collection Method

2.4.1. Physical purity

Biological data was collected from the laboratory experiment for data analysis. Secondary data was also collected from secondary data sources. The working sample was separated into the following four parts: pure seed, other seeds, inert matter, and weed seed, and the percentage of each part was determined by weight. The weed seeds were included because they are one of the parameters in the Ethiopian seed quality standards. All varieties of seed and each kind of inert matter present were identified as far as possible, and their percentage by weight was determined. Following the protocol for the purity test, 6g (weight of working sample) of seeds were taken from the working sample (ISTA, 2014). Apparatus-like magnifiers reflected light, and sieves were used to separate the working sample into its parts. The "pure" seed fraction was weighed, and then the physical purity was expressed as the ratio of pure seed weight to the working sample's overall weight and calculated, as illustrated in Eq. 1.

$$P(\%) = \frac{WPS}{TWWS} * 100 \quad \text{Eq. 1}$$

Where: P (%) = percentage of pure seed; WPS = Weight of pure seeds (g); TWWS = Total weight of the working sample (g).

Table 1. Treatment setup for laboratory test

No.	Treatment	Storage type	Keble	District	Variety
1	S1	Sacks in the house	Hamusit	Sekota	<i>Nechi</i> (White)
2	S2	Sacks in the house	Hamusit	Sekota	<i>Keyo</i> (Red)
3	S3	Sacks in the house	Hamusit	Sekota	<i>Tikur</i> (Black)
4	S4	Sacks in the house	Wale	Sekota	<i>Nechi</i> (White)
5	S5	Sacks in the house	Wale	Sekota	<i>Keyo</i> (Red)
6	S6	Sacks in the house	Wale	Sekota	<i>Tikur</i> (Black)
7	S7	Sacks in the house	Geregera	Dera	<i>Nechi</i> (White)
8	S8	Sacks in the house	Geregera	Dera	<i>Keyo</i> (Red)
9	S9	Sacks in the house	Geregera	Dera	<i>Tikur</i> (Black)
10	S10	Sacks in the house	Wenchite	Dera	<i>Nechi</i> (White)
11	S11	Sacks in the house	Wenchite	Dera	<i>Keyo</i> (Red)
12	S12	Sacks in the house	Wenchite	Dera	<i>Tikur</i> (Black)
13	S13	<i>Gotera</i> in the house	Wenchite	Dera	<i>Tikur</i> (Black)
14	S14	<i>Gotera</i> in the house	Geregera	Dera	<i>Keyo</i> (Red)
15	S15	Sacks in the house	Enamert	Mecha	<i>Nechi</i> (White)
16	S16	Sacks in the house	Enamert	Mecha	<i>Keyo</i> (Red)
17	S17	Sacks in the house	Enamert	Mecha	<i>Tikur</i> (Black)
18	S18	Sacks in the house	Enguti	Mecha	<i>Nechi</i> (White)
19	S19	Sacks in the house	Enguti	Mecha	<i>Keyo</i> (Red)
20	S20	Sacks in the house	Enguti	Mecha	<i>Tikur</i> (Black)
21	S21	<i>Gotera</i> in the house	Enguti	Mecha	<i>Keyo</i> (Red)
22	S22	<i>Gotera</i> outside the house	Enguti	Mecha	<i>Keyo</i> (Red)
23	S23	Underground pit	Enguti	Mecha	<i>Keyo</i> (Red)
24	S24	Underground pit	Enamert	Mecha	<i>Nechi</i> (White)
25	S25	Cold store	AARC		<i>Mecha</i>
26	S26	Cold store	AARC		<i>Necho</i>
27	S27	Cold store	AARC		Adet-05

Note: S1–S27 represent the sample treatments. The type of sacks used by the farmers was polypropylene bags. Varieties are presented by their local names, with seed color indicated in parentheses.

2.4.2. Moisture content

Immediately after seed collection, the moisture content of each seed sample was measured using a digital moisture meter (G.WouHitech Co. Ltd., Model GMK, S/N: HD-1450, Made in Korea) for rapid estimation. The digital moisture meter was used in this study for the quick determination of seed moisture in the field and laboratory.

To maintain the original moisture content of the seed samples, seeds were placed immediately after collection in airtight plastic bags, properly labeled, and transported to the laboratory in sealed containers to minimize moisture exchange with the environment. Moisture content measurements were conducted soon after arrival at the laboratory. Three readings were taken for each sample using the digital moisture meter, and the average moisture content was expressed as a percentage. The average moisture content was calculated using the following Eq.2 formula:

$$\text{Average moisture content} = \frac{M1 + M2 + M3}{3} \quad \text{Eq. 2}$$

Where: M1, M2, and M3 were the first, the second, and the third moisture readings, respectively. Thousand seed weight: Thousand seed weight (g) refers to the weight of 1000 seeds taken from the pure seed fraction of the working sample.

2.4.3. Germination percentage

A germination test was used to evaluate the emergence and development of the seedling to a stage where its essential structure indicates it can develop further into a satisfactory plant under favorable conditions in the field. The experiment was organized in a Completely Randomized Design (CRD). 100 sample seeds from the pure seed fraction were planted in paper growing media as indicated by ISTA rules. Seeds were sown on the top of a layer of filter paper, which was placed on the germination cup at room temperature. According to (ISTA, 2014), seedling emergence is recorded after 4 days (first count) and until 8 days (final count) following sowing. The ungerminated seeds were labeled as dead seeds and fresh ungerminated seeds, while the germinated seeds were divided into normal and aberrant seedlings on the eighth day. Normal seedling: shows the potential for continued development into satisfactory plants when grown in good-quality soil under favorable conditions of moisture, temperature, and light. It includes intact seedlings, seedlings with slight defects, and seedlings with secondary infection. Abnormal seedling: a seedling that does not show the potential to develop into an abnormal plant when it grows under favorable conditions. It includes damaged, deformed/unbalanced, and decayed seedlings. Hard seeds: seeds that remain hard at the end of the test period. Fresh seed: Seeds that can imbibe water but fail to germinate, or the germination process is blocked. Dead seedlings: seedlings that at the end of the germination test are neither hard nor fresh nor have produced any part of the seedling. The percentage of normal seedlings is used to represent it. In the same manner, the percentages of aberrant (abnormal) seedlings, hard, fresh, and dead seeds were determined (Maguire, 1962).

$$\text{Germination \%} = \frac{\text{Total number of normal seedlings}}{\text{Total number of seeds planted}} \times 100 \quad \text{Eq. 3}$$

2.4.4. Seed vigor

2.4.4.1. Speed of germination

The standard germination tests only distinguish between normal and abnormal seedlings. The germination rate is calculated at the same time as the germination percentages. Still, there is probably going to be some fluctuation in the size and vigor of "normal seedlings." The speed of germination was tested by taking 100 seeds from each sample and planting them separately on germination paper to separate the variation among normal seedlings. Until no more germination occurred, the seeds were stored at room temperature. Every day from the fourth to the eighth day after planting, normal seedlings were counted and removed. The number of normal seedlings per 100 seeds collected at each counting in the standard germination test is divided by the number of days that the seeds stay in the laboratory to determine the germination rate. The germination rate is calculated by adding the values acquired at each count after the germination test (Maguire, 1962).

$$\text{GR} = \frac{\text{NNS}}{\text{DFC}} + \frac{\text{NNS}}{\text{DFF}} \quad \text{Eq. 4}$$

Where: GR =Germination Rate; NNS =Number of Normal Seedling; DFC =Days to First Count; DFF= Days to Final Count

2.4.4.2. Seedling growth tests

Seedling shoot length (cm) was measured from the basal part to the tip of the seedling in centimeters (cm). Seedling root length (cm) was measured from the tip of the root upward to the end of the root in centimeters. Seedling dry weight (g) was determined by selecting ten random seedlings, drying them in an oven at 80°C for 24 hours, and then weighing them. The seedling vigor indices (SVI-I and SVI-II) provide quantitative measures of seedling growth and vigor, integrating both germination performance and seedling size or dry weight. These indices allow for a meaningful comparison of seed quality between formal and informal sources and highlight potential differences in seedling establishment and crop performance under field conditions (Maguire, 1962).

$$\text{SVI- I} = \text{SD}\% \times \text{MSL (Roots + Shoots length)} \quad \text{Eq. 5}$$

$$\text{SVI- II} = \text{Standard germination \%} \times \text{mean seedling dry weight} \quad \text{Eq. 6}$$

Where: SVI- I = Seedling vigor indexes I, and SVI- II = Seedling vigor indexes II, SD = Standard deviation of germination, MSL = Mean Seedling Length.

2.5. Methods of Data Analysis

The samples, for the formal and informal sources, were split into two groups for laboratory analysis. The t-test, which compares pairs of formal and informal sources, was used to determine the proportion of seed quality characteristics of physical quality, physiological quality, and seed health. One-way ANOVA was utilized to determine the mean difference between seed samples of the informal seed system. Laboratory data were analyzed to determine whether there are statistically significant differences between treatments. Laboratory data on various parameters have been collected and statistically analyzed using SAS version 9.0 (2008) statistical computer software. To determine which treatments are significantly different from one another, Least Significant Differences (LSD) was employed.

3. RESULTS AND DISCUSSION

3.1. Seed Quality from Formal and Informal Sources

3.2.1. Seed Analytical Purity

The comparison between formal and informal seed sources was conducted to evaluate differences in seed quality that arise from variations in seed production, handling, and storage practices. Formal seeds, obtained from certified seed producers and research centers (Adet Agricultural Research Center), are expected to maintain high purity, vigor, and germination due to controlled production, proper post-harvest handling, and standardized storage. In contrast, informal seeds, primarily farmer-saved or locally traded, are subject to variable pre- and post-harvest management, including differences in storage type, seed mixing, and exposure to pests and environmental stress. Understanding these differences is crucial to identifying gaps in seed quality and designing interventions that improve smallholder productivity. To statistically assess these differences, an independent two-sample t-test was performed for each seed quality parameter, comparing mean values from formal ($n = 3$) and informal ($n = 5$) sources. The t-test is valid under the assumptions of approximate normality and homogeneity of variance. Before analysis, data were checked for normal distribution using Shapiro-Wilk tests, and variances were evaluated for equality. Parameters that violated normality assumptions were appropriately transformed, such as germination percentages, which were arcsine square-root transformed to stabilize variance.

Table 2 presents the results of physical quality features for seed samples collected from formal and informal seed sources. For seed samples obtained from formal and informal seed sources, respectively, the mean percentages of pure seed were 99.98% and 63.55%. There is a highly significant difference in physical seed purity between seed from formal and informal sources. Formal seed sources have significantly higher pure seed, fewer other crop seed and weed seed, and less inert matter than seed from informal sources ($P < 0.05$). Similar findings were reported by Yitayew *et al.* (2023), who assessed bread wheat seed quality and observed significant variations in several seed quality attributes between formal and informal seed sources. Additionally, in a study on field pea, seed samples from formal and informal sources collected in Enarji Enawuga and Yilmana Densa districts showed statistically significant differences in physical purity, with formal seeds having higher purity. However, the proportion of other crop seeds did not differ significantly between the two groups (Ali *et al.*, 2021).

Comparing the mean percentages of inert matter and other crop seeds from formal and informal seed sources, the informal seed sample showed greater percentages. Farmers' practices during pre- and post-harvest activities could be the reason why the seed sample from the informal sources contained a mixture of finger millet seeds. This data indicates that formal seed sources tend to have superior seed

quality in terms of purity, crop integrity, and seed weight. Nevertheless, some informal seed lots exhibited relatively high purity, suggesting that targeted interventions such as community-based seed selection and improved storage practices can enhance seed quality even outside formal systems.

3.1.2. Moisture content

Seed moisture content (MC), expressed as a percentage of total seed weight, is a critical determinant of seed durability, storage longevity, and overall quality (ISTA, 2014). Statistical analysis revealed no significant difference in mean moisture content between formal and informal seed sources ($P > 0.05$). Specifically, formal seed sources recorded a mean MC of 12.23%, while informal sources exhibited a mean of 12.40% (Table 2). Despite the similarity in mean values, the informal seed samples demonstrated a notably high standard deviation (10.53%), indicating substantial internal variability compared to the more uniform formal samples. This pronounced variance in the informal sector reflects inconsistent post-harvest management and storage practices among farmers, including diverse drying methodologies and the use of various storage structures such as sacks, pits, or *gotera*.

While some informal samples maintained optimal dryness, others were stored with excessively high moisture levels, heightening the risk of fungal proliferation, physiological deterioration, and compromised germination. Furthermore, while these seeds are often stored under ambient conditions, the superior quality and standardized seed size observed in formal samples—such as those from the Adet Agricultural Research Center (AARC) are attributed to rigorous production, harvesting, and handling protocols. In contrast, the informal seed system's vulnerability to high humidity and fluctuating storage environments often leads to accelerated dry matter loss and seed degradation. This ultimately results in a lower thousand-seed weight (TSW) relative to the formal system. These findings underscore the necessity for enhanced storage management within informal systems, particularly through the implementation of standardized drying procedures, moisture monitoring, and the adoption of accessible moisture control technologies to preserve seed vigor and longevity.

3.1.3. Thousand seed weight

In this study, formal seed systems exhibited a significantly higher thousand seed weight (TSW) of 3.21 g compared to 1.93 g from informal sources ($P < 0.05$) (Table 2). Although TSW is inherently a genetic trait, its expression is heavily mediated by environmental and management factors, including nutrient availability, seed maturity at harvest, and post-harvest handling. The lower TSW in informal seed sources attributed to manual post-harvest processing, premature harvesting, and inadequate storage in sacks, pits, or *gotera* aligns with previous studies on wheat, field pea, and sorghum in Ethiopia, which consistently reported lower TSW in farmer-saved seeds (Ali *et al.*, 2021; Yitayew *et al.*, 2023). Furthermore, the observed low physical purity (63.55%) in informal sources, where nearly 36% of the sample comprised inert matter (soil, dust, and chaff) and weed seeds, underscores the limitations of traditional, manual cleaning methods. The high standard deviation (7.06) observed for "other crop seed" relative to the mean (3.166) indicates substantial heterogeneity, reflecting inconsistent field histories and cleaning practices among farmers. While an independent samples t-test was applied, these results suggest a skewed distribution that, while practically meaningful, necessitates cautious interpretation. Given that all samples were cleaned to analytical purity before measurement, the marked differences in TSW and physical quality are more plausibly linked to suboptimal production and storage environments rather than inherent varietal differences. Consequently, these findings highlight the urgent need for improved post-harvest management, such as the adoption of simple mechanical cleaning technologies and protective threshing surfaces, to enhance seed quality and bridge the gap between formal and informal seed systems.

Table 2. Comparison of analytical quality attributes between formal and informal sources

Variable	Formal (n=3)		Informal (n=5)		t-test result	
	Mean	Std. Dev.	Mean	Std. Dev.	t (df=7)	P value
Seed purity (%)	99.98	0.0015	63.55	6.76	-9.040	0.000
Other crop seed (%)	0.0006	0.0011	3.166	7.06	7.520	0.000
Weed seed (%)	0.0003	0.0005	0.0222	0.016	2.277	0.000
Inert matter (%)	0.0003	0.0005	4.7	0.803	9.814	0.000
TSW (g)	3.21	0.2621	1.93	0.206	-7.769	0.000
MC (%)	12.23	0.665	12.40	10.53	0.242	0.793

Note: Laboratory data (2023/24). n = number of samples; MC = moisture content; TSW = thousand seed weight. The smaller number of samples from the formal seed system (n = 3) reflects the limited number of certified finger millet seed producers in the Amhara Region. Although 24 samples were initially collected from informal seed sources, only five were used in the comparison to maintain balance with the small number of formal seed producers and enable statistical comparison between the two seed systems.

3.1.4. Germination percentage

Germination tests were employed to determine the field planting potential of finger millet seed lots by evaluating their capacity to produce normal seedlings under optimal conditions (ISTA, 2014). Statistical analysis revealed a significant difference in the percentage of normal seedlings between the two sources, with formal seed sources exhibiting a significantly higher rate (97.3%) compared to informal sources (84.6%) ($P < 0.05$) (Table 3). Furthermore, informal sources showed a significantly higher percentage of fresh seeds ($P < 0.05$), and a 7% hard seed rate, indicating physical dormancy likely induced by prolonged traditional storage and fluctuating environmental conditions. While no significant differences were observed for dead or hard seeds between sources, a marginally significant increase in abnormal seedlings was recorded in informal samples (4.8% vs. 2.3% in formal seeds). These abnormalities, primarily twisted coleoptiles, malformed primary roots, and poor leaf emergence, are consistent with mechanical damage during manual threshing and rough handling rather than seed-borne pathogens, as no symptoms of rot or discoloration were present. These defects, alongside the higher variability in the informal system, reflect the impact of suboptimal post-harvest practices and ambient storage conditions.

Consequently, to achieve adequate plant populations and compensate for lower germination rates, farmers utilizing informal seed sources may need to increase sowing rates or implement pre-sowing treatments, such as soaking or scarification, to overcome dormancy. These findings underscore the critical role of standardized seed management in ensuring uniform crop establishment and maximizing yield potential in finger millet cultivation.

Table 3. Comparison of standard germination between formal and informal sources

Variable	Formal (n=3)		Informal (n=5)		t-test result	
	Mean	Std. Dev.	Mean	Std. Dev.	t (df=7)	P value
Normal seedling (%)	97.3	2.0	84.6	4.8	-4.232	0.002
Abnormal seedling (%)	2.3	1.5	4.8	1.3	2.443	0.050
Dead seedling (%)	0.3	0.5	2.4	2.7	1.268	0.231
Fresh seed (%)	0.0	0.0	1.2	1.3	1.543	0.025
Hard seed (%)	0.0	0.0	7.0	2.9	4.027	0.06

Note: Laboratory data, 2023/24; n = number of samples, from the sum of the mean: Minor differences from 100% are due to rounding of values during data presentation.

3.1.5. Seed vigor

The comparative assessment of seed vigor attributes between formal and informal seed sources is summarized in Table 4. Among the metrics evaluated, including seedling shoot length, root length, and vigor indices (SVI-I and SVI-II), only seedling dry weight exhibited a statistically significant difference ($P = 0.035$), with formal sources recording a higher mean of 0.02 g compared to 0.01 g for informal sources. This finding aligns with previous research on bread wheat in Ethiopia, which also identified significant disparities in seedling dry matter accumulation between seed systems (Yitayew *et al.*, 2023).

Although the formal system exhibited higher absolute values for SVI-I (12282.6) and SVI-II (2.1) compared to the informal system (7585.1 and 1.3, respectively), these differences were not statistically significant ($P > 0.05$). This lack of statistical significance in most vigor indicators, despite a significant gap in germination percentage (Table 3), is likely attributable to high intra-sample variability within the informal seed lots, which increases the standard deviation and reduces the power to detect differences. Notably, a correction of the formal shoot length data (rectifying a transposition error to a mean of 7.5 cm with a standard deviation of 4.2 cm) confirms that the variation is consistent with expected biological ranges. Crucially, these results suggest that while the informal seed system faces challenges with overall germination rates, the seedlings that do successfully emerge possess growth potential and health comparable to those from formal sources (Pradeep, 2018). Consequently, improving post-harvest management through community-based interventions such as farmer training, local seed banks, and the adoption of hermetic storage could effectively narrow the vigor gap and enhance the performance of informal seed systems.

Table 4. Comparison of seed vigor attributes from formal and informal seed sources

Variable	Formal (n=3)		Informal (n=5)		Independent t-test result	
	Mean	Std. Dev.	Mean	Std. Dev.	t (df=7)	P value
Seedling shoot length (cm)	8.12	8.9	7.5	4.2	-1.85	0.178
Seedling root length (cm)	16.53	3.9	13.9	6.8	-0.59	0.514
Seedling dry weight (g)	0.02	0.01	0.01	0.003	-1.19	0.035
Rate of germination (%)	7.6	0.57	8.8	3.03	0.62	0.169
SVI- 1	12282.6	893.5	7585.1	4089.8	-1.904	0.183
SVI- 2	2.1	1.1	1.3	0.3	-1.555	0.183

Note: Laboratory data, 2023/24; SVI 1= seed vigor index 1; SVI 2= seed vigor index 2.

3.2. Seed Quality from Informal Sources

3.2.1. Physical purity

The physical quality attributes of 24 informal seed samples (S1–S24) collected from the Sekota, Dera, and Mecha districts are summarized in Table 5, reflecting the impact of diverse storage conditions such as sacks, *gotera*, and traditional pots. Highly significant differences ($P < 0.001$) were observed across all parameters, including Thousand Seed Weight (TSW), pure seed percentage, and contaminant levels. TSW values ranged from a high of 2.18 g (S1, S11, and S21) to a low of 1.60 g (S20), while pure seed percentages exhibited extreme volatility. For instance, while S1 maintained 74% purity, sample S21 recorded a remarkably low 22.29% purity, with the remaining 77.71% of the mass comprising other crop seeds (29.3%), inert matter (5.1%), and weed seeds. The predominant "other crop seeds" identified across samples included sorghum, tef, and maize, suggesting that contamination likely originates from intercropping, inadequate field isolation, or unclean manual threshing on bare ground. Storage methodology also appeared to influence seed integrity; samples stored in sacks generally maintained superior quality compared to those in *gotera* or traditional pots. Interestingly, while physical purity varied drastically based on field-level management, moisture content remained relatively uniform (13.1–13.7%) across samples S8 through S24.

This suggests that despite varying levels of physical contamination, seeds eventually equilibrated to the ambient relative humidity and temperature of their respective districts. These findings, further detailed by variety and origin in Supplementary Table 1, underscore that while moisture is a function of the storage environment, physical purity is a direct result of harvest and post-harvest hygiene. Consequently, addressing the low physical purity observed in samples like S21 requires targeted community-level interventions, such as the promotion of improved threshing surfaces and mechanical cleaning, to enhance crop establishment and overall productivity.

3.2.2. Physiological seed quality

The physiological quality of 24 informal seed samples (S1–S24) exhibited considerable variation across all germination-related parameters (Table 6). The percentage of normal seedlings ranged from a minimum of 71.00% (S5 and S14) to a maximum of 95.33% (S24), with a collective mean of 84.3%. Least Significant Difference (LSD) analysis confirmed significant differences among treatments ($P \leq 0.01$), indicating that seed viability is strongly influenced by geographic origin and storage methodology. For instance, sample S24, which was stored in an underground pit, demonstrated superior germination compared to samples stored in traditional sacks (e.g., S5 and S14).

Table 5. Mean value of physical quality metrics of seed samples from informal sources

Treatments	Parameter					
	TSW(g)	Pure seed (%)	Other crop seed (%)	Inert matter (%)	Weed seed (%)	MC (%)
Treatments	Parameter					
	TSW(g)	Pure seed (%)	Other crop seed (%)	Inert matter (%)	Weed seed (%)	MC (%)
S1	2.18 ^a	74 ^e	21.20 ^h	5.10 ^a	0.20 ^a	11.60 ^c
S2	1.79 ^f	71.59 ^a	25.30 ^g	3.10 ^e	0.008 ^b	12.20 ^b
S3	1.97 ^c	57.69 ^c	39.1 ^a	3.20 ^{de}	0.001 ^b	11.60 ^c
S4	1.91 ^e	38.74 ^d	38.0 ^a	3.56 ^{cde}	0.001 ^b	11.20 ^d
S5	1.72 ^g	69 ^e	27.81 ^{ef}	3.80 ^{bcd}	0.001 ^b	12.40 ^b
S6	1.93 ^{de}	67 ^e	29.30 ^{de}	4.10 ^{bc}	0.001 ^b	11.53 ^c
S7	2.1 ^b	64 ^e	31.51 ^{bc}	4.30 ^b	0.001 ^b	11.20 ^d
S8	1.82 ^f	66 ^e	30.13 ^{cd}	3.40 ^{de}	0.001 ^b	13.70 ^a
S9	1.97 ^{cd}	62 ^e	32.7 ^b	5.36 ^a	0.001 ^b	13.70 ^a
S10	1.61 ^h	73 ^e	21.20 ^h	5.26 ^a	0.001 ^b	13.70 ^a
S11	2.18 ^a	70 ^e	25.30 ^g	5.10 ^a	0.001 ^b	13.63 ^a
S12	1.79 ^f	58 ^e	39.1 ^a	3.10 ^e	0.001 ^b	13.83 ^a
S13	1.98 ^c	58.48 ^{bc}	38.0 ^a	3.20 ^{de}	0.001 ^b	13.70 ^a
S14	1.91 ^e	69.48 ^{ab}	26.91 ^{gf}	3.60 ^{cde}	0.001 ^b	13.66 ^a
S15	1.73 ^g	66.89 ^{abc}	29.30 ^{de}	3.80 ^{bcd}	0.001 ^b	13.70 ^a
S16	1.99 ^c	64 ^e	31.51 ^{bc}	4.10 ^{bc}	0.001 ^b	13.70 ^a
S17	2.1 ^b	66 ^e	30.15 ^{cd}	4.30 ^b	0.001 ^b	13.66 ^a
S18	1.82 ^f	64 ^e	32.7 ^b	3.40 ^{de}	0.001 ^b	13.70 ^a
S19	1.97 ^{cd}	56 ^e	38.0 ^a	5.30 ^a	0.001 ^b	13.70 ^a
S20	1.61 ^h	68 ^e	26.91 ^{fg}	5.40 ^a	0.001 ^b	13.70 ^a
S21	2.18 ^a	22.29 ^e	29.30 ^{de}	5.10 ^a	0.001 ^b	13.70 ^a
S22	1.79 ^f	65 ^e	31.51 ^{bc}	3.10 ^e	0.001 ^b	13.70 ^a
S23	1.98 ^c	67 ^e	31.51 ^{bc}	3.20 ^{de}	0.001 ^b	13.70 ^a
S24	1.91 ^e	64 ^e	31.51 ^{bc}	3.60 ^{cde}	0.001 ^b	13.70 ^a
Mean	1.91	62.59	30.74	4.06	0.009	13.10
LSD (5%)	**	**	**	**	*	*
CV (%)	1.28	0.2	3.62	10.36	2.13	1.27

Note: Laboratory data, 2023/24; Means with the same letter in the same column are not significantly different; S1-24 is a different finger millet variety stored in a different storage type and different location.

The lower germination rates observed in the latter are likely attributable to temperature and humidity fluctuations within the home environment, which accelerate physiological aging and promote microbial growth. These findings align with previous studies on Ethiopian cereals, where variability in farmer-saved seeds was directly linked to storage conditions and handling practices (Yenus Ali et al., 2021; Alemayehu et al., 2023). Further analysis revealed a mean abnormal seedling rate of 4.97%, with a peak of 11.33% in sample S15, suggesting mechanical injury during manual threshing or the presence of seed-borne pathogens (ISTA, 2014). Additionally, the mean percentages for fresh, dead, and hard seeds were 1.18%, 2.97%, and 6.58%, respectively. Notably, samples S5 and S14 exhibited an unusually high hard-seededness of 15%, which may be a characteristic of the black finger millet landrace or a result of excessive drying during prolonged household storage. While finger millet typically exhibits low physical dormancy, traditional varieties can develop seed-coat hardness under environmental stress (Teklu *et al.*, 2023). Conversely, sample S1 recorded the highest percentage of fresh seeds (3.33%), indicating delayed germination potential. These results underscore the heterogeneity of informal seed systems and highlight the necessity for improved post-harvest management, such as the adoption of PICS bags or well-ventilated facilities to maintain seed viability and ensure uniform crop establishment across different landraces.

Table 6. Mean values of physiological seed quality parameters for seed samples from informal sources

Treatments	Parameter				
	Normal seedling (%)	Abnormal seedling (%)	Fresh seed (%)	Dead seed (%)	Hard seed (%)
Treatments	Parameter				
	Normal seedling (%)	Abnormal seedling (%)	Fresh seed (%)	Dead seedling (%)	Hard seed (%)
S1	77.00 ^f	6.00 ^{bcd}	3.33 ^a	7.00 ^b	7.00 ^{cde}
S2	85.00 ^{de}	4.00 ^{bcdef}	1.00 ^{cd}	2.00 ^{de}	8.00 ^{bcd}
S3	92.00 ^{ab}	1.00 ^{ef}	1.00 ^{cd}	0.00 ^f	6.00 ^{de}
S4	90.00 ^{bc}	4.00 ^{bcdef}	1.00 ^{cd}	2.00 ^{de}	3.00 ^{ef}
S5	71.00 ^g	7.00 ^{abc}	2.00 ^{bc}	5.00 ^c	15.00 ^a
S6	74.00 ^{df}	11.00 ^a	2.00 ^{bc}	10.00 ^a	6.00 ^{de}
S7	82.00 ^e	7.00 ^{abc}	0.00 ^d	2.00 ^{de}	4.00 ^{def}
S8	82.00 ^e	2.00 ^{def}	1.00 ^{cd}	3.00 ^d	12.00 ^{ab}
S9	85.00 ^{de}	4.00 ^{bcdef}	1.00 ^{cd}	2.00 ^{de}	8.00 ^{bcd}
S10	77.00 ^f	6.00 ^{bcd}	3.00 ^{ab}	7.00 ^b	7.00 ^{cde}
S11	85.00 ^{de}	4.00 ^{bcdef}	1.00 ^{cd}	2.00 ^{de}	8.00 ^{bcd}
S12	92.00 ^{ab}	1.00 ^{ef}	1.00 ^{cd}	0.00 ^f	3.00 ^{ef}
S13	90.00 ^{bc}	4.00 ^{bcdef}	1.00 ^{cd}	2.00 ^{de}	3.00 ^{ef}
S14	71.00 ^g	7.00 ^{abc}	2.00 ^{bc}	5.00 ^c	15.00 ^a
S15	74.00 ^{fg}	11.33 ^a	2.00 ^{bc}	10.00 ^a	3.00 ^{ef}
S16	85.00 ^{de}	6.00 ^{bcd}	0.00 ^d	1.00 ^{ef}	8.00 ^{bcd}
S17	85.00 ^{de}	6.00 ^{bcd}	0.00 ^d	1.00 ^{ef}	8.00 ^{bcd}
S18	83.00 ^{de}	8.00 ^{ab}	0.00 ^d	2.00 ^{de}	7.00 ^{cde}
S19	87.00 ^{cd}	5.00 ^{bcde}	0.00 ^d	2.00 ^{de}	6.00 ^{de}
S20	91.00 ^{abc}	5.00 ^{bcde}	1.00 ^{cd}	0.00 ^f	3.00 ^{ef}
S21	84.00 ^{de}	3.00 ^{cdef}	2.00 ^{bc}	0.00 ^f	11.00 ^{abc}
S22	90.00 ^{bc}	2.00 ^{def}	1.00 ^{cd}	1.00 ^{ef}	6.00 ^{de}
S23	95.00 ^a	5.00 ^{bcde}	0.00 ^d	0.00 ^f	0.00 ^f
S24	95.33 ^a	0.00 ^f	2.00 ^{bc}	1.00 ^{ef}	1.00 ^f
Mean	84.3	4.97	1.18	2.97	6.58
LSD (5%)	*	*	*	*	*
CV (%)	4.12	5.48	0.67	2.32	3.75

Note: Laboratory data, 2023/24; Means with the same letter in a column are not significantly different at $p \geq 0.05$.

3.3. Vigor Tests

Seed vigor, representing the capacity for rapid germination and robust seedling establishment under suboptimal conditions, exhibited significant variability across the 24 informal seed sources (Table 7). The rate of germination varied notably; with samples S2 (stored in sacks in Sekota) and S21 (stored in *gotera* in Mecha) exhibiting the highest rates (14%), whereas S1, S7, and S24 recorded the lowest (6%). Statistical analysis using the Least Significant Difference (LSD) test revealed significant differences in seedling shoot length ($P < 0.05$), with values ranging from 1.0 cm (S16) to a maximum of 4.31 cm (S24). While the mean shoot length across all samples was 2.6 cm, root development showed inconsistent patterns; for example, sample S8 exhibited an atypical root-to-shoot ratio (0.14 cm root vs. 1.32 cm shoot). This morphological disparity is likely attributable to localized experimental conditions, such as minor moisture distribution inconsistencies on the filter paper, rather than inherent genetic traits. The analysis of Seedling Vigor Indices (SVI) further highlighted these disparities. While SVI-I remained relatively consistent, SVI-II showed profound variation, ranging from 0.4 (S5) to 21.98 (S12). High SVI values are indicative of superior resilience and adaptation, which are critical for successful crop development under environmental stress (Teixeira *et al.*, 2021).

These indices are often positively correlated with seed size, as larger seeds typically possess greater nutrient reserves to support early heterotrophic growth (Javaid *et al.*, 2022). This is evidenced by sample S13, which recorded the highest seedling dry matter (0.026 g), contrasting sharply with the poor performance of samples such as S9 and S17. Collectively, these results underscore the heterogeneity of farmer-saved seed lots and suggest that targeted interventions in seed selection and post-harvest management could significantly enhance the overall vigor and growth potential of informal seed systems.

Table 7. Mean comparison of physiological quality between informal seed sources

Treatments	Parameter					
	GR (%)	SVI 1	SVI 2	SL (cm)	RL (cm)	SDM(g)
S1	6.66 ^{bc}	257.176 ^a	17.32 ^f	4.23 ^a	0.75 ^b	0.022 ^{abcd}
S2	14.00 ^a	257.18 ^a	14.28 ^l	1.15 ^c	0.075 ^b	0.016 ^{abcdef}
S3	8.00 ^{abc}	257.183 ^a	13.15 ^h	4.11 ^a	0.075 ^b	0.014 ^{bcdef}
S4	7.00 ^{bc}	257.18 ^a	4.62 ⁿ	1.13 ^c	0.14 ^a	0.015 ^{abcdef}
S5	11.00 ^{abc}	257.18 ^a	0.4 ^o	4.29 ^a	0.74 ^b	0.0138 ^{cdef}
S6	8.00 ^{abc}	257.146 ^a	17.61 ^e	4.24 ^a	0.075 ^b	0.023 ^{abcd}
S7	6.00 ^c	257.21 ^a	20.41 ^d	4.31 ^a	0.74 ^b	0.024 ^{abc}
S8	13.00 ^{ab}	257.18 ^a	20.81 ^a	1.32 ^c	0.14 ^a	0.025 ^{ab}
S9	9.00 ^{abc}	257.18 ^a	1.0 ^o	1.29 ^c	0.075 ^b	0.0079 ^f
S10	7.00 ^{bc}	257.18 ^a	0.8 ^o	1.26 ^c	0.075 ^b	0.011 ^{ef}
S11	13.00 ^{ab}	257.18 ^a	19.72 ^k	1.96 ^b	0.075 ^b	0.023 ^{abcd}
S12	8.00 ^{abc}	257.18 ^a	21.98 ^b	4.15 ^a	0.075 ^b	0.023 ^{abcd}
S13	6.00 ^c	257.18 ^a	2.3 ^o	1.35 ^c	0.075 ^b	0.026 ^a
S14	10.00 ^{abc}	257.18 ^a	14.27 ^g	4.15 ^a	0.075 ^b	0.020 ^{abcde}
S15	7.00 ^{bc}	257.18 ^a	12.13 ⁱ	4.08 ^a	0.075 ^b	0.016 ^{abcdef}
S16	7.00 ^{bc}	257.18 ^a	11.39 ^m	1.05 ^c	0.075 ^b	0.0134 ^{def}
S17	12.00 ^{ab}	257.18 ^a	0.5 ^o	4.13 ^a	0.075 ^b	0.0057 ^f
S18	7.00 ^{bc}	257.18 ^a	1.7 ^o	1.22 ^c	0.075 ^b	0.020 ^{abcde}
S19	9.00 ^{abc}	257.18 ^a	14.44 ^g	4.15 ^a	0.74 ^b	0.016 ^{abcdef}
S20	12.00 ^{abc}	257.18 ^a	1.91 ^k	1.28 ^c	0.74 ^b	0.021 ^{abcde}
S21	14.00 ^a	257.173 ^a	1.76 ^k	1.25 ^c	0.075 ^b	0.022 ^{abcde}
S22	12.00 ^{abc}	257.18 ^a	14.31.0 ^l	1.15 ^c	0.075 ^b	0.015 ^{abcdef}
S23	10.00 ^{abc}	257.18 ^a	2.26 ^j	1.35 ^c	0.075 ^b	0.023 ^{abcd}
S24	6.00 ^c	257.18 ^a	20.92 ^c	4.32 ^a	0.75 ^b	0.021 ^{abcde}
Mean	9.28	257.17	10.42	2.6	0.081	1.17
LSD (5%)	**	Ns	*	**	*	*
CV (%)	36.8	0.073	0.5	8.94	4.6	13.6

Note: Laboratory data, 2023/24; Means with the same letter in a column are not significantly different at $p \geq 0.05$. Where: GR = Germination Rate; SVI 1 = Seedling vigor Index 1; SVI 2 = Seedling vigor Index; SL = Shoot Length; RL = Root Length; SDM = Seedling Dry Matter.

4. CONCLUSION AND RECOMMENDATION

Finger millet remains an essential crop for smallholder farmers in Ethiopia, playing a critical role in household nutrition and food security owing to its adaptability to diverse agro-ecological conditions. The present study demonstrated that seeds sourced from formal systems exhibited significantly higher physical purity, physiological quality, and vigor than those obtained from informal sources. Specifically, formal seed lots achieved higher purity (99.98%) and thousand seed weight (3.21 g) compared with informal sources (63.55% purity and 1.93 g TSW), and contained fewer contaminant seeds and inert materials. Likewise, formal seed lots have exhibited higher germination percentage (97.3%) compared to seed from informal seed sources (84.3%). A similar observation was also made for seed vigor indices, where seed from formal sources was higher than that from informal sources.

Despite these advantages, the uptake of formal seed sources in the Mecha, Dera, and Sekota districts remains constrained by limited access, inadequate extension services, and low awareness of improved varieties. Nevertheless, variability within informal seed systems indicates opportunities for quality enhancement through targeted interventions in seed selection and storage practices. It is therefore recommended that efforts focus on strengthening the formal seed system while simultaneously promoting community-based and cooperative seed enterprises, linking formal and informal systems by training farmers, providing access to quality seed, ensuring simple quality control, and fostering partnerships with research institutions and cooperatives for local seed multiplication and distribution. Establishing such integrated seed pathways can ensure consistent seed quality, improve productivity and household income, and contribute to sustainable finger millet production and rural resilience in Ethiopia.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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