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Assessment of Bambara Groundnut (*Vigna subterranea* (L.) Verdcourt) Seed Systems and Farmers' Seed-Saving Practices on Seed Quality

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Abstract

Bambara groundnut is an underutilized legume with significant potential for enhancing nutrition and food security. However, limited knowledge of its seed systems hinders the development of targeted interventions. This study assessed the Bambara groundnut seed systems and seed quality in Ghana. A semi-structured questionnaire was used to examine seed production, conditioning, and saving practices, while 150 farmer-saved seed samples were evaluated for quality. The findings revealed that the seed system is predominantly informal, with 99% of farmers relying on their own saved seeds, which showed poor germination and emergence. About 54.4% sourced seeds from local markets, and 60.7% recycled seeds for five years or more. Seeds were stored unshelled in polypropylene bags in Tolon and shelled in the Kintampo South and Talensi Districts. Seed selection was primarily based on size (in Tolon) and visible absence of disease symptoms (in Kintampo South and Talensi). An incidence (7.6%) of seed-borne pathogens was recorded, with *Aspergillus flavus* (38.8%) and *A. niger* (16.6%) being most prevalent. Other pathogens included *Macrophomina phaseolina* (11.5%), *Rhizopus* spp. (6.5%), *Curvularia lunata* (5.3%), and *A. fumigatus* (1.9%). This study highlights the need to support community-based seed systems to improve farmers' access to quality Bambara groundnut seed.

Keywords: farmer-managed seeds; germination; local landraces; seed health; seed-saving practices; traditional seed management

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1. Introduction

Bambara groundnut, *Vigna subterranea* (L.) Verdcourt, is an underutilized legume native to Africa which is primarily grown for its grain [1]. It ranks behind peanuts (*Arachis hypogea*), cowpea (*Vigna unguiculata*), and soybean (*Glycine max*) [2,3] in most parts of West Africa. The crop is mostly grown by women, often on abandoned lands at the subsistence level [4]. It is usually intercropped with major crops like peanuts, maize, cowpea, etc. and in crop rotations that enhance soil fertility nitrogen fixation [5,6]. Bambara groundnut is highly resilient, capable of producing reasonable yields under conditions of drought, low rainfall, and poor soil fertility [7–9]. In Ghana, it is grown across the Coastal Savanna, Transition, and Guinea Savanna agro-ecologies [6,10], with yields that do not surpass 300 kg/ha [6]. The grain contains approximately 63% carbohydrates, 19% proteins, and 6.5% oils, and is rich in essential minerals and vitamins [11–13].

Bambara groundnut is part of a broader group of neglected and underutilized species (NUS), often referred to as "orphan crops". These crops have received limited research and commercial attention despite their high nutritional value, adaptability to marginal environments, and cultural importance [14]. They play vital roles in traditional food systems and contribute to livelihood resilience. Promoting the cultivation and utilization of such crops can diversify diets and farming systems, strengthen rural agri-food systems, and advance sustainable development [15]. Given their adaptability to challenging climatic and soil conditions, these crops offer viable pathways to address food insecurity, malnutrition, poverty, and climate-related stresses [16].

Despite the numerous economic, environmental and nutritional prospects of Bambara groundnut, it still remains an underutilized plant genetic resource. Its cultivation in Ghana and other African countries is constrained by limited access to improved varieties, quality seeds, and production technologies [17–20]. Strengthening seed production and improving seed access are therefore critical at both policy and research levels [21]. Currently, most farmers rely on informal seed sources such as farmer-saved seed, local markets, and farmer-to-farmer exchanges [22]. Approximately 80% of growers conserve and reuse their own seed [23], while about 68% purchase seed from local markets, which often suffer from poor quality [12]. The low quality of farmer-saved seed remains a major constraint to productivity [21,24]. Although several studies have examined the crop's production practices, utilization, genetic characterization, varietal preferences, and constraints [6,10,25,26], limited attention has been given to its seed system. A better understanding of the Bambara groundnut seed system at national and sub-national levels is essential to improving seed quality and promoting sustainable production. This study thus aimed (i) to evaluate the seed system and identify the challenges and opportunities to improve the Bambara groundnut seed value chain; and (ii) to assess the seed quality characteristics of farmer-saved seed in three districts of Ghana.

2. Materials and Methods

2.1. The Study Area

This study was conducted in three districts of Ghana, namely Kintampo South in the Bono East Region, Talensi in the Upper East Region, and Tolon in the Northern Region (Figure 1). Kintampo South District is located within longitudes 1°20′ W and 2°10′ W and latitude 8°15′ N and 7°45′ N. The district has soil types which range from sandy loam to clay loam and gravels. The district has a bimodal rainfall with a mean annual rainfall of 1400–1800 mm. The mean monthly temperature is between 22 and 29 °C (with a mean of 24 °C) in August and 24–35 °C (mean of 30 °C) in March [27,28]. The soil is mainly sandy loam, making it suitable for the cultivation of tubers, cereals, teak, cash crops, vegetables, and legumes. Tolon District lies between latitudes 9°15′ and 10°02′ N and longitudes 0°53′ and 1°25′ W. Talensi District is located between longitude 0°31′ and 1°05′ and latitude 10°15′ and 10°60′. These two districts have a unimodal rainfall pattern that begins in April with minimal precipitation, increases to its peak in July–August, then declines in October–November. The dry season begins in November and lasts until March, with typical daytime temperatures ranging from 33 to 39 °C and 20 to 26 °C on average at night and annual rainfall between 950 mm and 1200 mm [28]. The soil is primarily sandy loam. In these districts, maize, rice, sorghum, pearl millet, cassava, groundnut, cowpea, soybean, and Bambara groundnut are the main food crops [29].

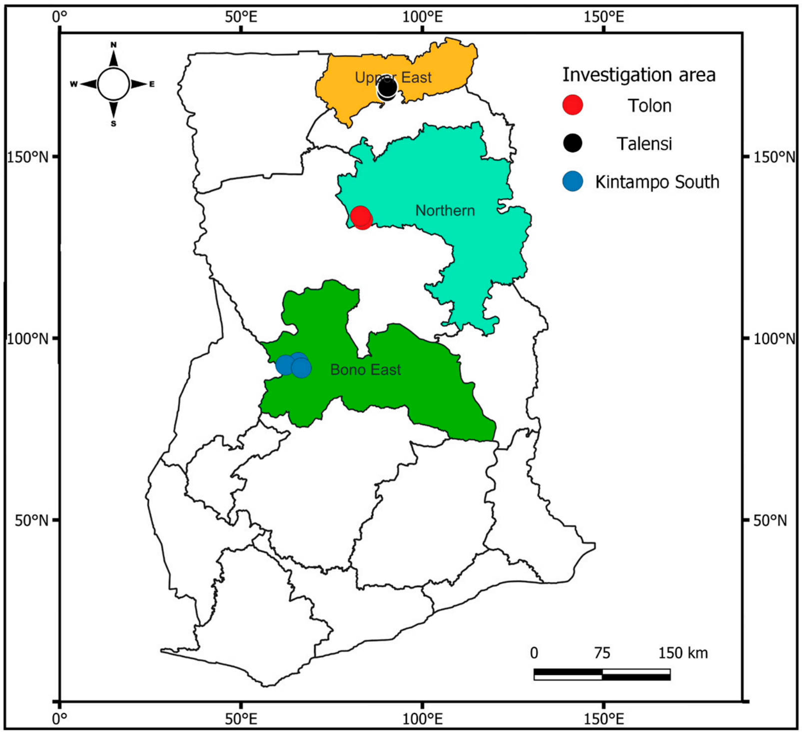

Figure 1. Map of Ghana showing the Bambara groundnut producing communities where studies were carried out.

2.2. Survey of Bambara Groundnut Seed System

A total of 150 Bambara groundnut farmers were sampled from the three districts in February 2023, approximately 3–5 months after harvest, with each district comprising three communities (Table 1). The Bambara groundnut-producing communities were selected based on clarification and consultation with the Agricultural Extension Agents (AEAs) from the Ministry of Food and Agriculture (MoFA) in those districts. At the household level, the snowballing technique was employed to identify other Bambara groundnut producers [30,31]. Both open-ended and close-ended questionnaires were administered to the respondents via a face-to-face interview after seeking their consent to participate in the survey. The survey continued until saturation of information, i.e., when additional respondent provided no new information [32–34]. The questionnaire captured information on seed system and production techniques such as the drying method, the variety grown, and storage and germination treatments. Focus groups, consisting of selected respondents from within the Bambara groundnut producers sampled across the districts, were used to identify the challenges and opportunities associated with the Bambara groundnut seed system in Ghana. The focus group was conducted using the procedure by Krueger and Casey [35]. Five respondents (who were identified as leaders of the communities) were sampled from each community and the topic was discussed using a question-and-answer interview format. Bambara groundnut seed samples (about 0.5–1.0 kg) were collected from farmers during the survey and packed in Ziplock bags which were labelled for seed quality analysis.

Table 1. Description and distribution of respondents covered across three districts.

Region	District	Communities	Sample Size
Bono East	Kintampo South	Nante Yamaokurum Chirehi	20 15 15
Upper East	Talensi	Winkogo Balungo Pusi-Namogo	20 15 15
Northern	Tolon	Gburimani Kpachiyili Gburimani-Tibogu	20 15 15
Total			150

2.3. Determination of Seed Physical Characteristics

The assessment of seed physical characteristics was carried out at Savanna Agricultural Research Institute (SARI), Nyankpala, Tamale, Northern Region of Ghana (9°25′4″ N; 0°58′42″ W). The average temperature recorded during the period (March to June 2023) was 30 ± 7 °C, with relative humidity ranging from 46% to 76.8%. Seed samples were collected from farmers during the survey. Data collected for physical characteristics included seed size, seed colour, 100-seed weight, and seed moisture content (Table 2).

Table 2. Seed physical characteristics.

Physical Characteristics	Procedures
Seed size (mm)	The seed size, which consists of length and width, was measured using a digital vernier calliper (TOTAL TMT321501). For each sample, three replicates of nine seeds placed between the two sleeves of a vernier caliper and data on length and width were taken.
Seed moisture content (%)	The moisture content was determined using the digital grain moisture analyzer (TENDTEK N163912, Hefei, China). For each sample, three replicates of Bambara groundnut seeds were poured gently into the empty cell until the grain approached the sensor.
100-seed weight (kg)	For each sample, three replicates of 100-seeds were randomly collected and weighed with a digital balance.

2.4. Determination of Seed Physiological and Health Characteristics

2.4.1. Standard Germination

A seed germination test was carried out with 100 seeds from each farmer's samples using the petri-dish method as described by Jidda et al. [36]. The seeds were first placed in petri dishes and sterilized in 70% ethanol. Tissue paper was then placed inside the petri dishes, moistened with distilled water, covered, and labelled appropriately. The samples were incubated for 7 days in a germination chamber (BJPX-B400, Biobase Bioindustry Co., Ltd., Shandong, China) at 28 °C. Germination counts were recorded daily, and the final count was recorded on the 7th day. The germination rate was determined using the formula (Equation (1)) as described by Damalas et al. [37]. A seed is said to have germinated if it exhibits at least 2 mm radicle protrusion.

$$\text{Germination (\%)} = \frac{\text{Number of germinated seeds}}{\text{Number of total seeds}} \times 100 \quad (1)$$

Data collected included germination percentage, days to 50% germination, germination velocity index, mean germination time, vigour index, seed damage percentage, and seed mycoflora percentage.

Days to first seed germination refers to the number of days until the seed shows the first radicle protrusion.

Days to 50% germination (T_{50}) was calculated as the number of days until 50% of the seeds show first seed germination (Equation (2)), as described by Farooq et al. [38]. Leaf count was determined at 21 days after sowing by counting the number of leaves per plant.

$$T_{50} = ti + \frac{[\left(\frac{N}{2} - ni\right)(tj - ti)]}{nj - ni} \quad (2)$$

where, N is the final number of emergence and ni, nj are the cumulative number of seeds germinated by adjacent counts at times ti and tj, respectively, when $ni < N/2 < nj$.

Germination velocity index: This was calculated as described by Damalas et al. [37] and Maguire [39] (Equation (3)).

$$\text{GVI} = \frac{G1}{N1} + \frac{G2}{N2} + \ldots + \frac{Gn}{Nn} \quad (3)$$

where $G1, G2\ldots\ldots Gn$ represent germination on the 1st, 2nd, and last count. $N1, N2\ldots\ldots Nn$ are the number of days at 1st, 2nd, and last count from the sowing day.

Mean germination time (MGT) measures the time it takes the seed to germinate, focusing on the day at which most seeds have germinated. This was estimated using the formula (Equation (4)) according to Damalas et al. [37].

$$\text{MGT} = \frac{\sum(\text{n1T1} + \text{n2T2} + \ldots + \text{nkTk})}{\sum(\text{n1} + \text{n2} + \ldots + \text{nk})} \quad (4)$$

where n = number of newly germinated seeds and T = time from the beginning of the experiment.

2.4.2. Seedling Vigour Test

After the 7th day of incubation, 15 normally germinated seedlings per sample were transferred to seed trays filled with sterilized river sand and placed in a screen house. On the 14th day, five seedlings were sampled, and their shoot lengths were measured using a string and ruler (cm). These seedlings were then dried in an oven (GenLab MINO/50, wolflabs, York, UK) at 75 °C for 48 h, and the dry weights (g) were recorded. Seedling vigour was estimated using the formulas (Equations (5) and (6)), as suggested by Abdul-Baki & Anderson [40] and Anupama et al. [41], respectively, as:

$$\text{Vigour index I} = \text{Germination (\%)} \times \text{(Mean shoot length)} \quad (5)$$

$$\text{Vigour index II} = \text{Germination (\%)} \times \text{seedling dry weight} \quad (6)$$

2.4.3. Field Emergence and Vigour Test

Each farmer's sample was evaluated in the field to ascertain the natural emergence potential of the collected samples in the month of March, May, and July in 2023. One-hundred (100) seeds from each farmer's samples were evaluated in three replicates. The seed bed was properly prepared, raised, and loosened. The samples were randomized within each block. Each plot measured 10 m long, with seeds planted at the spacing of 5 cm × 10 cm. The experimental plots were watered when necessary and weeding was done at the appropriate time. Data collected include emergence (%), emergence velocity index, mean emergence time, seedling vigour index-I and II, and leaf count, using similar formula as above in laboratory evaluation.

2.4.4. Seed Damage (%)

A seed lot of 50 g from each farmer's saved seed sample was segregated into whole, damaged, shrivelled, broken, mouldy, and insect-infected seeds. The proportion of damaged seed (%) was calculated using the formula (Equation (7)) as suggested by Patel et al. [42]:

$$\text{Seed damage (\%)} = \frac{\text{Number of seeds damage or infested}}{\text{Number of seeds sampled}} \times 100 \quad (7)$$

2.4.5. Determination of Seed Health

Thirty seeds per sample were used to identify seed-borne fungi pathogens associated with the collected Bambara groundnut seeds. Fifteen samples from each district were assessed. The seeds were surface-sterilized in 5% sodium hypochlorite for one minute and in 70% ethanol for another one minute and then rinsed properly in distilled water and spread on paper towels to dry. The samples were placed in sterile disposable cups covered with aluminum foil and transferred to the laminar flow chamber.

Full-strength Potato Dextrose Agar (PDA) media were prepared by weighing 20 g of PDA into a 1000 mL conical flask and dissolving in 500 mL of distilled water. The mixture was stirred on a magnetic stirrer for five minutes, after which the prepared media was autoclaved at 121 °C at a pressure of 15 psi for 15 min. The media was allowed to cool, and two drops of chloramphenicol were added to 500 mL of media using a syringe to minimize bacterial contamination. Then 20 mL of the media was pipetted into 9 cm plastic petri dishes. For each sample, three replicates of 10 sterilized seeds were plated in each petri dish using a pair of forceps. The petri dishes were sealed with masking tape and kept inside an incubator at 25 ± 2 °C for 7 days to observe the growth of seed-borne pathogens.

Seed mycoflora was calculated using the formula (Equation (8)) below:

$$\text{Seed mycoflora (\%)} = \frac{\text{Number of seeds infected by fungi}}{\text{Number of total seeds plated}} \times 100 \quad (8)$$

The isolated fungi were sub-cultured at 25 ± 2 °C for another 7 days to obtain pure cultures. Using an illustrated genera of imperfect fungi reference manual [43], the pathogens caused by fungi were identified based on their macro (colony colour and growth pattern) and micro (spore shape and colour) characteristics. A compound microscope (Novex binocular microscope, K-Range, Arnhem, The Netherlands) was used to examine each fungus isolate after it had been prepared on the slide. The hyphal structure, spore/conidia form, and colour of the pathogens were observed using a magnifying objective lens (10×) [44].

2.5. Data Analysis

Survey data were subjected to analysis using the Statistical Package for Social Sciences (SPSS) Version 20. A chi-squared test was performed to assess whether the categorical variables were independent of the districts. The *p*-value associated with the chi-square test was approximated using Monte Carlo simulations after 10,000 iterations. GenStat 12th edition was used to perform analysis of variance on the laboratory and field parameters collected. Means were separated using Fisher's protected least significant difference at a 5% probability level. A correlation analysis was performed on seed size with physiological and seed health quality variables. The count data, such as leaf count, seed damage, and seed mycoflora percentages were transformed using the square root data transformation.

3. Results

3.1. Socio-Demographic Characteristics of Bambara Groundnut Producers

Socio-demographic characteristics of Bambara groundnut producers varied significantly ($p < 0.05$) across the districts (Table 3). More males (57%) engaged in Bambara groundnut production compared to females (43%) across the districts. The majority (85%) of the producers were married, and most producers (40%) were between the ages of 40 and 60 years. The majority of the producers had no formal education (65%), up to 17% had primary education, 11% had secondary education, and 7% had tertiary education.

Table 3. Socio-demographic characteristics of Bambara groundnut producers in the Kintampo South, Talensi, and Tolon districts of Ghana.

Category	Description	Districts			Average (%)	*p*-Values for Chi-Squared Test
		Kintampo South (%)	Talensi (%)	Tolon (%)		
Gender	Male	44	48	78	57	$p < 0.001$
	Female	56	52	22	43	
Age	18–30	52	10	10	24	$p < 0.001$
	36–45	20	34	28	27	
	46–60	22	52	46	40	
	>60	9	4	16	9	
Educational level	No Education	66	54	76	65	$p = 0.005$
	Primary	14	28	8	17	
	Secondary	14	10	8	11	
	Tertiary	6	8	6	7	
Marital status	Single	8	4	6	6	$p < 0.001$
	Married	84	76	94	85	
	Widowed	8	20	0	9	

3.2. Seed System of Bambara Groundnut

The seed system practices varied significantly ($p < 0.05$) across the three districts, except for the proportion of certified seed used by farmers, which did not depend on districts ($p > 0.05$) (Supplementary Table S1). Slightly less than half the respondents (45%) cultivated Bambara groundnut on less than one hectare of land, and 33% of farmers cultivated the crop on 1–2 ha. About 65% of the farmers produced Bambara groundnut for household use. Across the districts, all (100%) of the Bambara groundnut producers did not utilize certified seeds in the previous season. The producers obtained seeds from informal sources such as local market (55%), farmer-saved seeds (31%), and farmer seed exchange (13%). A higher percentage of the respondents in the Kintampo South District (60%), Talensi District (52%), and Tolon District (52%) sourced seeds from the local market. There was a diversity of Bambara groundnut varieties in the area studied such that 42% of the producers cultivated cream-coloured, 24% mottle-coloured, 19% white-coloured, 7% black-coloured, and 5% red-coloured varieties (Supplementary Table S1 and Figure 2). Close to 90% of the cultivated varieties germinated in 7 days. Across the three districts, most producers recycled their seeds between 2 and 5 years (61%) (Supplementary Table S1).

Across the districts, most of the producers selected their seeds at the time of planting (66%), while others selected them during drying (18%), during harvest (10%), or during storage (6%) (Table 4). The criteria for seed selection were seed size (39%), absence of disease (38%), and pod size (14%). Seed selection criteria were similar in Kintampo South (52%) and Talensi (54%) districts, where most of the producers selected seeds because they were disease free. In the Tolon District, seed size (54%) was the dominant selection criterion compared with disease-free (8%) and pod size (12%). The drying methods employed were sun drying on a bare floor (72%), on raised platform (26%), and under the sun using a tarpaulin (2%). The majority of the producers stored seeds unshelled in polypropylene bags (35%), while others stored them shelled in polypropylene bags (29%), shelled in jute bags (20%), or unshelled in jute bags (9%). However, in the Kintampo South District, the majority of the producers stored shelled seeds in polypropylene bags (56%) and jute bags (32%). In contrast, for Tolon District, the greater proportion of producers (66%) stored seeds unshelled in polypropylene bags and jute bags (22%). About 70% of the producers experienced insect damage, and 15% experienced incidence of moulds in storage. The majority of the producers stored their seeds for up to 6–9 months (57%), while others stored them for 4–6 months (36%) or 1–3 months (7%). The common seed threshing methods used by producers were mortar and pestle (89%), pestle in a dug hole (8%), and trampling and flailing with stick (3%) (Table 4).

Figure 2. Characterization of Bambara groundnut seeds based on seed coat colour across three districts of Ghana. Where KS = Kintampo South (Bono East Region), TAL = Talensi (Upper East Region) and TL = Tolon (Northern Region).

Table 4. Seed selection, processing, and conditioning practices among producers in the Kintampo South, Talensi, and Tolon Districts of Ghana.

Variables	Description	Districts			Average (%)	p-Values for Chi-Squared Test
		Kintampo South (%)	Talensi (%)	Tolon (%)		
Time for seed selection	During drying	10	8	36	18	$p < 0.001$
	During crop harvest	25	2	4	10	
	At the time of planting	50	90	58	66	
	During storage	15	0	2	6	
Criteria for seed selection	Pod size	26	4	12	14	$p < 0.001$
	Seed size	22	40	54	39	
	Disease-free	52	54	8	38	
	Good germination	0	0	4	1	
	High yielding plants	0	2	16	6	
	Healthy plant (Vigour)	0	0	6	2	
Methods of drying seeds	Sun drying on a bare floor	62	72	72	69	$p < 0.001$
	Sun drying on raised platform	4	26	28	19	
	Sun drying on tarpaulin	34	2	0	12	
Form and methods of seed storage	Unshelled in jute bag	0	4	22	9	$p < 0.001$
	Unshelled in polypropylene bags	6	34	66	35	
	Shelled in polypropylene bags	56	30	2	29	
	Shelled in jute bag	32	26	4	21	
Post-harvest damage observed	Insect-pest damage	80	70	60	70	$p < 0.001$
	Moulds	16	18	12	15	
	No damage	4	12	28	15	
Maximum length of seed storge in months	1–3 months	22	0	0	7	$p < 0.001$
	4–6 months	78	4	26	36	
	7–9 months	0	96	74	57	
	>9 months	0	0	0	0	
Seed processing methods before planting	Mortar and pestle	78	96	94	89	$p < 0.001$
	Flailing with stick	2	4	2	3	
	Pestle in a dug hole	20	0	4	8	

Most farmers in the area did not treat Bambara groundnut seeds before planting (78%), while only 22% treated seeds to enhance early germination before planting (Table 5). The predominant local treatment was hot-water treatment (9%), while others included soaking in water (5%), chemicals (3%), and other indigenous botanicals (5%).

Table 5. Farmers' existing practices and use of seed treatment in the Kintampo South, Talensi, and Tolon Districts of Ghana.

Variable	Description	Districts			Average (%)	p-Values for Chi-Square Test
		Kintampo South (%)	Talensi (%)	Tolon (%)		
Do you treat your seed before planting	Yes	12	54	0	22	$p < 0.001$
	No	88	46	100	78	
Seed treatment methods used	Soaking in water	0	14	0	5	$p < 0.001$
	Treatment in hot water	10	16	0	9	
	Chemical	2	8	0	3	
	Others	0	16	0	5	
	None	88	46	100	78	

Challenges and Opportunities of Bambara Groundnut Seed System

Challenges highlighted by respondents across the districts during a focus group discussion included the absence of improved quality seeds, absence of early generation seeds, community-based seed banks, and availability of only local channels (limited diversity) (Supplementary Table S2). Furthermore, the neglect/absence of sound policy implementation, seed certification, and quality regulation, and the lack of support initiatives were also outlined by the farmers as part of the limiting factors in the seed system. In addition, the lack of interest by researchers and research funding agencies to engage in the improvement of the crop was also mentioned.

Opportunities for strengthening the Bambara groundnut seed system, which include food security of the crop, job creation for both men and women, and source of income to farmers, were outlined by the farmers. Access to early generation seeds and community-based seed banks were key points raised by the farmers across the districts as a measure of strengthening the seed system of the crop. Also, organizing seed fairs; improving local market seed diversity; improving storage methods, conditions, and ease of registration; appropriate and robust regulation; and proper policy implementation were identified as critical opportunities that could ensure a vibrant and robust seed system for the crop (Supplementary Table S2).

3.3. Assessment of the Seed Quality Characteristics of Farmer-Saved Seed

3.3.1. Physical and Seed Health Characteristics

Seed colour and seed size varied significantly ($p < 0.001$) among seeds from the districts (Figure 2 and Table 6). Larger seeds (length and width of 12.3 mm and 10.9 mm, respectively) were obtained from Tolon District compared with Talensi District, with length of 11.2 mm and width of 9.7 mm, and Kintampo South District, with length and width of 11 mm and 9.6 mm, respectively (Table 6). There was also significant difference ($p < 0.001$) among the districts for 100-seed weight. Seed moisture content, seed damage ($p < 0.001$), and seed microflora ($p = 0.01$) showed significant difference across the districts. Higher seed moisture content (8.8%), seed damage (4.7%), and seed microflora (8.5%) were recorded in seeds from Kintampo South District (Table 6).

Table 6. Physical and seed health characteristics of farmer-saved seed from the Kintampo South, Talensi, and Tolon Districts of Ghana.

Districts	100-Seed wt (g)	Seed Moisture (%)	Seed Length (mm)	Seed Width (mm)	Seed Damage (%)	Seed Mycoflora (%)
Kintampo South	57.6 ± 7.0 [a]	8.8 ± 1.0 [b]	11.0 ± 0.6 [a]	9.6 ± 0.6 [a]	22.2 (4.7) ± 7.1 [b]	80.4 (8.5) ± 3.0 [b]
Talensi	59.0 ± 14.7 [a]	7.3 ± 0.8 [a]	11.2 ± 0.7 [a]	9.7 ± 0.6 [a]	15.9 (4.0) ± 5.2 [b]	67.1 (7.7) ± 2.9 [ab]
Tolon	84.8 ± 21.4 [b]	7.1 ± 0.8 [a]	12.3 ± 1.0 [b]	10.9 ± 1.1 [b]	13.5 (3.7) ± 3.9 [a]	53.8 (6.6) ± 3.3 [a]
LSD	6.5	0.4	0.3	0.3	2.2 (0.3)	14.6 (1.2)
CV (%)	23.1	11.3	6.9	8.1	30.8 (16.2)	52.7 (38.3)
Grand mean	67.1	7.7	11.5	10.1	17.2 (4.1)	67.1 (7.6)
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.01

Within a column, means with the same superscripts are not significantly different ($p < 0.05$). Data sets presented in parenthesis were transformed using square root transformation. Values represent mean ± standard deviation.

3.3.2. Seed Germination and Vigour Characteristics

Regarding seed germination potential, samples from Tolon District took the least number of days to germinate (4.3 days), while samples from Kintampo South District took longer to germinate (5.4 days) (Table 7). Samples from Tolon District had a significantly higher ($p < 0.001$) seedling shoot length (16 cm), seedling fresh weight (1.8 g), seedling dry weight (0.3 g), seedling vigour-I (1136.2), seedling vigour index-II (21.7) and leaf count (11.4) compared with Talensi District (shoot length: 15.1 cm; seedling fresh weight: 1.4 g; seedling dry weight: 0.1 g; seedling vigour index-I: 1011.2; seedling vigour index-II: 8.3; leaf count: 11.0) and Kintampo South District, which had the lowest values (shoot length: 7.3 cm; seedling fresh weight: 0.5 g; seedling dry weight: 0.1 g; seedling vigour index-I: 410.3; seedling vigour index-II: 6.6; leaf count: 6.6) (Table 7).

Table 7. Seed germination and vigour characteristics of farmer-saved seeds in the Kintampo South, Talensi, and Tolon districts of Ghana.

Districts	DFG (Days)	T50 (Days)	Germination (%)	GVI	MGT (days)	Shoot Length (cm)	Seedling Fresh Weight (g)	Seedling Dry Weight (g)	SVI-I	SVI-II	Leaf Count at 21 DAS
Kintampo South	5.4 [c]	6.3 [b]	55.8 [a]	1.1 [a]	6.0 [b]	7.3 [a]	0.5 [a]	0.1 [a]	410.3 [a]	6.6 [a]	6.6 [a]
Talensi	4.7 [b]	5.9 [a]	65.3 [b]	1.4 [b]	5.6 [a]	15.1 [b]	1.4 [b]	0.1 [a]	1011.2 [b]	8.3 [a]	11.0 [b]
Tolon	4.3 [a]	5.8 [a]	70.7 [b]	1.4 [b]	5.6 [a]	16.0 [c]	1.8 [c]	0.3 [b]	1136.2 [c]	21.7 [b]	11.4 [b]
$LSD_{(0.05)}$	0.3	0.3	9.0	0.2	0.2	0.7	0.1	0.02	88.9	1.9	0.7
CV (%)	14.2	13.1	29.1	32.1	9.1	17.7	30.5	36.7	28.2	42.8	22.1
Grand mean	4.8	6.0	63.9	1.3	5.7	12.8	1.3	0.2	852.6	12.2	9.7
p-value	<0.001	0.012	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Where DFG = days to first germination, T50 = days to 50% germination, GVI = germination velocity index, MGT= mean germination time, SVI-I (seedling vigour index-I = germination (%) × shoot length), SVI-II (seedling vigour index-II = germination (%) × seedling dry weight). Within a column, means with the same superscripts are not significantly different ($p < 0.05$).

Samples from Tolon District had a significantly higher germination percentage (70.7%) ($p = 0.005$) and germination vigour index (1.4) ($p < 0.001$) compared with samples from the Talensi District (germination rate: 65.3%; germination vigour index: 1.4) and Kintampo South District (germination percentage: 55.8%; germination vigour index: 1.1). Significant differences were observed for the mean germination time ($p < 0.001$) and days to 50% germination ($p = 0.012$). Samples from Tolon District had the shortest mean germination time (5.6 days) and days to 50% germination (5.8 days) compared with the Talensi District (mean germination time: 5.6 days; days to 50% germination: 5.9 days) and Kintampo South District, which had the highest mean germination time (6 days) and days to 50% germination (6.3 days) (Table 7). Significant differences were observed for mean germination time ($p < 0.001$) and days to 50% germination ($p = 0.012$).

3.3.3. Field Emergence and Vigour Characteristics

The field emergence potential of the collected samples was evaluated in the months of March, May, and July in 2023. Only the result for May evaluation is presented in this work, as the outcome from the three periods followed a similar trend.

There were significant differences ($p < 0.001$) in the field emergence, seedling vigour index-I, seedling vigour index-II, and leaf count across the districts (Supplementary Table S3). Generally, seedling vigour index-II for the Kintampo South District and Talensi District samples were similar ($p \leq 0.01$). Seed samples from Tolon District had the highest final emergence (64.7%), seedling vigour index-I (1199.0), seedling vigour index-II (42.4), and leaf count (16.9) compared with Talensi District (final emergence: 55.9%; seedling vigour index-I: 844.0; seedling vigour index-II: 26.6) and Kintampo South District, which had the least final emergence (44.9%), seedling vigour index-I (812.0), and seedling vigour index-II (26.3) (Supplementary Table S3).

Seed length had a weak positive relationship with final germination percentage (r = 0.20), field emergence (r = 0.27), and germination velocity index (r = 0.13) but had a moderate positive relationship with seedling vigour index-I (r = 0.43) and seedling vigour index-II (r = 0.45) (Figure 3). However, it had a strong positive relationship with 100-seed weight (r = 0.66). Seed length had a strong negative relationship with mean germination time (r = −0.18), seed moisture content (r = −0.20), seed damage % (r = −0.20), and seed microflora % (r = −0.10).

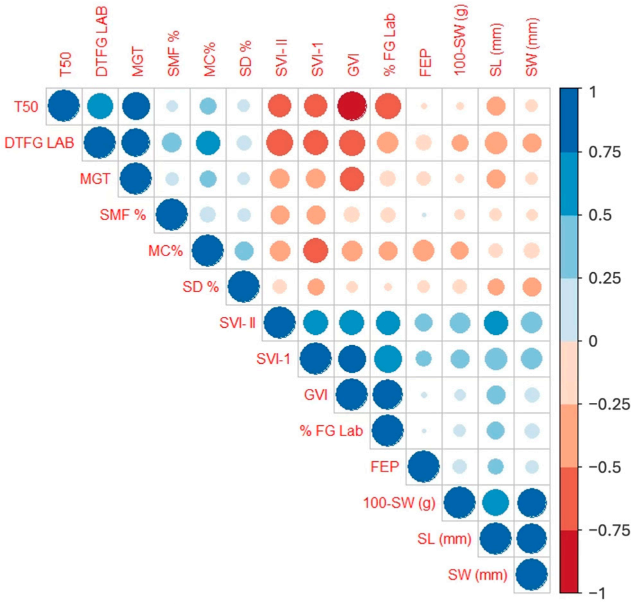

Figure 3. Correlogram showing the relationship between the physical, physiological, and health characteristics of farmers-saved seeds.

Seed width had a weak positive relationship with final germination percentage (r = 0.19), field emergence (r = 0.21), and germination velocity (r = 0.06), but had a moderate positive relationship with seedling vigour index-I (r = 0.43) and seedling vigour index-II (r = 0.42). However, it had a strong positive relationship with 100-seed weight (r = 0.77). Seed width had a strong negative relationship with mean germination time (r = −0.09), seed moisture content (r = −0.24), seed damage % (r = −0.21), and seed microflora % (r = −0.07). Also, seed moisture content had a weak positive relationship with the mean germination time (r = 0.20), seed damage percentage (r = 0.31), and seed microflora percentage (r = 0.18) (Figure 3).

3.4. Seed Health Analysis

There was variation in the occurrence of the seed-borne fungi pathogen across the districts (Table 8). The three dominant pathogens were *Aspergillus flavus* (38.8%), *A. niger* (16.6%), and *Macrophomina phaseolina* (11.5%). The other minor pathogens were *Rhizopus* spp. (6.5%), *Curvularia lunata* (5.3%), and *A. fumigatus* (1.9%).

Table 8. Incidence (%) of seed-borne fungi of Bambara groundnut sampled from the Kintampo South, Talensi and Tolon Districts of Ghana.

Fungi Pathogen	Districts/Communities											
	Kintampo South				Talensi				Tolon			
	Nante	Yamaokurum	Chirehi	Mean	Winkogo	Balungu	Pusi-Namongo	Mean	Gburimani	Kpachiyili	Gburimani-Tibogu	Mean
Aspergilus flavus	61.3	54.7	44.0	53.3	52.0	45.3	46.7	48.0	20.0	16.0	9.3	15.1
Aspergillus niger	30.7	25.3	25.3	27.1	16.0	12.0	6.7	11.6	10.7	10.7	12.0	11.1
Aspergillus fumigatus	2.7	1.3	4.0	2.7	1.3	2.7	1.3	1.8	1.3	2.7	0.0	1.3
Microphomina phaseolina	6.7	21.3	14.7	14.2	9.3	2.7	9.3	7.1	10.7	5.3	24.0	13.3
Rhizopus spp.	2.7	12.0	12.0	8.9	10.7	1.3	8.0	6.7	9.3	2.7	0.0	3.8
Curvularia lunata	0.0	0.0	0.0	0.0	10.7	10.7	10.7	107	9.3	5.3	1.3	5.3

Samples from the Kintampo South District had the highest incidence of *A. flavus* (53.3%) and *A. niger* (27.1%), followed by the Talensi District, with incidence of *A. flavus* (48.0%) and *A. niger* (11.6%), and Tolon District, with incidence of *Aspergillus flavus* (15.1%) and *A. niger* (11.1%) (Table 8).

4. Discussion

4.1. Characteristics of Bambara Groundnut Seed System, Challenges, and Opportunities

A seed system refers to all processes involved in creating, producing, storing, and disseminating seed varieties [45], serving as the main channel through which farmers access their preferred seeds [46]. In Africa, seed systems are generally categorized into formal and informal systems, with some countries recognizing a third, intermediate type known as Quality Declared Seed (QDS)/semi-formal. The formal systems rely on scientific breeding methods and government oversight for varietal certification. They consist of several related activities that are divided into three primary groups: varietal development, seed certification and multiplication, seed sales, and seed marketing [47]. On the other hand, informal or traditional seed systems comprise the use of farmer-saved seeds, exchanges among farmers, and seed sourced from local or regional grain markets [48].

In Ghana, and similar to what happens in most African countries, Bambara groundnut production is largely dependent on the informal seed system. Farmers primarily rely on their own saved seeds or purchase seeds from local markets [23,49]. These seeds typically show lower physical purity and genetic quality compared to those from the formal system due to the absence of standard quality control [50]. The lack of a structured seed delivery mechanism for Bambara groundnut remains a constraint in achieving consistent crop performance.

Most farmers involved in this study cultivated cream-coloured landraces, citing their sweet taste, ease of cooking, and consumer preference as reasons for selection. Berchie et al. [6] also found similar preferences in the Brong Ahafo and Upper East regions. Red and black landraces were cultivated mainly in the Tolon District for cultural uses and their suitability for roasting. Farmers in this study reported recycling seeds for periods ranging between 2 to 5 years, and in some cases, up to 10 years. Similar findings were made by Aviara et al. [13], who reported that farmers in North-East Nigeria recycled Bambara groundnut varieties for up to 15 years. Prolonged recycling raises concerns about genetic degradation and reduced seed vigour. These findings could be attributed to the lack of improved varieties and a seed delivery system for Bambara groundnuts.

One limitation of the current seed system in Ghana is the absence of community-based seed banks, which are essential for conserving genetic material and maintaining seed quality. The introduction of community seed banks can provide farmers with access to well-preserved and viable seeds [51], reducing dependence on poor-quality farm-saved seed and increasing genetic purity. Such banks can also serve as hubs for seed distribution, varietal trials, and local training in seed quality maintenance [52–55].

In addition, there is limited research attention and funding dedicated to Bambara groundnut improvement compared to other crops such as maize, cowpea, and soybean. There is a noticeable lack of interest among researchers and research funding agencies to improve the existing landraces. As a result, farmers have continued to rely on low-quality saved seeds, often with uncertain genetic purity. Addressing this research gap would lead to the development of superior Bambara groundnut varieties with higher yields and better adaptation to local conditions [56].

Again, the lack of efforts to promote seed diversity, such as through seed fairs, have limited awareness of the different available landraces. Farmers are less exposed to alternative varieties that may offer better yield, nutrition, or resilience [57]. Organizing seed fairs and exhibitions in major production areas would provide opportunities for farmers to interact, exchange seed, and learn about varietal differences. These platforms also help foster competition and innovation along the value chain [58].

Strengthening farmer networks and community awareness campaigns is another strategy to enhance Bambara groundnut seed system development. Increased farmer engagement not only supports varietal exchange but also promotes a sense of ownership and sustainability within the system. Therefore, a collaboration between farmers, the National Seed Trade Association of Ghana (NaSTAG), seed producers (e.g., Legacy Crop Improvement Centre [LCIC], SeedCo, M & B Seeds, Agriseed Limited, etc.), the Ministry of Food and Agriculture (MoFA), research institutions (West Africa Centre for Crop Improvement [WACCI], Crops Research Institute [CRI], Savanna Agriculture Research Institute [SARI] etc.), and other private stakeholders can lead to the development of robust marketing and awareness platforms. These platforms can highlight the nutritional, agronomic, and economic benefits of the crop, increasing both farmer and consumer demand.

In terms of policy, opportunities exist to streamline variety registration processes, provide incentives for Bambara groundnut research, and establish flexible regulatory frameworks that encourage both formal and informal systems to co-exist. A balanced regulatory approach would ensure seed quality without discouraging traditional practices of seed saving and farmer exchange [59–61]. Policy support should aim to stimulate variety development, expand seed industry growth, and enhance seed security. It can also facilitate increased private sector involvement by reducing entry barriers and offering incentives for investment in underutilized crops like Bambara groundnut [62].

Furthermore, there are opportunities for developing novel value chains for Bambara groundnut [63]. By organizing seed production, marketing, and processing systems more efficiently, the crop's market potential can be significantly expanded. This can lead to access to larger markets, improved distribution networks, and the creation of new employment opportunities. The involvement of local farmers in well-structured value chains could provide independent economic pathways out of poverty, especially in rural areas.

Lastly, developing integrated seed systems that include both formal mechanisms and farmer-led innovation will ensure that farmer knowledge and preferences remain central. Marketing strategies should emphasize the versatility, nutritional richness, and climate resilience of Bambara groundnut, encouraging its broader use and enhancing food and income security in Ghana.

In summary, improving the Bambara groundnut seed system in Ghana requires a comprehensive, inclusive, and multi-stakeholder approach. Addressing current constraints, such as poor seed quality, lack of diversity, inadequate research, and weak institutional support, can unlock the crop's potential. Collaborative efforts that blend policy reform, research investment, local knowledge, and market development will not only strengthen the seed system but also promote the wider utilization and commercialization of this underutilized legume.

4.2. Seed Selection, Processing, and Conditioning Practices

Bambara groundnut growers selected their seeds at the time of harvest, during drying, and in storage using criteria such as seed size, pod size, and freedom from disease symptoms. Seed size criterion is particularly important, as larger seeds are generally more vigorous and tend to produce higher yields compared to smaller seeds [64]. After harvest, seeds were typically sun-dried on bare ground. However, drying on raised platforms or tarpaulins is strongly recommended to minimize the risk of contamination [65,66]. Drying seeds on bare floors increases the risk of infection by seed-borne pathogens, which can compromise seed quality [67]. Seeds were commonly stored unshelled in polypropylene or jute bags. These materials offer some degree of protection against moisture absorption, pathogens, insect infestation, and physical damage [68,69]. Their use is likely due to their affordability and widespread availability in local communities. In terms of storage duration, seeds are typically stored for 4–6 months in Kintampo South District, and for 7–9 months in Talensi and Tolon Districts. The variation in storage periods reflects differences in the length of the dry season across the districts. However, prolonged storage, especially using conventional methods, can result in significant post-harvest losses and deterioration in seed quality.

Processing of Bambara groundnut in the study areas is traditionally done using mortar and pestle, flailing with sticks, or using a pestle in a dug hole. In countries such as Niger and Nigeria, shelling with mortar and pestle is also the predominant method [13,70]. While effective, this method subject seeds to direct impact, often causing mechanical damage such as cracking or breakage. Some producers, in the absence of a mortar, resort to shelling in a dug hole using a pestle. This method minimizes impact on hard surfaces like wooden mortars, thereby reducing mechanical damage. Increased mechanical damage during threshing adversely affects seed quality, highlighting the importance of choosing appropriate processing methods to preserve seed integrity.

Furthermore, farmers in the study areas do not treat their seeds prior to storage or planting. A few, however, induce germination by soaking seeds in either hot or cold water, and some use synthetic chemicals. The limited use of seed treatment may be attributed to a lack of awareness regarding available treatments and their effectiveness. Additionally, the socio-economic conditions of the producers, mostly smallholder farmers with limited formal education, likely contribute to the low adoption of seed treatment practices.

4.3. Effect of Physical Seed Quality on Germination and Vigour

Seed physical properties such as size, moisture content, and 100-seed weight are essential physical indicators of the physiological quality of seeds [71]. However, the effect of seed size on germination and crop establishment can vary depending on the crop species, cultivation practices, location, and environmental conditions in which the crop is grown [72,73]. In this study, seed samples with larger seed sizes exhibited higher germination rates, seedling vigour index I and II, under both laboratory and field conditions. Previous studies have similarly reported that larger seeds tend to demonstrate better field emergence due to their higher food reserve content [72,73]. On the other hand, smaller seeds may germinate faster due to a higher surface-area-to-volume ratio, which facilitates water absorption [74]. This study also revealed that seed size was positively correlated with seedling vigour index I and II, further confirming the relationship between larger seed size and higher seedling vigour. Although the impact of seed colour was not the primary focus of this study, seed samples with black, red, and cream seed coats exhibited higher germination rates and vigour indices compared to other coloured seeds. Chibarabada et al. [75] observed a similar trend, reporting higher germination rates, vigour indices, and lower mean germination times in plain red and black-speckled seeds compared to cream-coloured seeds. Similarly, Obura et al. [49] recorded greater germination vigour for AbiBam 003, a plain black landrace, compared to seeds of other colours.

This study also observed strong heterogeneity within local Bambara groundnut varieties, as evidenced by the wide variability in seed coat colour across districts. This diversity highlights the genetic variation within the species. The variation in seed colour may also be influenced by the source of the seeds, as producers relied on diverse sources such as farmer-saved seeds, local markets, and neighbours, often selecting based on consumer preferences and market demand.

In addition to seed size and colour, moisture content is an important parameter affecting seed quality, especially with respect to germination, vigour, and storability. Seed longevity and quality decline when moisture levels are too high, as this makes them susceptible to seed-borne pathogens and promotes mould growth [76]. Conversely, extreme desiccation (moisture content below 4%) can damage seeds and reduce viability [77]. In this study, seeds from Kintampo South District had higher moisture content, which correlated with increased seed damage, higher incidence of seed-borne pathogens, and lower germination rates. The elevated moisture levels may be attributed to inadequate drying and the use of poor-quality packaging materials. In general, seeds stored in moisture-permeable bags, such as paper bags, jute sacks, or fertilizer bags, tend to absorb moisture from the surrounding environment, as seeds are naturally hygroscopic [78].

4.4. Occurrence of Fungi Pathogen on Bambara Groundnut Seed

In this study, six fungal species (*Aspergillus flavus*, *A. niger*, *A. fumigatus*, *Macrophomina phaseolina*, *Curvularia lunata*, and *Rhizopus* spp.) were found to be associated with Bambara groundnut seed samples. Previous study has reported that these fungal pathogens are commonly present in the air, soil, and are often linked to poorly dried seeds [79]. Their presence in the sampled districts may be attributed to suboptimal post-harvest practices, including poor drying methods (e.g., drying on bare floors) and inadequate storage conditions in household storage containers.

Among the districts studied, seed samples from the Kintampo South District recorded the highest percentage of mycoflora contamination, which was significantly higher than that observed in the Tolon District, but statistically similar to the Talensi District. This higher prevalence in Kintampo South could be due to the district's climatic conditions, as it lies within the transitional zone characterized by bimodal rainfall (1400 mm–1800 mm annually) and high relative humidity (90–95%) [27]. In contrast, the Tolon and Talensi Districts fall within the Guinea and Sudan savannah zones, respectively, which experience a unimodal rainfall pattern with lower annual precipitation (950–1200 mm), drier environmental conditions, relative humidity between 32–60%, and average temperatures of 32 ± 8 °C during the storage period.

Furthermore, storage practices played a significant role in fungal occurrence. In Kintampo South, most farmers stored their seeds in shelled form, which increased their susceptibility to pest and fungal attacks. Conversely, farmers in the Tolon District typically stored their seeds unshelled, and the presence of the protective shells served as a physical barrier, offering additional protection against fungal invasion and other external threats.

5. Conclusions

This study revealed that the Bambara groundnut seed system in Ghana is predominantly informal, with most producers relying on farmer-saved seeds for cultivation. Generally, the use of farmer-saved seed presents several challenges, including poor germination and emergence, insect pest and fungal infestations, and low yield. These factors collectively reduce the crop's economic potential. Significant variations were observed in seed production practices across communities, including seed selection, sorting, drying, packaging, processing, and storage methods. These practices influenced the quality of farmer-saved seeds, particularly affecting germination rates, vigour indices, seed damage levels, and incidence of seed-borne fungal pathogens.

Given these findings, there is an urgent need to intensify training and extension services to promote improved seed conditioning practices, such as appropriate drying techniques, proper storage, effective packaging, and the use of seed dressers to minimize the impact of seed-borne pathogens under on-farm storage conditions. In operational terms, such training can be channelled through existing agricultural knowledge systems, including the Ministry of Food and Agriculture's (MoFA) district-level extension directorates, Farmer-Based Organizations (FBOs), lead-farmer demonstration platforms, and non-governmental organizations engaged in community agricultural programmes. These platforms already support farmer education and can be strengthened to integrate modules on seed quality management, safe seed handling, and post-harvest sanitation specific to underutilized crops such as Bambara groundnut.

From a policy perspective, stronger engagement among actors within the Bambara groundnut seed value chain is required to address the persistent issue of poor seed quality in Ghana. Policymakers can integrate Bambara groundnut into national seed policy frameworks, including the National Seed Roadmap and MoFA's Feed Ghana initiatives, to ensure that the crop receives consistent institutional support. Establishing incentives for community seed banks, streamlining variety release procedures for neglected crops, and promoting flexible regulatory spaces where formal and informal seed systems can co-exist would enhance seed security and quality assurance.

Establishing a reliable supply chain for early generation seeds is critical for sustainable production and requires active collaboration among farmers, agricultural agencies, and research institutions. Academic institutions and research centres (e.g., WACCI, CRI, SARI) also have an important role in developing improved varieties, conducting participatory varietal selection, and generating evidence-based guidelines for seed handling. Strengthening these research–farmer linkages will ensure that scientific innovations respond directly to farmer needs and local production realities.

Moreover, in the absence of private seed companies producing certified Bambara groundnut seed, the development and support of a community-based seed system will be essential in ensuring farmers have consistent access to high-quality seed. Such systems can also serve as decentralized learning hubs, supporting farmer-to-farmer knowledge transfer, varietal conservation, and community-led seed quality monitoring.

Overall, the operational, academic, and policy implications highlighted in this study underscore the need for a coordinated, multi-stakeholder approach to unlock the full potential of Bambara groundnut. Strengthening seed quality management, expanding research attention, and embedding the crop within national agricultural support systems will not only improve farmer access to quality seed but also enhance the wider utilization and commercialization of this climate-resilient legume.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/seeds4040065/s1, Table S1: Characteristics of Bambara groundnut seed systems across Kintampo South, Talensi and Tolon districts of Ghana; Table S2: Challenges and opportunities of Bambara groundnut seed systems; Table S3: Field emergence and vigour of farmer-saved seeds in Kintampo South, Talensi and Tolon districts of Ghana.

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Abbreviations

The following abbreviations are used in this manuscript:

WACCI	West Africa Centre for Crop Improvement
CSIR-SARI	Council for Scientific and Industrial Research–Savanna Agricultural Research Institute
GVI	Germination Velocity Index
MGT	Mean Germination
SVI	Seedling Vigour Index
DFG	Days to first germination
DFE	Days to first Emergence
T50	Days to 50% Germination/emergence
ANOVA	Analysis of Variance
CV	Coefficient of Variation
LSD	Least Significant Difference
SMF	Seed Microflora
SMC	Seed Moisture Content
SD	Seed Damage
PDA	Potato Dextrose Agar

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