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Influence of variety and harvesting stage on germination and vigour of mung bean (*Vigna radiata*) seeds

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Abstract

Mung bean seed quality is greatly affected by the inherent difficulty of determining the optimal harvest time, which is further complicated by asynchronous flowering and pod maturation, resulting in considerable losses. This study assessed how harvesting maturity impacts seed quality of five mung bean varieties, namely Nduru, Nuru, TARI Green Gram 1 (TG1), TARI Green Gram 2 (TG2), and Imara, harvested at 60, 70, 80, and 90 days after sowing (DAS). A split-plot design under a randomized complete block design was used in the field, and a two-factor factorial arrangement was applied in the laboratory. Significant varietal differences ($p \leq 0.05$) were observed for 1000-seed weight, seed geometric mean, seedling length, seedling dry weight, and seedling vigour index I and II, while germination percentage ($p = 0.1$) and the percentage of abnormal seedlings ($p = 0.25$) showed no significant effect. Harvesting maturity significantly influenced 1000-seed weight ($p = 0.0003$), seed count per 100 g ($p = 0.001$), germination, percentage of abnormal seedlings, seedling dry weight, and vigour index II ($p \leq 0.05$). The interaction between variety and maturity notably affected seedling dry weight and vigour indices, with TG1 and TG2 performing best at 90 DAS. Principal component analysis showed that the first two components explained over 60% and 80% of the variance for harvesting maturity and variety, respectively. Strong correlations were found between 1000-seed weight and vigour index II ($r = 0.64$), and between germination and vigour index I ($r = 0.65$). These findings emphasise the importance of choosing suitable varieties and harvesting at the right time to enhance mung bean seed quality and crop performance.

Keywords Harvesting maturity, Genotype, Seed quality, *Vigna radiata*, Physiological seed quality

1 Introduction

Green gram (*Vigna radiata* (L). Wilczek), also known as mung beans, green bean, moong bean, or golden gram, belongs to the family Fabaceae and is a vital annual crop with a short growth period of 65 to 90 days [1–3]. The crop is a crucial legume in the semi-arid tropics of Asia, Africa, Southern Europe, and Central and Southern America [4], providing a plant-based source of dietary proteins, vitamins, and other essential

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micronutrients [5, 6]. Across diverse ecosystems, the global area under mung bean cultivation is estimated at 7.3 million hectares per annum [7, 8]. India, Bangladesh, Pakistan, and Myanmar contribute over 74% of the total area under mung bean production [9]. Moreover, global mung bean production is estimated at 5.3 million tons, with India and Myanmar contributing approximately 30% each [4], while China and Indonesia contribute 16% and 5%, respectively [10]. In the East African Community, mung beans are a potential source of protein, iron, and calcium, making them crucial in the daily human diet [11]. However, its production is far below the global average, which could be attributed to biotic and abiotic factors [12]. In Africa, the crop is termed a neglected crop due to a small area under cultivation, being underutilized, and not much effort is being put into breeding new mung bean varieties [13]. Currently, in Tanzania, mung bean production has increased from 31,526.5 tonnes in the 2019/2020 cropping season to 145,731.4 tonnes in the 2023/2024 season, driven by rising demand from domestic and international markets [14]. For instance, Tanzania exported ~ 46.4 kMT, with export values of ~USD19 million, to the United Arab Emirates, Uganda (24.7%), Vietnam (18.1%), and India (12.1%) [4].

In Tanzania, mung beans are the third most crucial pulse crop after soybeans and common beans. The crop occupies 0.3 million hectares of land [12]. Based on the country's agro-ecological conditions, there is considerable potential for expansion, as the crop can thrive and perform better even under nutrient-limited conditions and tolerate abiotic stress [2, 15]. In Tanzania, mung beans are widely grown in the Simiyu, Shinyanga, Dodoma, Tabora, and Mtwara Regions, producing 73,073 metric tons with an average yield of 400 kg/ha during the 2016/2017 season, making it the leading producer in Africa. According to [16], Mung beans offer an economic advantage to smallholder farmers by providing a reliable source of income through sales and labour across the production chain. Moreover, mung beans thrive well on marginal land with minimal inputs compared to other crops, reducing the fertilizer burden and making it suitable for smallholder farmers [15]. Despite its potential, mung bean production is very low, with an average on-farm output of approximately 0.5 tons/ha, far below the potential of 1.5 tons/ha [12]. This is associated with biotic [17] and abiotic stresses [18], as well as the prevalence of poor seed quality due to the lack of hybrid seeds, which requires farmers to save their seeds for propagation [13, 19]. According to Mmbando [12], low seed quality is a prevalent challenge facing mung bean production in Tanzania. Seed quality, encompassing genetic, physiological, and health characteristics, is crucial for achieving vigorous plant growth, high yields, and resilience against biotic and abiotic stresses. Costa [20] revealed that to be deemed of high quality, a seed must possess perfectly balanced attributes, each holding equal importance in determining its overall excellence. Moreover, Dayal [21] and Shaheb [22] revealed that seed-harvesting maturity plays a crucial role in physiological quality, as it directly affects the duration of seed filling. Ensuring optimal seed maturity on the plant is essential for maximizing seed quality, and every crop has an ideal harvesting time range [23, 24].

Mung bean exhibits an indeterminate growth pattern, characterized by multiple flowering flushes, resulting in asynchronous pod maturation. The inconsistent pod maturation poses a challenge in obtaining quality seed, loss of seed crop due to pod shattering, high labour demand, overall crop yield, and low harvesting index (HI) [25]. Moreover, early harvesting due to adverse factors, including climatic conditions, pests, and

diseases, can result in low-quality seeds in terms of physical and physiological attributes [26]. Discrepancies in seed maturity, or the remaining time for seed maturation on the parent plant, within the pod, account for variability in physiological seed quality and their storability under varying storage conditions. Due to uneven crop maturity, farmers often face uncertainty about the best time to harvest their crops and save planting material for the next growing season. While some pods reach maturity, some remain green. This leads to a contradictory decision: whether farmers should wait for the green pods to mature or harvest them in their current state is a viable option. This study aims to assess the impact of pod maturity on seed quality parameters and provide valuable insights for farmers and producers on high-quality seed production practices. The study hypothesis was that there is no significant difference in key seed quality parameters of mung bean seeds harvested at different maturity stages.

2 Materials and methods

2.1 Experimental site

The study was carried out in Bunamhala ward, Bariadi Town Council, Simiyu Region (2.890 S: 34.044 E) (Fig. 1) from November 2024 to March 2025. The area experiences a tropical climate, with temperatures ranging from 15 °C in July to 35 °C in January, February, April, and October. Annual rainfall ranges from 600 to 900 mm, with peaks in April and November. Sunshine is most abundant in May and October. The soil is mainly black, well-drained, and loamy. The soil, combined with favorable temperatures and sufficient rainfall, meets the ecological needs of green gram (25–35 °C, 350–700 mm, pH 6.0–7.0)) [16]. Bunamhala ward was chosen because it has high potential for green gram production, supporting higher yields and seed quality. During the research period from November 2024 to March 2025, the mean monthly rainfall was 180.02 mm and the average temperature was 22.85 °C. Rainfall ranged from 29.99 mm in February to 345.46 mm in November, while temperatures varied from 21.50 °C in December to 23.83 °C in November. The selected plot had a pH of 5.94, with 0.092% nitrogen, 15.52 ppm phosphorus, and 1.49 cmol+/kg potassium. On the other hand, laboratory analysis at the African Seed Health Centre at Sokoine University of Agriculture, Morogoro.

2.2 Source of planting materials

The certified seeds of four green gram (*Vigna radiata*) varieties of Nuru, TARI Green Gram 1 (TG1), TARI Green Gram 2 (TG2), and Imara, were procured from the Tanzania

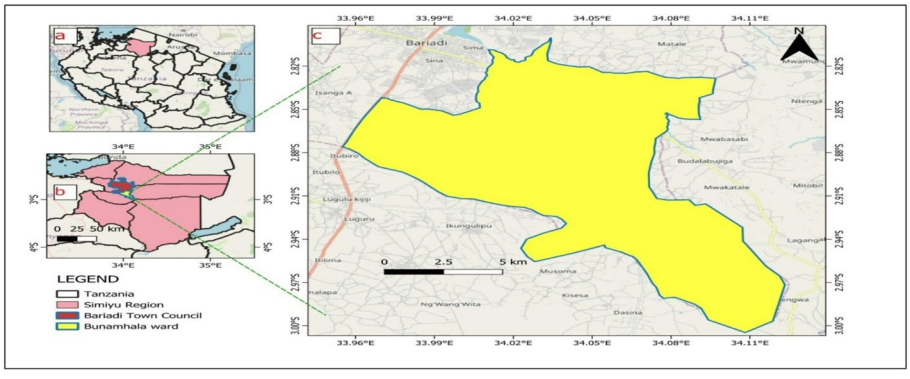


Fig. 1 The map showing the study area (**a**). Tanzania (**b**). Simiyu region and Bariadi (**c**). Bunamhala Ward, where the field study on seed production was conducted

Agricultural Research Institute (TARI)–Ilonga Station. In contrast, seeds of the Nduru, a local variety, were collected from farmer-saved seed stocks available during the 2023/2024 cropping season.

2.3 Experimental design

The experiment was laid out in a split-plot design under a Randomized Complete Block Design (RCBD) with three replications. Each plot measured 13 m × 4 m, with 5 m separation within and between replications, giving a total area of 1,960 m². Seeds of each variety were sown at two seeds per hill, spaced 50 cm × 20 cm, for a plant density of 1,040 plants per plot. Standard field management practices, including weeding and pesticide application, were applied to prevent yield loss. Pods from 64 tagged middle plants per variety were harvested at 60, 70, 80, and 90 DAS, sun-dried, threshed, and cleaned, with moisture monitored by physical feel and a digital moisture meter. The dried seeds were then packaged in paper bags and transported to the laboratory for quality evaluation.

2.4 Laboratory analysis

In the laboratory, the experiment utilized a factorial design with two factors: variety and harvesting maturity in three replications to produce 60 experimental units. The treatment variety was allocated using an RCBD. The harvested seeds underwent laboratory testing to evaluate quality parameters, including 1000-seed weight, number of seeds per 100 g, seed geometric mean, moisture content, germination percentage, percentage of abnormal seedlings, average seedling length, average seedling dry weight, and seedling vigour indices.

2.4.1 Determination of 1000 seed weight and the number of seeds in 100 g of seed weight

The 1000-seed sample was obtained through manual counting. Seeds were thoroughly mixed, and individual seeds were counted by hand in ten groups of 100 until a total of 1000 true seeds was reached. The counted seeds were then weighed using an electronic beam balance. To determine the number of seeds per 100 g, a 100 g subsample was first measured using a digital beam balance. All seeds in this subsample were then manually counted to obtain the exact number of seeds corresponding to the 100 g seed weight.

2.4.2 Determination of seed geometric mean

Twenty seeds were randomly selected from the 1000 true seeds; their respective length and width were measured using a digital Vernier caliper, nd the geometric mean was calculated using Eq. 1 as described by [27]. The average geometric characteristics were computed.

$$\mathrm{SGM} = \sqrt[3]{xwxt} \tag{1}$$

whereby:

SGM = Seed Geometric Mean.

l = the individual seed length, w = is the individual seed width, and t = the individual seed thickness.

2.4.3 Determination of seed moisture content (MC)

The method employed follows the guidelines established by ISTA [28]. Initially, the weight of an empty Petri dish, including its cover, was recorded. Subsequently, 5 g of the working seed sample was placed in an oven maintained at 103 ± 2 °C for 24 h. The seed moisture content was determined using Eq. 2 as Milivojević [29] described.

$$\text{SMC } (\%) = \frac{W2 - W3}{W2 - W1} \text{x } 100 \tag{2}$$

whereby:

SMC = Seed moisture content.

W1 is the weight of the empty petri dish plus its cover.

W2 is the weight of the petri dish, plus cover and sample, before drying.

W3 is the weight of the petri dish, cover, and sample after drying.

2.4.4 Determination of germination percentage(GP)

As per ISTA [28], a germination test was conducted involving 300 seeds in three replications, each comprising 100 seeds. Seeds were placed in sterilized sand that was adequately moistened and within a seed germination chamber set at room conditions, having an average temperature of 24.5 °C and a relative humidity of 62%. After 7 days, all germinated seeds were counted, and GP was calculated as described by Milivojević [29] in Eq. 3 below.

$$\text{Germination percentage } (\%) = \frac{Number\ of\ germinated\ seeds}{Number\ of\ seeds\ planted} \times 100 \tag{3}$$

2.4.5 Determination of the percentage of abnormal seedlings (PAS)

The total number of abnormal seedlings was counted, and the percentage of abnormal seedlings was calculated from Eq. 4 below.

$$\text{Percentage of abnormal seedlings } (\%) = \frac{Number\ of\ abnormal\ seedlings}{Number\ of\ seeds\ germinated} \times 100 \tag{4}$$

2.4.6 Determination of average seedling length and dry weight

Ten seedlings were randomly selected from each germination container, and their lengths were measured using a ruler to compute the average length. Ten seedlings were randomly selected and oven-dried at 80 ± 1 °C for 24 h to determine seedling dry weight. The average dry weight was calculated using Eq. 5.

$$\text{Seedling dry weight} = W3 - W1 \tag{5}$$

whereby:

W1 the weight of an empty dry paper bag, W3 = the weight of the dried sample plus the dry paper bag.

2.4.7 Determination of seedling vigour index (SVI) I and II

The seedling vigour indices I and II were calculated using Eqs. 6 and 7, respectively, based on the method described by Sharma [30] using the recorded average seedling length and dry weight.

$$\text{SV I} = Standard\ germination\ percentage\ (\%) \times\ Average\ seedling\ length\ (cm) \quad (6)$$

$$\text{SV II} = \ Standard\ germination\ percentage\ (\%) \times\ Average\ seedling\ dry\ weight\ (mg) \quad (7)$$

2.5 Statistical data analysis

Data analysis was conducted in R and R Studio to evaluate the effects of variety and harvest maturity on outcomes. A two-way analysis of variance (ANOVA) was conducted to investigate the main and interactive effects of the factors. Before analysis, all the data were checked for normality using the Shapiro–Wilk test and homogeneity of variances using Levene's test. When assumptions were not met, the data were log10 (x + 1) transformed. Where significant differences were identified at the 5% probability level, Tukey's Honest Significant Difference (HSD) test was subsequently used to separate means and identify statistically distinct groups. The PCA revealed relationships among the varieties and seed quality parameters.

3 Results

3.1 Effect of variety and harvesting maturity on physical and physiological seed quality

The study revealed a significant difference in 1000-seed weight among various varieties and harvest maturities ($p < 0.001$). The TG2 variety had the highest average 1000-SW, which was at par with Imara, while Nduru recorded the lowest values, averaging 37.38 ± 0.83 g (Table 1). Moreover, the results revealed increased seed weight with delayed harvesting, emphasizing the importance of physiological maturity in seed quality. The seeds harvested 90 days after sowing had the highest weight of 45.28 ± 1.05 g, which was statistically similar to that of 70 and 80 days, while those at 60 days weighed the least at 38.98 ± 0.87 g. These results are consistent with a previous report by Tetteh [31], who found a strong correlation between physiological maturity and seed weight of the pepper seeds. The highest 1000-seed weight was in TG2 at 80 days (49.53 ± 0.64 g), followed

Table 1 The effect of variety and harvesting maturity on 1000 seed weight, number of seeds in 100 g, seed geometric mean, germination percentage, percentage of tukey's seedlings, and seedling length (Mean ± SE)

Variety	Mean 1000-SW (g)	Mean No. of seeds in 100 g	Mean GM (mm)	Mean GP (%)	Mean PAS (%)	Mean seedling length (cm)
NDURU	37.38 ± 0.83^{c}	2668.17 ± 66.12^{a}	3.69 ± 0.07^{b}	88.92 ± 1.73^{a}	4.96 ± 1.09a	26.68 ± 0.45^{b}
IMARA	45.34 ± 1.56^{ab}	2169.08 ± 62.14^{b}	4.14 ± 0.04^{a}	87.58 ± 1.03^{a}	3.77 ± 0.84a	27.53 ± 0.69^{ab}
TG1	43.63 ± 0.40^{ab}	2266.58 ± 21.74^{b}	4.10 ± 0.05^{a}	87.50 ± 1.86^{a}	3.18 ± 0.53a	28.99 ± 0.61^{a}
TG2	45.93 ± 1.14^{a}	2119.75 ± 51.54^{b}	4.10 ± 0.04^{a}	92.75 ± 1.59^{a}	2.74 ± 0.50a	29.24 ± 0.20^{a}
NURU	43.25 ± 0.68^{b}	2290.83 ± 36.41^{b}	4.11 ± 0.04^{a}	90.17 ± 1.28^{a}	3.72 ± 0.68a	$29.55 \pm 0.40_{a}$
p-value	0.0005	0.006	0.003	0.1	0.25	0.001
HM						
60	38.98 ± 0.87^{b}	2446.33 ± 88.48^{a}	4.03 ± 0.08^{a}	87.47 ± 1.21^{b}	5.13 ± 0.87b	28.49 ± 0.56^{a}
70	43.33 ± 1.00^{a}	2302.40 ± 54.88^{ab}	3.98 ± 0.06^{a}	88.60 ± 1.12^{b}	4.10 ± 0.63b	28.59 ± 0.35^{a}
80	44.84 ± 1.08^{a}	2242.07 ± 53.46^{b}	4.01 ± 0.06^{a}	88.67 ± 1.42^{b}	2.66 ± 0.55a	28.65 ± 0.52^{a}
90	45.28 ± 1.05^{a}	2220.73 ± 52.04^{b}	4.08 ± 0.05^{a}	92.80 ± 1.58^{a}	2.81 ± 0.12a	27.86 ± 0.63^{a}
p-value	0.0003	0.001	0.47	0.042	0.02	0.60
Interaction	Ns	Ns	Ns	Ns	Ns	Ns

HM Harvesting maturity, *TG1* TARI green gram1, *TG2* TARI green gram 2, *1000-sw* 1000-seed weight, *GM* Geometric mean, *GP* Germination percentage, *PAS* Percentage of Abnormal seedlings, and *Ns* No significant difference

*Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$ according to Tukey's HSD test

by Imara at 90 days (48.90 ± 2.33 g), and the lowest weight by Nduru at 60 days (33.87 ± 2.02 g). However, no interaction effects were revealed (Table 1). Further, the number of seeds per 100 g differed significantly among different varieties and harvesting maturity (p = 0.001). The variety Nduru had the highest seed count, averaging (2268.167 ± 66.118), while TG2 recorded the lowest (2119.75 ± 51.536); similarly, no interactive effect was shown between variety and harvesting maturing in the number of seeds per 100 g (p = 0.54). In addition, the effect of variety and harvesting maturity showed a significant difference (p = 0.001) in the seed geometric mean of the mung bean, with the variety Imara recording the highest seed geometric mean, followed by Nuru, TG1, and TG2. At the same time, the Variety Nduru revealed the least geometric mean (Table 1). The TG2 variety showed a relatively high germination percentage; however, there was no significant difference among the varieties (p = 0.1). The effect of harvesting maturity was significant (p = 0.042), with 90 DAS showing significantly higher germination percentages than other harvesting maturities (Table 1). Similarly, no significant differences were observed in germination percentages between harvesting maturity and variety. Moreover, there was no significant difference in the effect of variety on the rate of abnormal seedlings (PAS) (p = 0.25). However, the variety Nduru had a relatively higher PAS of 4.96 ± 1.09%, compared to other varieties (Table 1). Furthermore, the results showed a significant variation in PAS on harvesting maturity (p = 0.0266); seeds harvested at 60 DAS revealed the highest PAS of 5.13 ± 0.87%. This was statistically similar to those harvested at 70 DAS (4.10 ± 0.63%). However, seeds harvested 80 and 90 days after sowing recorded the least PAS (Table 1). These results align with a previous report by Obura and Lamo [32], who documented the influence of seed storage reserve during the germination stage. Moreover, the results showed significant variation in average seedling length (p = 0.001) among varieties, with Nuru having the highest at 29.55 ± 0.396 cm. At the same time, Nduru recorded the shortest length, while TG2, TG1, and Imara had similar lengths to Nuru. Furthermore, the harvesting maturity and the overall interaction between harvesting maturity and variety revealed no significant difference (p = 0.6) in seedling length (Table 1).

Additionally, the study revealed a significant variation in the effect of variety and harvest on seedling dry weight (p = 0.001). The results showed that seedling dry weight increased with harvesting maturity, with the lowest seedling dry weight averaging 5.84 ± 0.28 mg at 60 DAS increasing to 11.33 ± 0.58 mg at 90 DAS, but not significantly different from that of 80 DAS. The varieties TG1 and TG2 at 90 DAS showed the highest seedling dry weight (Table 2). Furthermore, the interaction between variety and harvesting maturity revealed significant differences (p = 0.003), with the interactions [TG1 × 90] and [TG2 × 90] showing high seedling dry weight (Fig. 2). Moreover, the study revealed a significant variation in the effect of variety on vigour index I and II (p < 0.001). The interaction between harvesting maturity and variety on the seedling vigour index I showed no significant differences (p = 0.64) (SI 1). In contrast, the interaction between harvesting maturity and variety on seedling vigour index II showed a significant difference (p = 0.002), The seeds harvested at 90 DAS exhibited the superior SV II of 978.99 ± 29.46 insignificant to that of 80 DAS seeds declining to 60 DAS harvested seeds at 513.31 ± 28.94, moreover the interaction [TG2 × 90] and [TG1 × 90] revealing the highest seedling vigour index II (Fig. 3).

Table 2 The effect of variety and harvesting maturity on seedling dry weight and seedling vigour index I and II, (Mean ± SE)

Variety	Mean seedling dry weight (mg)	Mean SV I	Mean SV II
NDURU	7.13 ± 0.80^{c}	2371.30 ± 58.82^{b}	639.62 ± 76.90^{c}
IMARA	8.32 ± 0.56^{b}	2411.08 ± 65.10^{b}	729.84 ± 51.26^{bc}
TG1	9.51 ± 0.59^{a}	2531.80 ± 62.14^{ab}	834.74 ± 58.34^{a}
TG2	9.31 ± 0.53^{a}	2712.35 ± 49.67^{a}	865.44 ± 55.10^{a}
NURU	9.00 ± 0.61^{a}	2663.64 ± 48.86^{a}	815.59 ± 60.85^{ab}
p-value	0.0002	< 0.001	< 0.001
HM			
60	5.84 ± 0.28^{c}	2491.26 ± 58.25^{a}	513.31 ± 28.94^{c}
70	7.96 ± 0.49^{b}	2533.35 ± 44.52^{a}	705.27 ± 44.78^{b}
80	11.27 ± 0.23^{a}	2542.66 ± 69.31^{a}	910.61 ± 20.93^{a}
90	11.33 ± 0.58^{a}	2584.86 ± 70.52^{a}	978.99 ± 29.46^{a}
p-value	0.001	0.64	0.002
Interaction	0.003	Ns	0.021

HM Harvesting maturity, *TG1* TARI green gram1, *TG2* TARI green gram 2, *SVI* Seedling vigour index I, *SVII* Seedling vigour index I, and *Ns* No significant difference

*Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$ according to Tukey's HSD test

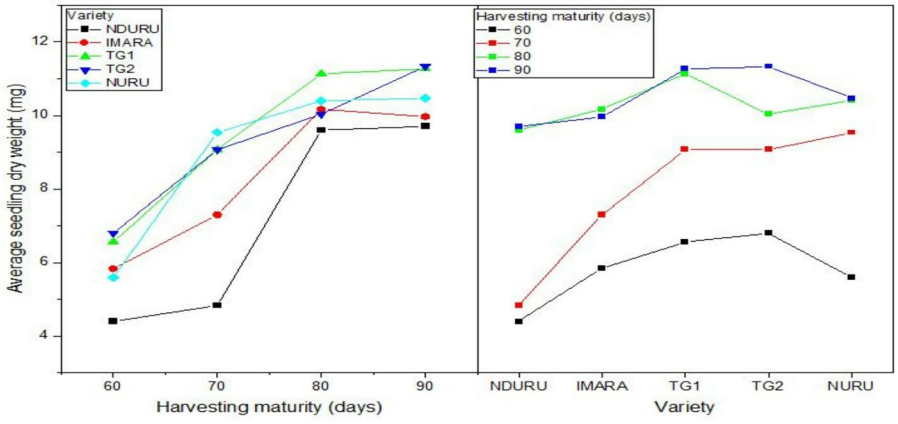


Fig. 2 Interaction of variety and harvesting maturity in seedling dry weight of mung bean (dw.g) (Two-way analysis of variance, $p \leq 0.05$)

3.2 Correlation between seed parameters

This study revealed a weakly positive relationship between 1000-SW and germination percentage ($r = 0.18$), which was not statistically significant ($p = 0.1613$). However, 1000-SW showed a strong positive correlation with Vigour Index II ($r = 0.64$; $p = 0.001$) and a weak correlation with Vigour Index I ($r = 0.34$; $p = 0.001$), the findings which are in accordance to reports by Obura and Lamo [32] and Chauhan and Williams [33] both working on physiological seed quality of mung bean. Furthermore, GP was strongly positively correlated with SV I ($r = 0.65$) and moderately with SV II ($r = 0.50$), both significant at $p = 0.001$. (Table 3).

Principal component analysis was performed to assess relationships among varieties, harvest maturity, and seed quality parameters (Figs. 4 and 5). The PCA revealed that the proportion of variance from the first two PC axes for harvesting maturity was 46.76% and 14.83% for PC1 and PC2, respectively (Fig. 4), with a cumulative variance of 61.59% (eigenvalues). The PC1 axis is mainly linked to the harvesting maturity 70, 80, 90 DAS,

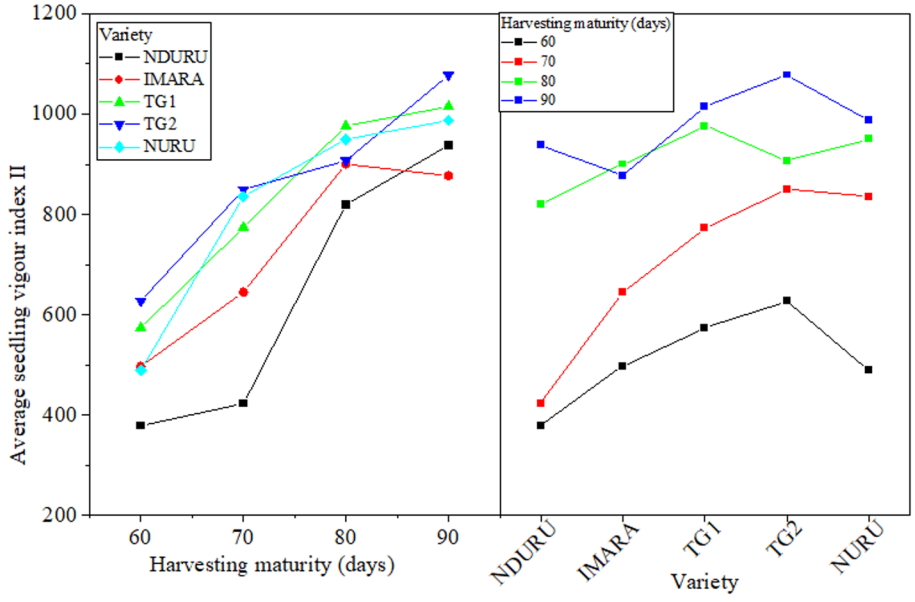


Fig. 3 Interaction of variety and harvesting maturity in seedling vigour index II of mung bean (Tow-way analysis of variance, $p \leq 0.05$)

Table 3 The correlation coefficient between thousand seed weight (1000SW) with germination percentage (GP), seedling vigour index I (SV I), and seedling vigour index II (SV II), and the correlation between germination percentage (GP) with both SV I and SV II

	GM	%MC	PAS	1000SW	No.of seeds in 100 g	GP	SeedL	Seed (dw.g))	SVI	SVII
GM	1	-0.33	-0.17	0.57	-0.66	-0.01	0.30	0.301	0.22	0.29
%MC	-0.33	1	0.26	-0.40	0.32	-0.24	-0.09	-0.36	-0.24	-0.39
%AbS	-0.17	0.26	1	-0.66	0.60	-0.18	-0.19	-0.61	-0.26	-0.58
1000SW	0.57	-0.40	-0.66	1	-0.89	0.18	0.29	0.65	0.34	0.64
NoS100g	-0.66	0.38	0.60	-0.89	1	-0.15	-0.37	-0.52	-0.38	-0.50
GP	-0.01	-0.24	-0.18	0.18	-0.15	1	-0.02	0.29	0.65	0.49
SeedL	0.30	-0.09	-0.19	0.29	-0.37	-0.022	1	0.15	0.74	0.13
SeedrW	0.31	-0.36	-0.61	0.62	-0.52	0.29	0.15	1	0.31	0.97
SVI	0.22	-0.24	-0.26	0.34	-0.38	0.65	0.74	0.31	1	0.43
SVII	0.29	-0.39	-0.58	0.64	-0.50	0.49	0.13	0.97	0.43	1

*******GM* Geometric mean, *%MC* Moisture content, *1000-SW* Thousand seed weight, *PSA* Percentage abnormal seedlings, *GP* Germination percentage, *SeedL* seedling length, *SVI* seedling vigour index I and SVII = seedling vigour index II

Seedling dry weight, Geometric, Seedling vigour index II, and 1000-SW on the positive PC value, and 60, 70, and 80 harvesting maturity on the negative PC value. The PC2 axis is associated with SV I, Germination percentage, Seedling length, 80 and 90 days harvesting maturity (positive PC value), and linked to the number of seeds in 100 g weight, Moisture contents, and 60 days harvesting maturity (negative PC value).

Furthermore, Fig. 5 revealed the relationship between varieties and seed quality parameters; the PCA showed that the proportion of variation from the two PC axes for variety was 62.89 and 21.77 for PC1 and PC2, respectively (Fig. 5), with a cumulative variance of 84.66 per cent (eigenvalues). The PC1 axis was linked to SV II, TG2, TG2 and Imara on the positive PC value and Nduru and Imara on the negative PC value. The PC2 axis is associated with SV I, Nuru, TG1, and TG2 (positive PC value) and linked to the number of seeds in 100 g, Imara, Nduru, and TG1 on the negative PC value.

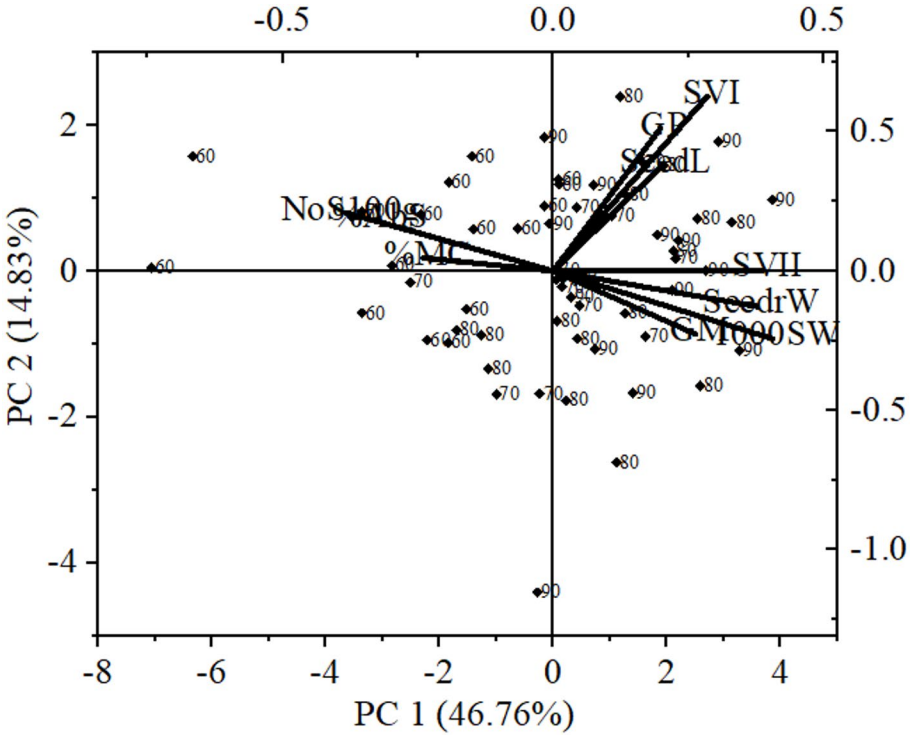


Fig. 4 PCA diagram representing the relationships between harvesting maturity (days) and seed quality parameters

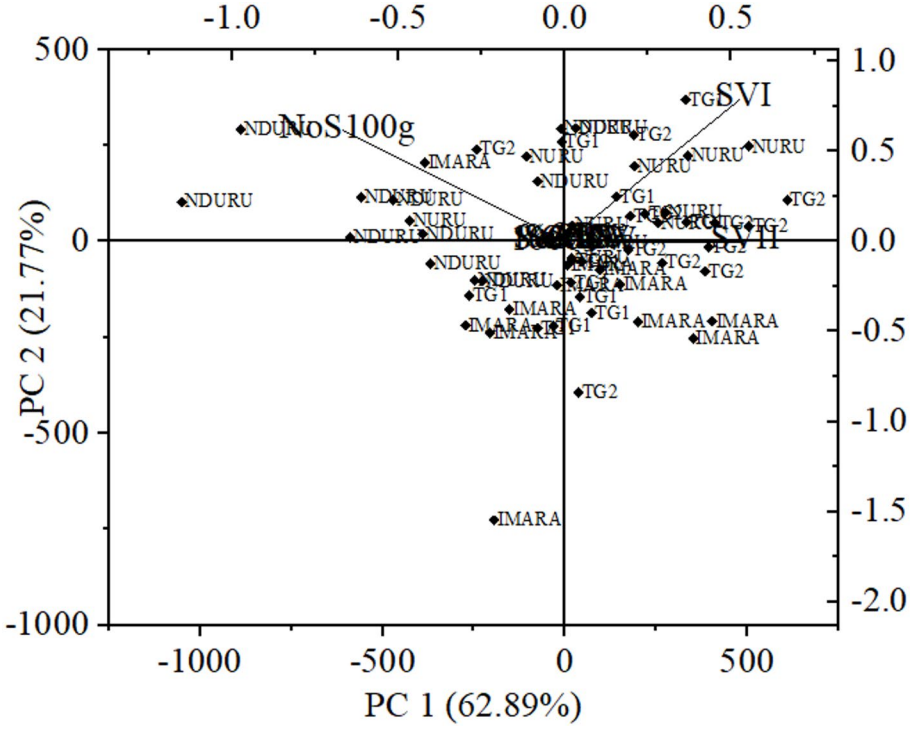


Fig. 5 PCA diagram representing the relationships between varieties and seed quality parameters

4 Discussion

4.1 Effect of variety on seed quality parameters

The observed variation in 1000-SW among the studied varieties is primarily attributed to the distinct genetic makeup of these varieties. This variation primarily results from differences in seed filling rates and duration, which are genetically controlled. Yin [34], who worked on maize, revealed the potential of genotype in seed filling. The TG2 exhibited the highest weight among the tested varieties, suggesting a more rapid seed-filling rate. This aligns with a previous report by Dayal [21], who observed high seed weight in maize and concluded that harvesting seeds at physiological maturity is important. In contrast, Nduru demonstrated a slower seed-filling rate than the other varieties, contributing to its lower 1000-SW, which is also attributed to its genetic makeup. The discrepancies in the number of seeds per 100 g of seed weight across the varieties can be linked to variations in the size and weight of individual seeds, which are also influenced by genetics [35, 36]. Furthermore, the average seed geometric mean varied among green gram varieties due to their unique genetic makeup, which influences molecular pathways that control seed shape, structure, and biochemical characteristics. In the present result, the variety Imara revealed a larger grain size compared to other varieties, which could be associated with its genetic makeup. Li [37] reviewed several molecular pathways controlling seed geometric characteristics of seeds and revealed pathways such as the ubiquitin-proteasome pathway, G-protein signaling, mitogen-activated protein kinase (MAPK) signaling, phytohormone perception and homeostasis, and some transcriptional regulators.

The limited variation in germination percentage and abnormal seedling incidence is primarily due to the genetic similarity of the seed varieties, which influence key traits such as seed coat thickness, permeability, and dormancy, affecting water absorption and germination initiation [24, 38]. This genetic similarity might arise from a narrow genetic base of the collected planting material, resulting from low breeding priority mung beans receive compared to other crops [12]. Moreover, seed weight and size variations among the tested varieties may explain the incidence of abnormal seedlings since heavy-weighted seeds produced better seedlings than small-sized seeds. In the present study, the variety Nduru had the lowest weight and the highest percentage of abnormal seedlings, while TG2 revealed the highest weight and the fewest abnormal seedlings. This study aligns with previous reports by Xiao [39] and Upadhaya [40], who reported the influence of seed size and weight on germination percentage in mung beans.

The observed variation in average seedling length, measured from the root tip to the highest point of the plant, and in average seedling dry weight can be attributed to the unique genetic makeup of the tested varieties. This genetic diversity influences seed size, the seed reserves available for developing seedlings, and their responses to varying environmental conditions. Previous reports by Golijan [41], and Carles [42] revealed similar observations, indicating that genetic factors also determine seedling growth rates. For example, the Nuru variety exhibited the longest seedlings despite having a lower 1000-SW than TG2. Additionally, seedling vigour indexes among varieties are shaped by genetic influences that affect chemical composition, toughness, and resilience to biotic and abiotic stresses. Furthermore, the correlation between seed size and seedling vigour is notable, with heavier seeds generally producing more vigorous seedlings [32, 41, 43]. This is exemplified by the TG2 variety, which, having the heaviest seeds, demonstrated

superior vigour in both indices, while the Nduru variety, with a smaller 1000-SW, exhibited the least vigour.

4.2 Effect of harvesting maturity on seed quality parameters

The recorded increase in 1000-SW with lengthened harvesting maturity suggests the variation in seed filling and maturation duration [44]. For instance, seeds harvested 1000-SW at 90 DAS surpassed the other harvests followed by 80, 70, and 60 DAS, respectively, with insignificant mean separation as the time spent by pods on the mother also increases starch accumulation, leading to endosperm enlargement. The same phenomenon leads to a discrepancy in the number of seeds per 100 g of seed weight among varieties tested. Similarly, Önder [45] reported that reduced seed-filling duration and endosperm seed storage reserves lead to a reduced in individual and overall seed weight. However, the lack of significant differences among harvesting maturities in seed geometric mean can be attributed to the fact that at 60 DAS, seeds may have reached physiological or near-maturity. At this stage, the seeds have already accumulated sufficient reserves and have nearly reached full seed size [46]. The observed variation in germination percentage across different harvesting maturities can be attributed to seeds being harvested before reaching physiological maturity, incomplete accumulation of storage reserves, underdeveloped seed coats, and higher moisture content [47]. Seed at 60 DAS had a lower germination percentage, progressively increasing to 90 DAS. The same pattern can be attributed to a variation in the percentage of abnormal seedlings. However, the percentage of abnormal seedlings declined from 60 DAS to 80 DAS, then increased at 90 DAS, suggesting the deterioration of the seeds on the plant by being exposed to weather conditions and or other biotic stresses, a finding supported by Martins [48] who concluded that delayed harvesting of the seed compromised seed quality and may increase pathogens incidence.

The lack of a significant difference in average seedling length suggested that the seed may have accumulated early storage reserves to support seedling development. Once this reserve threshold had been reached, the early seedling development stage wouldn't be affected [46]. Seeds from 90 DAS showed shorter seedling lengths than those from 60, 70, and 80 DAS, indicating deteriorated performance due to delayed harvesting [26]. However, these seeds exhibited a higher seedling vigour index I, likely linked to a positive correlation with germination percentage Swain [49]. Additionally, the significant rise in seedling dry weight with delayed harvest from 60 to 90 DAS reflects differences in reserve deposition and maturation. This explains the lower seedling dry weight at 60 DAS, where some seeds might not have fully completed post-maturation. This finding aligns with Sripathy and Groot [46], who noted that maximum seed quality is not achieved until physiological maturity, reinforcing the positive correlation between average seedling dry weight and seedling vigour II.

4.3 Interaction effect of variety and harvesting maturity on seed quality parameters

The lack of significant difference in the effect of variety and harvesting maturity interaction on 1000-SW, number of seeds per 100 g seed weight, and average seed geometric mean could be attributed to a similar response among the tested varieties to the changing harvesting maturities. This finding aligns with Kara [50], who suggested that 1000-SW is influenced by variety or harvesting maturity rather than their interaction. Tetteh

[31] and Negasu [51] argued that seed weight is a stable trait unaffected by the interaction between variety and harvesting maturity. Furthermore, some varieties showed greater 1000-SW at early stages than later, suggesting deterioration due to prolonged exposure to field conditions. The pattern was displayed by TG2 and Nduru varieties, a finding supported by Vergara [26].

The absence of a significant interaction between variety and harvest maturity regarding germination percentage, percentage of abnormal seedlings, and average seedling length implies that these physiological quality traits exhibited similar responses across all varieties, regardless of the harvest stage. This trend could have been caused by the difference in maturity level used, which was not extreme enough to cause physiological stress or deterioration that could affect their germination ability, percentage of abnormal seedlings, and average seedling length. At 60 DAS, the seed could have accumulated the necessary storage reserve for the early seedling development processes [44]. The lack of a significant difference in seedling length caused the same pattern in seedling vigour index I, which depends on both germination percentage and average seedling length.

Furthermore, the presence of significant differences in average seedling dry weight and seedling vigour index II could be attributed to variation in the ability of the seed to mobilize the food reserves, which is affected by the interaction of both genetic and physiological maturity at harvest. The interaction between variety and harvesting maturity affects the seedling total conversion rate because different varieties possess different reserve allocation mechanisms [32]. Sripathy and Groot [46] documented that seed vigour tends to increase in the later maturation phase after attainment of physiological maturity. Padilha [52] reported that the varieties having a higher rate of seed reserve utilization favoured the development of more vigorous seedlings. For instance, TG2 and TG1 varieties at 60 DAS were more vigorous than Nduru, Nuru, and Imara, suggesting more advanced reserve utilization mechanisms and early maturation than the latter.

5 Conclusion and recommendation

This study highlights the importance of selecting mung bean genotypes and achieving optimal harvesting maturity to maximize seed quality, crop performance, and production. The varietal difference strongly affected numerous seed and seedling traits in mung bean, suggesting that genetic makeup plays a role in determining inherent seed quality parameters. In contrast, harvesting maturity was significantly related to physiological maturity and seed viability. The lack of significance in the factor interaction suggests that the factors exert independent additive effects on mung bean seed quality. These findings emphasize the importance of genotype selection and optimum harvesting maturity for high-quality seeds and crop performance. Farmers must prioritize high-performing varieties such as TG2 and TG1. Mung bean seeds must be harvested at physiologically appropriate maturities, ideally between 70 and 80 DAS. However, for the Nduru and Imara varieties, the harvest can be extended to 90 days after sowing, as they showed improved quality rather than decline under the late harvest. This research was based on a single season; further research could be extended to include multiple seasons and locations. Furthermore, future research could explore the interaction between varietal and harvesting maturity on seed quality under biotic and abiotic stresses.

5.1 Compliance with regulations

The cultivated plant species used in this study, *Vigna radiata*, is a common agricultural crop and does not require a permit for collection. However, all experimental research was conducted in strict accordance with the guidelines and legislation provided by Sokoine University of Agriculture through letter with Ref No. SUA/DPRTC/MST/D/2023/0002/04 and the formal approval to execute experimental trials by the President's Office –Regional Administration and Local Government through a letter with Ref No. AB/307/323/01/184.

Supplementary Information

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Supplementary Material 1.

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The authors declare that no Generative AI was used to create this manuscript.

Author contributions
SJM: Conceptualization, methodology, field trials, data collection, data curation, formal analysis, investigation, visualization, and writing of the original draft. LDL: Conceptualization, methodology, data curation, formal analysis, resources, investigation, supervision, validation, visualization, review, and editing of the original draft. GMT: Conceptualization, project administration, visualization, review, and editing of the original draft.

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Data availability
The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Declarations

Ethics approval and consent to participate
No part of this study involved human subjects.

Consent for publication
Not applicable.

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