Advances in Agriculture

WILEY

RESEARCH ARTICLE OPEN ACCESS

Interaction Effects of Harvest Maturity and Seed Position in the Pod on Seed Quality of Green Gram (*Vigna radiata* L.)

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Received: 25 September 2025 | **Revised:** 6 March 2026 | **Accepted:** 16 April 2026

Academic Editor: Nidhi Chaudhary

Keywords: asynchronous pattern | germination percentage | physiological maturity | seed vigour indices

ABSTRACT

The asynchronous flowering and pod maturity of mung beans create challenges for farmers, seed producers and researchers when establishing optimal seed selection practices. This study, conducted in Bunamhala Ward (Simiyu Region) and at Sokoine University of Agriculture (Morogoro, Tanzania), evaluated how harvest maturity and seed position within the pod affect seed quality in five Vigna radiata varieties. Field trials used a triplicate split-plot design, while laboratory experiments employed a three-factor factorial layout, both based on a randomised complete block design (RCBD). Harvesting was performed at 60, 70, 80 and 90 days after sowing and seeds were collected from basal, middle and apical pod positions. Significant differences emerged among varieties and harvest maturities for most seed quality traits at $p = 0.05$. Seed position notably impacted 1000-seed weight, germination percentage and seedling vigour index II. The interaction between variety and harvest maturity influenced several seed quality parameters, while other interactions were minimal. The varieties Imara, Tari Green Gram 1 and Tari Green Gram 2, harvested at 70–80 days and from the basal end of the pod, exhibited the best quality. Additionally, a negative correlation was observed between seeds per pod and seed quality. These results highlight the crucial roles of harvest timing and seed position in improving green gram seed quality.

1 | Introduction

Green gram (*Vigna radiata* (L.) Wilczek), commonly referred to as 'mung bean', is an annual legume from the Fabaceae family [1, 2]. Native to South and Southeast Asia, mung beans are widely cultivated across tropical and subtropical regions for their exceptional nutritional and agronomic value [3, 4]. The seeds are high in protein, essential amino acids and micronutrients, playing an important role in food and nutrition security. Mung beans also improve soil fertility through biological nitrogen fixation, making them valuable for sustainable agriculture. Its short growth cycle of around 65–90 days [5], early maturity and low input needs make it suitable for a range of production systems, including marginal and semi-arid environments. Worldwide, mung beans are cultivated on about 7.3 million hectares, yielding ~5.3 million tonnes annually [6, 7]. More than 74% of production comes from India, Bangladesh, Pakistan and Myanmar, with India and Myanmar each producing about 30% of the global total. China and Indonesia contribute 16% and 5%, respectively [7, 8].

In East Africa, mung beans are an important source of protein, iron and calcium, ranking third among pulses after soybeans and common beans. In Tanzania, mung beans are cultivated on around 0.3 million hectares, while in Kenya, the area is about

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0.15 million hectares [9, 10]. Production in Tanzania reached 73,073 metric tonnes during the 2016/2017 season, with an average yield of about 400 kg/ha [9]. Despite its ability to grow in nutrient-poor soils and its tolerance to several abiotic stresses [5, 11], on-farm yields remain low at 400 to 500 kg/ha compared to the potential yield of 1.5 t/ha. This yield gap is mainly due to biotic and abiotic stresses, limited access to improved varieties and the widespread use of low-quality farmer-saved seed [12]. Therefore, improving seed quality is a crucial step in increasing productivity and strengthening the seed system.

One major biological constraint affecting seed quality in mung bean is its indeterminate growth habit, which results in multiple flowering flushes and asynchronous pod maturity [13]. This uneven maturation complicates harvesting and often leads to a trade-off between early harvesting—associated with immature, low-vigour seeds—and delayed harvesting, which increases the risk of pod shattering and field losses [14–16]. Previous studies have demonstrated that the harvesting stage significantly influences physical and physiological seed quality parameters, emphasising the importance of identifying the optimal harvest window. However, these studies largely focus on harvest timing as an independent factor, with limited consideration of within-pod variability.

The position of a seed within the pod has been found to influence its weight, germination rate and vigour. Differences in seed development along the pod can lead to variation in physical and physiological traits at maturity. For instance, research on cowpea indicates that seeds near the base of the pod are usually heavier and of higher physiological quality than those at the tip [17, 18]. This positional advantage is primarily attributed to differential assimilate partitioning, in which seeds closer to the peduncle receive a greater assimilate supply during the seed-filling period [19]. These findings highlight positional heterogeneity in seed development, which may contribute to variability in seed lot quality. Nevertheless, most studies have evaluated seed position effects independently of harvest maturity stage, and evidence specific to mung bean remains limited.

Although both harvest maturity and seed position have been individually studied, little is known about their interaction and its combined effect on seed quality in mung bean. Given the crop's asynchronous flowering pattern, farmers and seed producers often face uncertainty about the appropriate harvest stage and whether to preferentially select seeds from specific pod positions to optimise quality. The absence of integrated knowledge on these two factors represents a critical research gap. Therefore, this study was designed to examine the interaction between harvest maturity and seed position within the pod on selected seed quality parameters of the mung bean. It is hypothesised that both factors, as well as their interaction, significantly influence seed physical and physiological quality attributes. The findings are expected to provide evidence-based guidance for farmers and seed producers to improve seed quality and overall crop productivity.

2 | Materials and Methods

2.1 | Experimental Site

Seed production took place in Bunamhala Ward, Bariadi Town Council, Simiyu Region, Tanzania (2.890°S, 34.044°E) (Figure 1). This region experiences a tropical climate with temperatures ranging from 15°C in July to 35°C in January, February, April and October. Annual rainfall is between 600 and 900 mm, with the highest amounts occurring in April and November, while May and October see the most sunshine. The area's soil is mainly black, well-drained and loamy [20], which is ideal for mung bean cultivation. These soil conditions, combined with suitable temperatures and adequate rainfall, fulfil the ecological requirements for green gram (25–35°C, 350–700 mm, pH 6.0–7.0) [21, 22]. Bunamhala Ward was selected for its strong potential for green gram production, with favourable yields and seed quality. The experimental plot had a pH of 5.94, 0.092% nitrogen and 15.52 ppm phosphorus. Laboratory analyses were conducted at

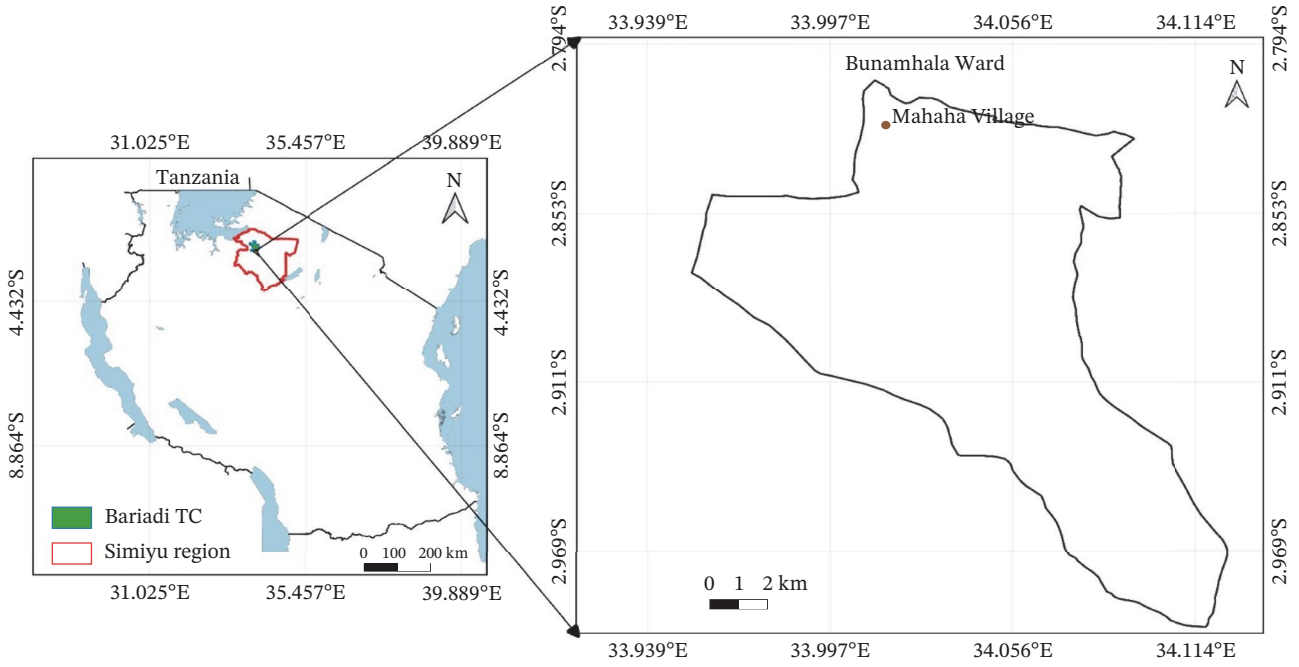


FIGURE 1 | The selected area for seed production in Mahaha village, located in Bariadi TC, Simiyu region, Tanzania.

the African Seed Health Center, Sokoine University of Agriculture, Morogoro.

2.2 | Origin of Planting Materials

Certified seeds of four green gram varieties: Nuru, TARI Green Gram 1 (TG1), TARI Green Gram 2 (TG2) and Imara were sourced from the Tanzania Agricultural Research Institute (TARI)–Ilonga Station. The Nduru variety, a farmer-maintained local type, was collected from farmer-saved seeds in the study area and produced during the 2023/2024 cropping season. TG1 and TG2 exhibit semi-asynchronous growth patterns depending on environmental conditions, with maturation occurring 60 to 90 days after sowing (DAS). In contrast, Imara, Nuru and Nduru exhibit asynchronous maturation, typically maturing 65 to 90 DAS. TG2 produces large, heavy black seeds, while TG1 and Nuru produce medium-sized, shiny green seeds. Nduru seeds are smaller and greenish, whereas Imara seeds are larger and also greenish.

2.3 | Field Experiment

The experiment was conducted in triplicate using a split-block design within a randomised complete block design (RCBD). Each whole plot measured 13 m by 4 m, separated by 5 m both within and between replications to facilitate management, while each subplot was 3 m by 4 m, resulting in a total experimental area of 1,960 m2. Seeds from each variety were planted at a rate of 2 seeds per hole, spaced 50 cm by 20 cm, resulting in a total plant density of 1,040 plants per plot [23]. Standard management practices, such as weeding and pesticide application, were carried out to prevent yield loss. Pods were harvested from 32 tagged plants in the middle rows of each variety, between 60 and 90 DAS, at 10-day intervals. The average pod length and seed count per pod were recorded. Pods were first sun-dried for two days, then manually sorted into basal (B), middle (M) and apical (A) sections, threshed, further dried and cleaned. Moisture levels were monitored throughout using both tactile assessment and a moisture metre. The final dried seeds were packed in paper bags and sent to the laboratory for quality assessment.

2.4 | Laboratory Seed Quality Testing

The study employed a factorial laboratory design that included three key factors: variety, harvesting maturity and seed position in the pod. The treatment varieties were allocated using a RCBD, and the categorised seeds were analysed in the laboratory to evaluate various quality parameters. These included metrics such as 1000-seed weight, moisture content (MC), germination percentage (GP), the proportion of abnormal seedlings, average seedling length, average seedling dry weight and seedling vigour indices.

2.4.1 | Evaluation of the Average Pod Length and Average Number of Seeds per Pod

At each harvest stage, pods were collected from the mother plant, and 20 mature pods were randomly chosen. Their lengths were measured to determine the average pod length. These same pods were manually shelled to calculate the average number of seeds per pod.

2.4.2 | Evaluation of 1000-Seed Weight and Seed MC

A 1000 true seeds were counted by hand and weighed with an electronic balance. To measure MC according to ISTA [24] procedures, the empty Petri dish and its cover were first weighed. Then, 5 g of seed were placed in the dish and dried in an oven at $103 \pm 2°C$ for 24 h. The seed moisture content was determined using Equation (1) as outlined by ISTA [24].

$$\mathrm{SMC}(\%) = \frac{\mathrm{W2} - \mathrm{W3}}{\mathrm{W2} - \mathrm{W1}} \times 100, \tag{1}$$

where

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.

2.4.3 | Evaluation of GP (%)

A germination test was performed using 300 seeds, divided into three replicates of 100 seeds each. The seeds were placed in sterilised and moistened sand inside a seed germination chamber maintained at optimal room conditions for 7 days, following ISTA [24] guidelines. GP was calculated using Equation 2 from ISTA [24].

$$\text{Germination percentage}\,(\%) = \frac{\text{Number } of \text{ germinated seeds}}{\text{Number } of \text{ seeds planted}} \times 100. \tag{2}$$

2.4.4 | Evaluation of the Percentage of Abnormal Seedlings

The total count of abnormal seedlings was recorded, and their percentage was determined using Equation 3 below.

$$\text{Percentage abnormal seedling}\,(\%) = \frac{\text{Number of abnormal seedlings}}{\text{Number of seeds germinated}} \times 100. \tag{3}$$

2.4.5 | Evaluation of Average Seedling Length and Dry Weight

Ten seedlings were chosen at random, their length recorded and dried in an oven at $80 \pm 1°C$ for 24 hours to measure dry weight. The mean dry weight was then calculated using Equation 4.

$$\text{Seedling dry weight} = \mathrm{W3} - \mathrm{W1}, \tag{4}$$

where

W1 is the weight of an empty dry paper bag,

W3 is the weight of the dried sample plus the dry paper bag.

2.4.6 | Evaluation of Seedling Vigour Indices

Seedling vigour indices I and II were calculated following Sharma [25], using Equations 5 and 6, which rely on measured average seedling length and dry weight.

$$\text{SVI} = \text{Germination percentage}\,(\%) \times \text{Average seedling length}\,(cm), \quad (5)$$

$$\text{SV II} = \text{Germination percentage}\,(\%) \times \text{Average seedling dry weight}\,(mg). \quad (6)$$

2.5 | Statistical Data Analysis

R and RStudio were used for data analysis to evaluate how variety, harvesting maturity and seed position influenced the results. Average pod length and seed number per pod at the whole-pod level were analysed using a two-way ANOVA, while a three-way ANOVA assessed the main and interactive effects of these factors on the other traits. Prior to these analyses, data normality was checked with the Shapiro-Wilk test, and homogeneity of variances was tested with Levene's test. When significant differences occurred at the 5% level, Tukey's Honest Significant Difference (HSD) test was applied to distinguish statistically different groups.

3 | Results

3.1 | The Effect of Variety and Harvesting Maturity on Pod Characteristics

The results showed that variety ($p = 0.001$), harvesting maturity ($p = 0.016$) and their interaction ($p = 0.006$) all significantly influenced average pod length. Imara produced the longest pods, whereas Nuru had the shortest (Table 1). While maturity stages differed significantly overall, no significant differences were found in pairwise comparisons; pods collected at 90 DAS were the longest (Table 1). Imara consistently had the longest pods across all maturity stages. Regarding seeds per pod, variety had a significant effect ($p = 0.0003$). Nduru and Imara had the highest average seed counts (13.2 and 12.98, respectively), while TG1 and Nuru had the lowest. However, there was no significant difference in the number of seeds per pod due to harvesting maturity ($p = 0.772$). Likewise, the interaction between harvesting maturity and variety was not significant ($p = 0.318$) (Table 1).

TABLE 1 | The effect of variety and harvesting maturity on average pod length and average number of seeds per pod (Mean ± SE).

Variety	Mean average pod length (cm)	Mean average seed per pod
IMARA	10.35 ± 0.03^{a}	12.98 ± 0.06^{ab}
NDURU	8.97 ± 0.06^{d}	13.2 ± 0.05^{a}
NURU	8.70 ± 0.07^{e}	12.31 ± 0.15^{c}
TARI green gram 1	9.30 ± 0.04^{c}	12.36 ± 0.06^{bc}
TARI green gram 2	9.84 ± 0.05^{b}	12.61 ± 0.11^{abc}
p-Value	**0.001**	**0.006**
Harvest maturity		
60	9.38 ± 0.18^{ab}	12.74 ± 0.13^{a}
70	9.36 ± 0.18^{b}	12.62 ± 0.15^{a}
80	9.47 ± 0.14^{ab}	12.70 ± 0.12^{a}
90	9.51 ± 0.14^{a}	12.71 ± 0.09^{a}
p-Value	**0.016**	**0.676**
Interaction	**0.006**	**0.131**
L.s.d	**0.233**	**0.567**
CV (%)	**1.5**	**2.2**

Note: For each factor, means within the same column that share superscript lowercase letters are not significantly different at $p \leq 0.05$ based on Tukey's HSD test. The bold values are the *p*-Value for each parameter including the interaction.

For each factor, means within the same column that share a letter are not significantly different at $p \leq 0.05$ based on Tukey's HSD test.

3.2 | The Effect of Variety, Harvesting Maturity and Seed Position on Seed Quality

The study revealed significant effects of variety, harvesting maturity, seed position and the interaction between variety and harvesting maturity on thousand-seed weight. Imara and TG2 had the highest weights (~45 g), while Nduru had the lowest (~37 g) (Table 2). Seed weight increased from 60 to 80 DAS and then declined at 90 DAS, except for Nduru and Nuru, which continued to increase. These results concur with Bhuker et al. [26], who reported that seeds harvested later in the growing season had higher seed weights. Seed position also influenced weight, with values generally decreasing from basal to apical pod sections. However, no significant interactions were observed among variety × seed position, harvesting maturity × seed position, or the three-way interaction. Overall, seed weight tended to increase from apical to basal positions, although Imara and Nuru recorded the highest weights at the middle pod section at 70 DAS (Figure 2)

In line with seed weight, GP was also significantly influenced by variety, harvesting maturity, seed position and the interaction between variety and harvesting maturity (Table 2). TG2 (95.97%) and TG1 (92.17%) exhibited the highest germination rates, while Nduru had the lowest (89.28%), as reported by Makungu et al. [23]. Germination increased with advancing maturity, from 85.23% at 60 DAS to 95.78% at 90 DAS, though the difference between 80 and 90 DAS was not significant. Across pod sections, germination decreased from basal (92.98%) to apical (90.90%) positions. Within the variety × harvest maturity interaction, germination improved with maturity for Imara, Nduru and Nuru but declined slightly at 90 DAS for TG1 and TG2. As observed for seed weight, interactions involving seed position were not significant. Generally, basal seeds recorded the highest germination rates, although minor deviations occurred, with middle seeds slightly outperforming basal seeds at 90 DAS.

Consistent with the improvements observed in germination at advanced maturity stages, harvesting maturity also significantly affected the proportion of abnormal seedlings ($p = 0.001$). Abnormalities decreased from 7.70% at 60 DAS to 2.46% at 80 DAS before slightly increasing at 90 DAS. Variety, seed position and all interaction effects were not significant. Nduru and Nuru showed relatively higher abnormal rates, whereas TG2 had the lowest (Table 2). Although abnormalities were highest at the apical position and lowest at the basal position, the pattern was not statistically significant. Thus, delayed harvesting generally

TABLE 2 | The effect of variety, harvesting maturity and seed position on 1000-seed weight, germination percentage, percentage of abnormal seedlings and average seedling length (Means ± S.E).

Variety	1000-seed weight (g)	Germination percentage (%)	Percentage of abnormal seedlings (%)	Mean seedling length (cm)
IMARA	45.11 ± 0.78^{a}	90.44 ± 1.35^{b}	4.32 ± 0.69^{a}	27.38 ± 0.25^{b}
NDURU	37.35 ± 0.44^{b}	89.28 ± 0.93^{b}	5.22 ± 0.70^{a}	28.67 ± 0.44^{a}
NURU	44.09 ± 0.48^{a}	91.83 ± 1.07^{b}	4.67 ± 0.76^{a}	29.03 ± 0.17^{a}
TARI green gram-1	43.43 ± 0.28^{a}	92.17 ± 0.95^{ab}	4.24 ± 0.58^{a}	28.45 ± 0.17^{a}
TARI green gram-2	45.04 ± 0.56^{a}	95.97 ± 0.39^{a}	3.17 ± 0.49^{a}	29.47 ± 0.24^{a}
p-Value	**0.001**	**0.001**	**0.134**	**0.0002**
Harvest maturity (DAS)				
60	39.62 ± 0.58^{b}	85.24 ± 1.0^{c}	7.70 ± 0.74^{a}	28.05 ± 0.28^{b}
70	43.16 ± 0.58^{a}	91.62 ± 0.73^{b}	4.11 ± 0.37^{b}	28.82 ± 0.32^{ab}
80	44.87 ± 0.63^{a}	95.11 ± 0.48^{a}	2.46 ± 0.40^{b}	28.45 ± 0.24^{ab}
90	44.34 ± 0.47^{a}	95.78 ± 0.47^{a}	2.98 ± 0.42^{b}	29.07 ± 0.16^{a}
p-Value	**0.001**	**0.001**	**0.001**	**0.035**
Seed position				
Apical	42.29 ± 0.58^{b}	90.90 ± 0.88^{b}	4.84 ± 0.55^{a}	28.59 ± 0.28^{a}
Middle	43.23 ± 0.59^{ab}	91.93 ± 0.83^{ab}	4.07 ± 0.51^{a}	28.56 ± 0.20^{a}
Basal	43.49 ± 0.50^{a}	92.98 ± 0.71^{a}	4.03 ± 0.46^{a}	28.63 ± 0.20^{a}
p-Value	**0.023**	**0.008**	**0.357**	**0.950**
Interactions				
Variety × harvest maturity	**0.0003**	**0.0006**	**ns**	**ns**
Variety × seed position	**ns**	**ns**	**ns**	**ns**
Harvest maturity × seed position	**ns**	**ns**	**ns**	**ns**
Variety × harvest maturity × Seed position	**ns**	**ns**	**ns**	**ns**

Note: For each factor, means within the same column that share superscript lowercase letters are not significantly different at $p \leq 0.05$ based on Tukey's HSD test. The bold values are the *p*-Value for each parameter including the interaction.
Abbreviation: ns, No significant difference.

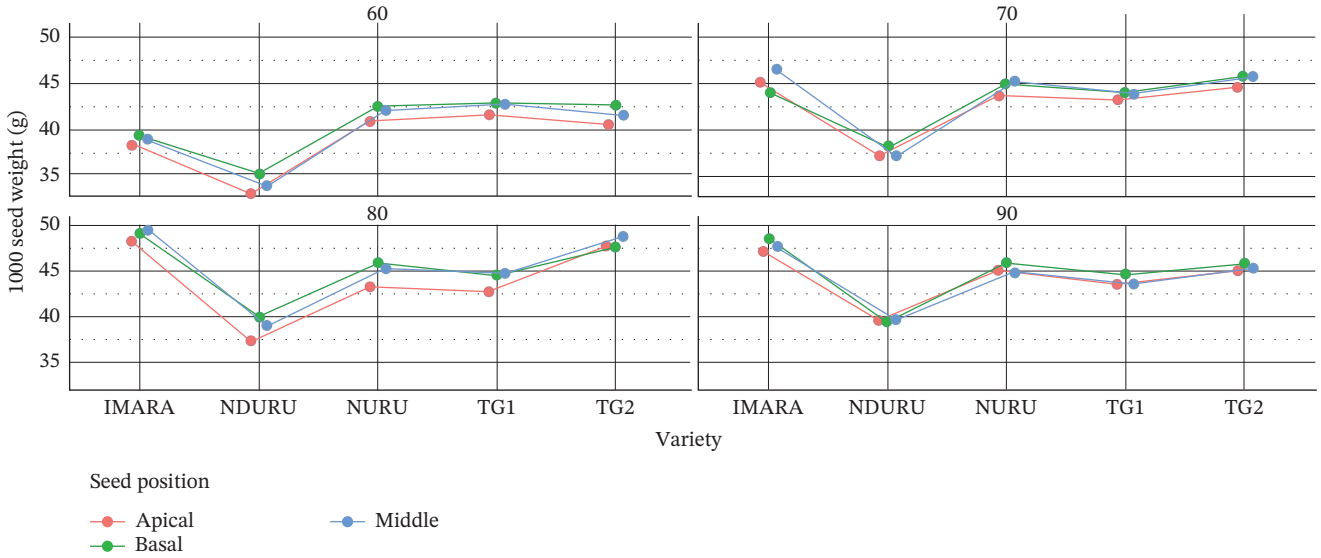


FIGURE 2 | The interaction of variety, harvesting maturity, and seed position in the 1000-seed weight.

reduced seedling abnormalities, reinforcing the importance of physiological maturity for seed quality.

Beyond germination and abnormality rates, seedling growth traits further reflected the influence of variety and maturity. Seedling length was significantly affected by variety ($p = 0.0002$) and harvesting maturity ($p = 0.035$). TG2 and Nuru produced the longest seedlings, while Imara had the shortest. Seedling length increased with delayed harvesting, peaking at 90 DAS (29.06 cm) compared to 60 DAS (28.05 cm). Seed position and all interactions were not significant, though seeds from the middle and apical sections produced slightly shorter seedlings. While most varieties showed increased seedling length with maturity, positional patterns were inconsistent, indicating that maturity played a stronger role than intrapod position in determining elongation.

A comparable trend was observed for seedling biomass accumulation. Seedling dry weight was significantly influenced by variety, harvesting maturity and their interaction ($p = 0.001$). TG1 and TG2 recorded the highest dry weights, whereas Nduru had the lowest. Dry weight increased steadily with maturity, from 5.95 mg at 60 DAS to 10.61 mg at 90 DAS (Table 3). This increasing trend was consistent across varieties; for example, Nduru rose from 4.34 mg to 9.96 mg between 60 and 90 DAS. Although seed position effects were not statistically significant, dry weight generally increased from apical to basal sections, with minor deviations in some varieties. These findings suggest that physiological maturity enhances reserve accumulation, thereby supporting stronger seedling establishment.

The cumulative effects of improved germination and seedling growth were further reflected in the vigour indices. Seedling vigour index I was significantly affected by variety, harvesting maturity and their interaction ($p = 0.001$). TG2 exhibited the highest vigour, while Nduru had the lowest (Table 3). Vigour index I increased with delayed harvesting, from 2397.47 at 60 DAS to 2789.59 at 90 DAS (Figure 3), whereas TG2 peaked earlier at 70 DAS and then declined slightly (Table 4). Seed position effects were not significant, but values generally increased from apical to basal positions.

Similarly, vigour index II was significantly influenced by variety, harvesting maturity and their interaction ($p = 0.001$). TG1, TG2 and Nuru recorded the highest values, whereas Nduru remained the lowest (Table 3). Vigour index II increased markedly with delayed harvesting, from 507.84 at 60 DAS to 1015.87 at 90 DAS, although TG1 declined slightly at the final stage. Unlike most

TABLE 3 | The effect of variety, harvesting maturity and seed position on the seedling dry weight and seedling vigour indices (Means ± S.E).

Variety	Mean seedling dry weight (mg)	Seedling vigour index I	Seedling vigour index II
IMARA	8.61 ± 0.30^{ab}	2478.48 ± 46.00^{c}	789.64 ± 35.60^{ab}
NDURU	7.33 ± 0.45^{b}	2563.17 ± 50.74^{bc}	664.23 ± 44.92^{b}
NURU	9.00 ± 0.33^{a}	2666.76 ± 38.00^{b}	835.24 ± 36.68^{a}
TARI green gram 1	9.69 ± 0.32^{a}	2621.87 ± 31.52^{bc}	899.74 ± 35.17^{a}
TARI green gram 2	9.25 ± 0.31^{a}	2828.15 ± 25.15^{a}	887.66 ± 29.88^{a}
p-Value	**0.001**	**0.001**	**0.001**
Harvest maturity (DAS)			
60	5.95 ± 0.17^{c}	2397.47 ± 43.20^{c}	507.84 ± 15.91^{c}
70	8.26 ± 0.26^{b}	2643.80 ± 37.37^{b}	758.09 ± 26.25^{b}
80	10.28 ± 0.10^{a}	2703.88 ± 21.66^{ab}	978.40 ± 11.39^{a}
90	10.61 ± 0.12^{a}	2783.59 ± 19.41^{a}	1015.87 ± 12.25^{a}
p-Value	**0.001**	**0.001**	**0.001**
Seed position			
Apical	8.67 ± 0.29^{a}	2601.35 ± 38.00^{a}	797.28 ± 30.61^{b}
Middle	8.77 ± 0.28^{a}	2627.85 ± 33.13^{a}	815.35 ± 30.17^{ab}
Basal	8.88 ± 0.29^{a}	2665.85 ± 29.62^{a}	833.28 ± 30.28^{a}
p-Value	**0.337**	**0.148**	**0.019**
Interactions			
Variety × harvest maturity	**0.001**	**0.001**	**0.001**
Variety × seed position	**ns**	**ns**	**ns**
Harvest maturity × seed position	**ns**	**ns**	**ns**
Variety × harvest maturity × seed position	**ns**	**ns**	**ns**

Note: For each factor, means within the same column that share superscript lowercase letters are not significantly different at $p \leq 0.05$ based on Tukey's HSD test. The bold values are the *p*-Value for each parameter including the interaction.
Abbreviation: ns, No significant difference.

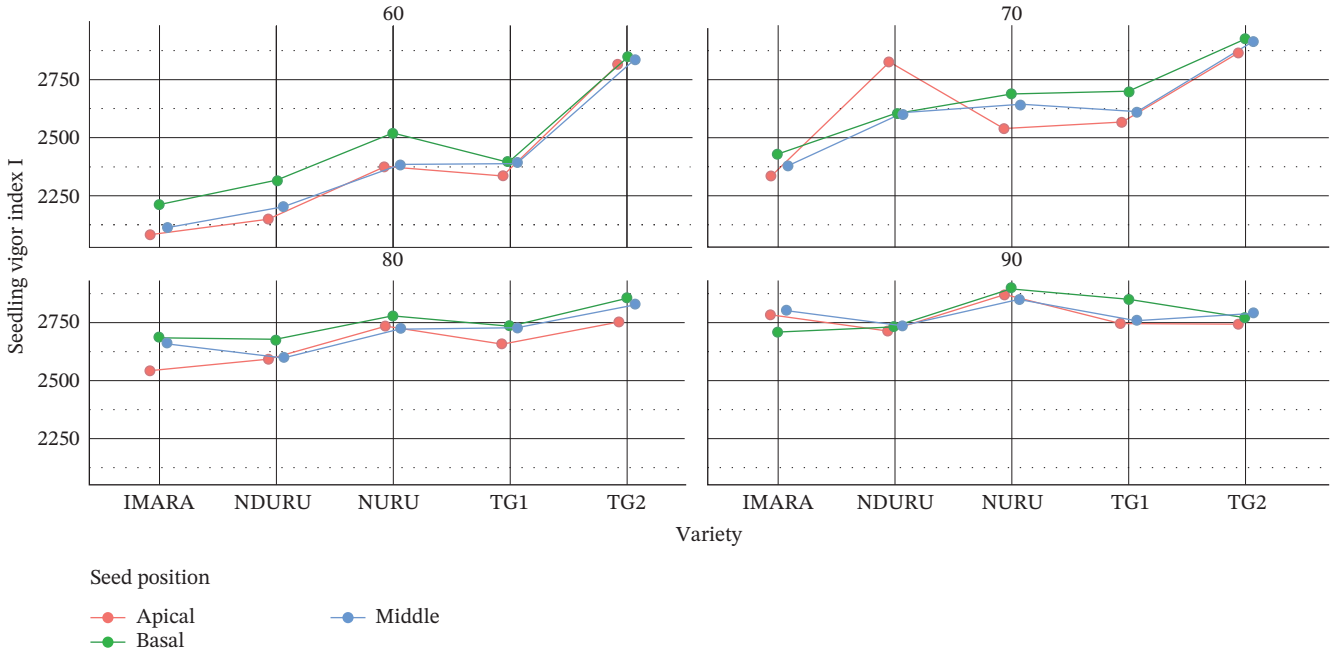


FIGURE 3 | Interaction of variety, harvesting maturity and seed position in the pod on seedling vigour index I.

TABLE 4 | The interaction effect of variety and seed harvesting maturity on 1000-seed weight, seed germination percentage, seedling dry weight and the seedling vigour indices (Mean ± SE).

Interaction	1000-seed weight (g)	Germination percentage (%)	Seedling dry weight (mg)	Seedling vigour index I	Seedling vigour Index II
IMARA × 60DAS	38.76 ± 0.38^{fg}	79 ± 0.87^{g}	6.36 ± 0.35^{fg}	2136.82 ± 68.38^{e}	501.4 ± 26.06^{h}
IMARA × 70DAS	45.1 ± 1.2^{abcde}	89 ± 1^{de}	7.82 ± 0.29^{e}	2379.72 ± 18.44^{cde}	694.41 ± 20.44^{f}
IMARA × 80DAS	48.87 ± 0.66^{a}	95.78 ± 1.4^{abc}	10.21 ± 0.24^{abcd}	2630.78 ± 43.53^{abc}	976.21 ± 16.74^{abcd}
IMARA × 90DAS	47.7 ± 1.05^{abc}	98 ± 0.8^{ab}	10.07 ± 0.04^{bcd}	2766.6 ± 32.34^{a}	986.54 ± 9.13^{abc}
NDURU × 60DAS	33.87 ± 0.49^{h}	82 ± 1.65^{fg}	4.34 ± 0.17^{h}	2223.2 ± 86.87^{de}	356.54 ± 16.23^{i}
NDURU × 70DAS	37.28 ± 0.69^{gh}	88.78 ± 0.74^{de}	5.4 ± 0.56^{gh}	2680.11 ± 122.85^{ab}	477.12 ± 46.69^{h}
NDURU × 80DAS	38.73 ± 0.55^{fg}	93.67 ± 1.12^{abcd}	9.6 ± 0.15^{cd}	2622.82 ± 35.61^{abc}	900.38 ± 24.46^{cde}
NDURU × 90DAS	39.5 ± 0.25^{fg}	92.67 ± 0.44^{abcd}	9.96 ± 0.27^{cd}	2726.54 ± 34.82^{a}	922.86 ± 27.09^{bcde}
NURU × 60DAS	41.7 ± 0.98^{def}	84.56 ± 1.07^{efg}	5.7 ± 0.19^{fg}	$2424.8\ 53.11^{bcd}$	481.17 ± 14.06^{h}
NURU × 70DAS	44.56 ± 1.01^{bcde}	91.33 ± 2.37^{cd}	9.62 ± 0.15^{cd}	2623.17 ± 59.99^{abc}	878.59 ± 24.94^{de}
NURU × 80DAS	44.81 ± 0.97^{bcde}	93 ± 0.71^{abcd}	10.23 ± 0.03^{abcd}	2746.87 ± 48.59^{a}	951.71 ± 8.08^{bcde}
NURU × 90DAS	45.28 ± 0.37^{abcde}	98.44 ± 0.71^{a}	10.46 ± 0.15^{abc}	2872.21 ± 53.41^{a}	1029.49 ± 18.39^{ab}
TG 1 × 60DAS	42.28 ± 0.52^{def}	85.33 ± 1.89^{ef}	6.86 ± 0.31^{ef}	2372.51 ± 42.38^{cde}	580.9 ± 15.41^{gh}
TG 1 × 70DAS	43.6 ± 0.57^{de}	92.22 ± 1.27^{bcd}	9.38 ± 0.08^{cd}	2624.29 ± 37.88^{abc}	864.87 ± 14.31^{e}
TG 1 × 80DAS	43.94 ± 0.85^{cde}	96.67 ± 0.88^{abc}	11.18 ± 0.12^{ab}	2706.48 ± 28.03^{a}	1080.79 ± 17.47^{a}
TG 1 × 90DAS	43.88 ± 0.24^{cde}	94.44 ± 0.97^{abcd}	11.36 ± 0.11^{a}	2784.19 ± 37.59^{a}	1072.41 ± 14.77^{a}
TG 2 × 60DAS	41.51 ± 1.3^{ef}	95.33 ± 0.85^{abc}	6.49 ± 0.18^{fg}	2830.03 ± 59.08^{a}	619.2 ± 20.34^{fg}
TG 2 × 70DAS	45.29 ± 0.73^{abcde}	96.78 ± 0.76^{abc}	9.1 ± 0.07^{d}	2901.69 ± 25.42^{a}	880.46 ± 6.32^{cde}
TG 2 × 80DAS	48.01 ± 0.74^{ab}	96.44 ± 0.65^{abc}	10.19 ± 0.07^{abcd}	2812.47 ± 58.28^{a}	982.93 ± 12.45^{abcd}
TG 2 × 90DAS	45.36 ± 0.36^{abcd}	95.33 ± 0.87^{abc}	11.21 ± 0.32^{ab}	2768.39 ± 48.83^{a}	1068.03 ± 28.25^{a}

Note: For each factor, means within the same column that share superscript lowercase letters are not significantly different at $p \leq 0.05$ based on Tukey's HSD test. The bold values are the *p*-Value for each parameter including the interaction.
Abbreviations: DAS, Day's after sowing; TG1, TARI green gram 1; TG2, TARI green gram 2.

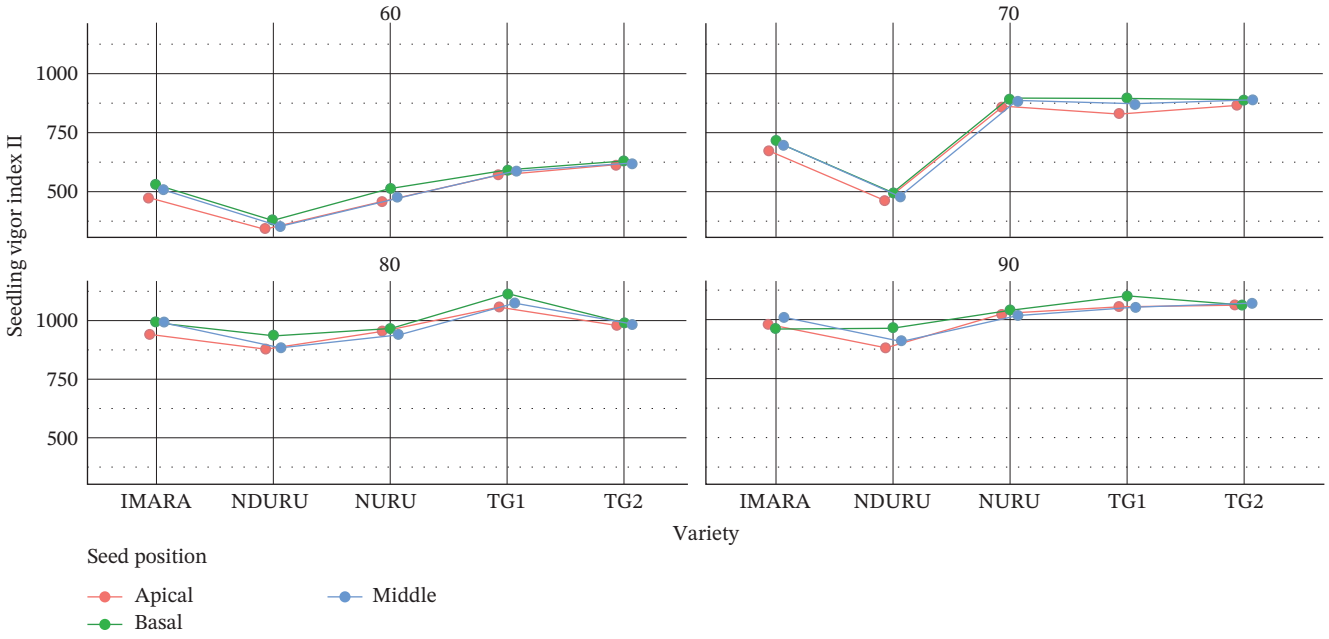


FIGURE 4 | Interaction of variety, harvesting maturity and seed position in the pod on seedling vigour index II.

other traits, seed position had a significant effect ($p = 0.019$), with vigour increasing from apical to basal pod sections. While most varieties followed this pattern, some deviations were observed, particularly at 90 DAS (Figure 4).

3.3 | Correlation Relationship Between Seed Quality Parameters

Correlation analysis revealed that the GP was positively associated with 1000-seed weight ($r = 0.534$, $p < 0.001$), suggesting that heavier seeds tend to have higher germination rates. There was also a strong positive correlation between seedling length and vigour index I ($r = 0.754$, $p < 0.001$), highlighting the influence of seedling length on vigour. In contrast, GP showed a negative correlation with the proportion of abnormal seedlings ($r = -0.469$, $p < 0.001$), indicating that higher germination rates are associated with fewer abnormal seedlings. Furthermore, 1000-seed weight displayed a weak positive correlation with average pod length ($r = 0.38$, $p < 0.001$) and a negative correlation with the average number of seeds per pod ($r = -0.4$, $p < 0.001$). The average pod length was also weakly positively correlated with seeds per pod and negatively correlated with the percentage of abnormal seedlings (Table 5).

4 | Discussion

4.1 | The Effect of Variety on Seed Quality Parameters

The differences in average pod length among mung bean varieties are due to genetic factors that affect pod development. Other crops also show that organ size is controlled by genetics, suggesting pod

TABLE 5 | The correlation coefficients among seed quality attributes and pod characteristics.

Seed quality parameter	1000SW	GP (%)	%AbS	SeedL	SV I	SeedrW	SV II	AvL	AsP
1000SW	1	—	—	—	—	—	—	—	—
GP (%)	0.53***	1	—	—	—	—	—	—	—
%AbS	−0.46***	−0.47***	1	—	—	—	—	—	—
SeedL	0.12	0.22**	−0.19*	1	—	—	—	—	—
SV I	0.43***	0.80***	−0.42***	0.75*	1	—	—	—	—
SeedrW	0.61***	0.61***	−0.56***	0.14	0.49***	1	—	—	—
SV II	0.63***	0.74***	−0.57***	0.15*	0.58	0.98***	1	—	—
AvL	0.38***	0.14	−0.17*	−0.19**	−0.02	0.12	0.13	1	—
AsP	−0.4***	−0.11	0.13	−0.21**	−0.21***	−0.31***	−0.29***	0.28***	1

Note: 1000SW = Thousand seed weight, GP (%) = Germination percentage, %AbS = Percentage of abnormal seedlings, SeedL = Average seedling length, SV I = Seedling vigour index I, SV II = Seedling vigour index II, SeedrW = Seedling dry weight, AvL = Average pod length and AsP = Average seeds per pod.
*Significant at $p < 0.05$.
**Significant at $p < 0.01$.
***Significant at $p < 0.001$.

length is determined by inherited traits [27, 28]. Most varieties reached near-maximum pod development by 60 DAS, with limited growth afterward, consistent with Dracup and Kirby [29], who observed rapid pod elongation after setting in narrow-leaf lupin. The significant variety and maturity interaction suggests differing growth rates across genotypes, as seen in Nduru, which elongated notably between 60 and 90 DAS, likely due to differences in cell division, growth rate, or resource allocation [30].

Variation in seed number per pod was likewise genotype-dependent, consistent with reports that ovule number, fertilisation efficiency and floral architecture are under strong genetic control [30]. The absence of a harvesting maturity effect indicates that seed number is determined early during pod development and remains stable thereafter [31]. Although a positive association between pod length and seed number was observed, shorter pods, such as those of Nduru, occasionally produced more seeds, suggesting that internal seed arrangement and size also influence final seed count [32].

Genotypic differences were also evident in 1000-seed weight, GP, seedling growth and vigour indices. Higher seed weight in Imara and TG2 indicates superior seed-filling capacity, reflecting differences in seed-filling rate and duration [33, 34]. These differences translated into improved physiological performance, with TG2 consistently exhibiting higher germination and vigour. Seed weight is closely associated with reserve accumulation, which supports early seedling establishment [35]. In contrast, Nduru produced lighter seeds and exhibited a higher proportion of abnormal seedlings, supporting the notion that lighter seeds are more susceptible to developmental deficiencies [36]. Genetic factors affecting seed coat permeability, dormancy and hormonal signalling pathways can also explain the pattern observed in GP [37, 38].

Although larger seeds generally produced more vigorous seedlings, the observation that Nduru seedlings were longer despite lower seed weight suggests that seedling elongation is not solely determined by seed mass but also by genetic differences in reserve mobilisation efficiency and growth strategy. Overall, varietal performance in vigour indices reflects integrated effects of seed size, physiological quality and genetic control over reserve utilisation, a finding supported by Golijan-Pantović et al. [35] and Ambika et al. [39]. The strong positive association between GP and seed vigour indices provides additional evidence for this relationship.

4.2 | The Effect of Harvesting Maturity on Seed Quality Parameters

Delayed harvesting significantly enhanced seed weight, germination, seedling growth and vigour indices, indicating progressive reserve accumulation during seed development. Increased 1000-seed weight up to 80 DAS reflects continued deposition of carbohydrates, proteins and lipids during the seed-filling phase, as per findings by Begum and Ayub [31], Aswin et al. [40] and Groot [41]. The slight decline at 90 DAS suggests the onset of field weathering or deterioration due to prolonged exposure after physiological maturity, as reported by Martins et al. [42].

Lower germination and higher abnormal seedlings at 60 DAS confirm that premature harvesting results in incomplete physiological development [43]. Improvement in germination up to 90 DAS indicates attainment of physiological maturity; however, the slight increase in abnormalities at the final stage suggests early deterioration under field stress. Enhanced seedling length, dry weight and vigour indices at later harvest stages further demonstrate the importance of adequate reserve accumulation. Seed vigour improves once a critical threshold of stored reserves is reached, enabling rapid and uniform seedling establishment [19]. Although extended field exposure may eventually reduce physiological quality, the overall trend suggests that harvesting at or slightly after physiological maturity optimises seed performance.

4.3 | The Effect of Seed Position in the Pod on Seed Quality Parameters

Seed position within the pod significantly affected 1000-seed weight and GP, with seeds at the basal end exhibiting superior quality traits due to earlier development and longer filling and after-ripening periods. Basu and Groot [44] reported that assimilate partitioning favours basal seeds due to their proximity to the vascular connection to the mother plant. The findings of the highest seed weight, the highest GP and the lowest abnormal seedling rate at the basal end align with Adie et al. [17], who reported comparable results in cowpea. Seedling length, dry matter and vigour indices followed a similar trend. Despite minor variations in dry weight, the significance of the seedlings' vigour index II reflects the compounding effects of higher GP, as Sharma [25] reported.

4.4 | The Interaction Effect on the Seed Quality Parameters

The notable interaction between variety and harvest maturity for 1000-seed weight, germination rate, seedling dry weight and vigour indices suggests that differences in seed reserve accumulation and use depend on genotype. While Kara et al. [45] and Tetteh et al. [46] reported seed weight as relatively stable across interactions, the present findings suggest that varietal differences in reserve deposition and tolerance to delayed harvest can alter final seed performance. Variability in reserve mobilisation efficiency among genotypes likely contributed to differences in seedling vigour, consistent with Padilha et al. [47]. The decline in vigour observed at 90 DAS in TG1 and TG2 further demonstrates the adverse effects of delayed harvesting beyond physiological maturity, as similarly reported by Martins et al. [42]. Moreover, the positive association between higher seed weight and improved germination and vigour supports earlier findings that heavier seeds generally exhibit superior physiological performance [48].

The absence of significant interactions between variety and seed position suggests that seed-filling patterns and pod structural characteristics are broadly similar across genotypes. In legumes, assimilate partitioning typically favours basal seeds due to earlier development and proximity to vascular connections [49], which may explain their relatively superior performance. Although minor deviations were observed, such as slightly higher seed weight in the middle section for Imara, these differences likely reflect genotype-specific pod architecture rather than fundamental changes in assimilate distribution. Similarly, the lack of harvesting maturity × seed position interaction indicates that physiological maturity was largely synchronised across pod

sections at harvest. Variations in pod length and seed number among varieties may explain occasional inconsistencies in seed weight trends with delayed harvesting, as noted by Sakthivel et al. [50]. The nonsignificant three-way interaction further suggests that seed quality stabilises at maturity across varieties and pod positions.

5 | Conclusion and Recommendation

This study demonstrated that genotype, harvesting maturity and seed position within the pod significantly influence mung bean seed quality. Varieties exhibiting favourable morphological traits, such as higher 1000-seed weight, higher GP and improved seedling vigour. Seeds harvested 70–80 DAS achieved the best overall quality, indicating that timely harvest at or near physiological maturity enables optimal reserve accumulation and seed development. Seeds located at the basal end of the pod generally outperformed those from middle and apical positions, reflecting earlier fertilisation and more effective assimilate partitioning. The lack of a significant interaction among variety, harvesting maturity and seed position indicates that, after physiological maturity is reached, seed quality remains consistent across different genotypes and pod positions.

These findings emphasise that selecting genotypes with favourable pod and seed morphological traits, combined with harvesting at optimal maturity, can enhance seed quality and support sustainable production. For practical application, mung bean farmers and seed producers should focus on monitoring pod development and harvesting seeds at physiological maturity, while paying attention to seed positioning to ensure high-quality seed selection. Future research should examine how these factors interact under variable environmental conditions and storage conditions to inform broader strategies to improve seed quality and yield in mung bean and related legume crops.

Author Contributions

Sosoma James Makungu was responsible for conceptualisation, methodology, conducting field trials, collecting laboratory data, data curation, formal analysis, investigation, visualisation and drafting the original manuscript. Liberatus Dominick Lyimo contributed to conceptualisation, methodology, supervision, validation, visualisation, as well as reviewing and editing the original draft. George Muhamba Tryphone handled conceptualisation, project administration and review of the original draft.

Acknowledgments

The authors gratefully acknowledge the Tanzania Agricultural Research Institute (TARI) – Ilonga Station for supplying the seed materials for this study. We are especially grateful to Samueli Mahalu for his expert technical assistance in the field and to Jackson Bagilisha for his committed support in the laboratory. We also thank Mwalimu Nyerere University of Agriculture and Technology for their vital financial contribution, which enabled this research. The authors declare that no Generative AI was used to create this manuscript.

Funding

The authors state that funding for data collection was provided exclusively by the Mwalimu Nyerere University of Agriculture and Technology.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors will provide the raw data supporting this article's conclusions upon request, without unnecessary restrictions.

References

1. S. Udayasri, G. R. Lavanya, and G. M. Lal, "Estimation of Variability and Genetic Divergence in Greengram [*Vigna radiata* (L.) Wilczek] for Yield Characters," *International Journal of Plant & Soil Science* 34, no. 23 (2022): 49–56.

2. G. Mohan Naik, P. Abhirami, and N. Venkatachalapathy, "Mung Bean," in *Pulses: Processing and Product Development*, (Springer International Publishing, 2020): 213–228.

3. P. B. Manjunatha, R. Harisha, M. Kohli, et al., "Exploring the World of Mung Bean: Uncovering its Origins, Taxonomy, Genetic Resources, and Research Approaches," *International Journal of Plant & Soil Science* 35, no. 20 (2023): 614–635.

4. M. Huppertz, D. Kachhap, A. Dalai, et al., "Exploring the Potential of Mung Bean: From Domestication and Traditional Selection to Modern Genetic and Genomic Technologies in a Changing World," *Journal of Agriculture and Food Research* 14 (2023): 100786.

5. B. HanumanthaRao, R. M. Nair, and H. Nayyar, "Salinity and High Temperature Tolerance in Mungbean [Vigna radiata (L.) Wilczek] from a Physiological Perspective," *Frontiers in Plant Science* 7 (2016): 957.

6. Y. Kassa, A. Abie, D. Mamo, and T. Ayele, "Exploring Farmer Perceptions and Evaluating the Performance of Mung Bean (*Vigna radiata*, L) Varieties in the Amhara Region, Ethiopia," *Heliyon* 8, no. 12 (2022): e12525.

7. R. M. Nair, "Establishing the International Mung Bean Improvement Network," 2022, Final report https://www.cabidigitallibrary.org/doi/full/10.5555/20220252831, 1-118 ISBN: 978-1-922787-09-5.

8. P. Schreinemachers, T. Sequeros, S. Rani, et al., "Counting the Beans: Quantifying the Adoption of Improved Mungbean Varieties in South Asia and Myanmar," *Food Security* 11, no. 3 (2019): 623–634.

9. F. Mmbando, E. Mbeyagala, P. Binagwa, et al., "Adoption of Improved Mungbean Production Technologies in Selected East African Countries," *Agriculture* 11, no. 6 (2021): 528.

10. R. M. Nair, R. Y. Yang, W. J. Easdown, et al., "Biofortification of Mungbean (*Vigna radiata*) as a Whole Food to Enhance Human Health," *Journal of the Science of Food and Agriculture* 93, no. 8 (2013): 1805–1813.

11. E. Kisetu and C. N. Medutieki, "Response of Green Gram (*Vigna Radiata* L.) to an Application of Minjingu Mazao Fertilizer Grown on Olasiti Soils From Minjingu-Manyara, Tanzania," *Pakistan Journal of Biological Sciences* 16, no. 22 (2013): 1601–1604.

12. T. Sequeros, J. Ochieng, P. Schreinemachers, et al., "Mungbean in Southeast Asia and East Africa: Varieties, Practices and Constraints," *Agriculture & Food Security* 10, no. 1 (2021): 1–13.

13. J. A. Iqbal, S. Muhammad, and A. Muhammad, "Appraisal of Gene Action for Indeterminate Growth in Mung Bean [*Vigna radiata* (L.) Wilczek]," 6 (2015).

14. S. M. A. Rahman and A. R. Ansori, "An Assessment of Rice Seed Quality at Various Physiological Harvest Maturity Stages," *Gading Journal of Science and Technology (e-ISSN* 4, no. 1 (2021): 55–61, 2021, https://ir.uitm.edu.my/id/eprint/46247/.

15. W. E. Finch-Savage and G. Leubner-Metzger, "Seed Dormancy and the Control of Germination," *New Phytologist* 171, no. 3 (2006): 501–523.

16. R. Vergara, R. N. O. da Silva, A. P. Nadal, G. I. Gadotti, T. Z. Aumonde, and F. A. Villela, "Harvest Delay, Storage, and Physiological Quality of Soybean Seeds," *Journal of Seed Science* 41, no. 4 (2019): 506–513.

17. M. M. Adie, A. Krisnawati, and R. T. Hapsari, "The Effect of Seed Position in Pod on The Seed Viability of Cowpea (*Vigna unguiculata*)," *Biosaintifika: Journal of Biology & Biology Education* 11, no. 1 (2019): 68–76.

18. K. U. Ekwealor, C. F. Iroka, V. C. Okezue, W. C. Anyanele, and H. N. Eze, "Effect of Seed Position in the Pod on the Germination and Development of *Telfairia occidentalis*," *Asian Plant Research Journal* 3, no. 3-4 (2020): 1–6.

19. K. V. Sripathy and S. P. C. Groot, "Seed Development and Maturation," in *Seed Science and Technology: Biology, Production, Quality*, (Springer, 2023): 17–38.

20. D. M. M. Mulungu and S. E. Munishi, "Simiyu River Catchment Parameterization Using the SWAT Model by 1 Deogratias M.M," *Physics and Chemistry of the Earth, Parts A/B/C* 32, no. 15–18 (2007): 1032–1039.

21. M. K. Muchomba, E. M. Muindi, and J. M. Mulinge, "Overview of Green Gram (*Vigna radiata* L.) Crop, Its Economic Importance, Ecological Requirements, and Production Constraints in Kenya," *Journal of Agriculture and Ecology Research International* 24, no. 2 (2023): 1–11.

22. B. R. Bobade, B. V. Asewar, S. M. Nikam, and K. K. Dakhore, "Thermal Requirement of Green Gram (*Vigna radiata* L.) Varieties at Different Phenological Stages Under Varied Weather Conditions," *International Journal of Current Microbiology and Applied Sciences* 8, no. 12 (2019): 925–930.

23. S. J. Makungu, L. D. Lyimo, and G. M. Tryphone, "Influence of Variety and Harvesting Stage on Germination and Vigour of Mung Bean (*Vigna radiata*) Seeds," *Discover Agriculture* 4, no. 1 (2026): 94.

24. ISTA, "Introduction to the ISTA Rules, Chapters 1–19," *International Rules for Seed Testing*no. 1 (2018).

25. S. Sharma, "Seed Vigour Testing: Principles and Methods," *Agrobios Newsletter* 17, no. 2 (2018): 80–82.

26. A. Bhuker, M. S. Harish, M. S. Raj, V. S. Mor, and R. Duhan, "Effect of Pod Maturity on Seed Quality Parameters of Green Gram (*Vigna radiata*) Seeds," *Journal of Food Legumes* 36, no. 4 (2024): 308–311.

27. A. S. Basaroh, M. Afiyanti, J. Kusnadi, et al., "Genes Responsible in the Shape and Size of Solanaceae Fruits," *BIO Web of Conferences* 94 (2024): 05006.

28. C. Wang, J. Cao, N. Hao, and T. Wu, "Genetic and Molecular Regulation Mechanisms in the Formation and Development of Vegetable Fruit Shape," *Applied Sciences (Switzerland)* 12, no. 3 (2022): 1514.

29. M. Dracup and E. J. M. Kirby, "Pod and Seed Growth and Development of Narrow-Leafed Lupin in a Water-Limited Mediterranean-Type Environment," *Field Crops Research* 48, no. 2-3 (1996): 209–222.

30. M. Rahim, A. Mia, F. Mahmud, N. Zeba, and K. Afrin, "Genetic Variability, Character Association and Genetic Divergence in Mungbean (Vigna radiata L. Wilczek)," *Plant Omics* 3, no. 1 (2010): 1–6.

31. F. Begum and G. Ayub, "Effect of Harvesting Stage on Yield and Quality of Okra (*Abelmoschus esculentus* L. Moench) Seed," *Sarhad Journal of Agriculture* 38, no. 3 (2022): 871–884.

32. G. Rabani, M. Tariq, M. K. Naeem, and M. S. Iqbal, "Character Association and Path Analysis of Yield and Yield Components in Mungbean," *Pakistan Journal of Agricultural Research* 53, no. 2 (2015): 165–172.

33. A. Dayal, N. R. Rangare, A. Kumar, and M. Kumari, "Effect of Physiological Maturity on Seed Quality of Maize (*Zea mays* L.)," *Forage Research* 40, no. 1 (2014): 1–6, 2014, https://forageresearch.in/wp-content/uploads/2014/06/1-6.pdf.

34. A. Yadav, R. Yadav, M. S. Singh, C. Maurya, Y. Singh, and R. Pratap, "Study of Gene Action for Yield and its Contributing Traits in Green Gram (Vigna radiata L. Wilczek)," *International Journal of Statistics and Applied Mathematics* 8, no. 6S (2023): 1049–1053.

35. J. Golijan-Pantović, V. Popović, M. Sečanski, A. Popović, O. Đorđević Melnik, and L. Šarčević Todosijević, "Factors Affecting Seed Vigour," *Agriculture and Forestry* 70, no. 3 (2024): 85–103.

36. X. Shu, X. Yang, and Z. Yang, "Variation in Seed and Seedling Traits among Fifteen Chinese Provenances of *Magnolia officinalis*," *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 40, no. 2 (2012): 274–283.

37. P. C. Nautiyal, K. Sivasubramaniam, and M. Dadlani, "Seed Dormancy and Regulation of Germination," in *Seed Science and Technology: Biology, Production, Quality*, (Springer, 2023): 39–66.

38. J. Zhao, Y. He, H. Zhang, and Z. Wang, "Advances in the Molecular Regulation of Seed Germination in Plants," *Seed Biology* 3, no. 1 (2024): e006.

39. S. Ambika, V. Manonmani, and G. Somasundaram, "Review on Effect of Seed Size on Seedling Vigour and Seed Yield," *Research Journal of Seed Science* 7, no. 2 (2014): 31–38.

40. C. Aswin, R. Geetha, K. Sujatha, C. Vanniarajan, and T. Sivakumar, "Effect of Harvesting Time on the Seed Quality of Hybrid Maize (*Zea mays* L.) COHM. 8," *Agricultural Science Digest - A Research Journal* 43 (2023): 622–629.

41. S. P. C. Groot, "Seed Maturation and its Practical Implications," *Seed Science and Technology* 50, no. 2 (2022): 141–151.

42. A. G. Martins, C. Z. Alves, A. M. Zuffo, et al., "Impact of Harvest Delay on the Physiological and Sanitary Quality of Sorghum sp," *Seeds. Revista Ciência Agronômica* 55 (2024): 1–9.

43. O. T. Isaac, B. K. Banful, S. Amoah, S. Apuri, and E. A. Seweh, "Effect of Harvesting Stages on Seed Quality Characteristics of Three Soybean (*Glycine Max* (L) Merrill) Varieties," *Journal of Scientific and Engineering Research* 3, no. 4 (2016): 326–333.

44. S. Basu and S. P. C. Groot, "Seed Vigour and Invigouration," in *Seed Science and Technology: Biology, Production, Quality*, (Springer, 2023): 67–89.

45. N. Kara, G. Gürbüzer, M. Bıyıklı, and H. Baydar, "Effect on Yield and Some Quality Characteristics of Seed Harvest at Different Stages of Maturity in *Nigella sativa* L," *Journal of Agricultural Sciences* 27, no. 3 (2021): 341–346.

46. R. Tetteh, L. M. Aboagye, R. Darko, and E. A. Osafo, "Effect of Maturity Stages on Seed Quality of Two Tomato Accessions," *African Crop Science Journal* 26, no. 2 (2018): 237.

47. M. S. Padilha, C. M. M. Coelho, and G. C. De Andrade, "Seed Reserve Mobilization Evaluation for Selection of High-Vigor Common Bean Cultivars," *Revista Caatinga* 33, no. 4 (2020): 927–935.

48. B. Nigussu, T. Bulti, and F. Asnake, "Assessment of Seed Quality Parameters in Different Seed Sources of Chickpea (*Cicer arietinum* (L.)," *African Journal of Agricultural Research* 14, no. 33 (2019): 1649–1658.

49. E. J. Bennet, J. A. Robert, and C. Wagstaff, "The Role of the Pod in Seed Development: Strategies for Manipulating Yield," *New Phytologist* 190, no. 4 (2011): 838–853.

50. S. Sakthivel, J. Renugadevi, K. Raja, and R. Swarnapriya, "Effect of Maturity Stages on Seed Quality in Winged Bean [*Psophocarpus tetragonolobus* (L.) DC.] – A Multipurpose Legume," *Madras Agricultural Journal* 107, no. 4–6 (2020): 4–9.