

Radicle Emergence Test of Various Sorghum Varieties (*Sorghum bicolor* (L.) Moench) Using the Between Paper and Top of Paper Germination Methods

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Abstract: High reliance on rice and limited national production drive the need to develop sorghum as an alternative food crop. This development requires high-quality seed and rapid, reliable testing methods. This study evaluated the effect of germination methods on radicle emergence (RE), assessed varietal differences in RE rate, and examined the ability of the RE test to estimate germination percentage (GP). The experiment used a nested design with germination method as the main factor, between paper and top of paper, and five sorghum varieties nested within each method, namely Mandau, Super 1, Bioguma 1, Bioguma 2, and Bioguma 3, with four replications. Top of paper detected radicle emergence earlier than between paper, with the optimal observation time at 48 hours. Super 1 showed the highest RE and GP, followed by Bioguma 3, while Mandau and Bioguma 2 showed lower performance. Regression analysis between RE and GP produced the equation $y = 1.038x - 3.32$ with $R^2 = 0.7474$, indicating a strong positive relationship. These results demonstrate that RE observation at 48 hours provides a rapid and accurate indicator of sorghum seed viability and supports the selection of superior varieties for seed production.

Keywords: Germination percentage; *Radicle emergence*; Sorghum; Rapid test

Introduction

Food is a basic human need that plays a strategic role in national food security. In Indonesia, food consumption is still dominated by rice, with per capita consumption reaching 92.1 kg per year (National Food Agency of Indonesia, 2025). This condition is not matched by national production, which in 2024 reached only 30.62 million tons, a decrease of 1.54% compared to the previous year (Statistics Indonesia, 2025b). Continuous population growth increases rice demand and has driven import policies, with imports exceeding 4.5 million tons in 2023 (Statistics Indonesia, 2025a). This high dependence on a single food commodity highlights the importance of developing alternative food sources.

Sorghum is one of the cereal crops with strong potential as an alternative food source due to its high carbohydrate content and its global importance after wheat, rice, maize, and barley (Hossain et al., 2022). Sorghum development in Indonesia is directed toward

three main objectives, namely food, feed, and bioenergy, in accordance with the 2022–2024 development roadmap (Ministry of Agriculture of the Republic of Indonesia, 2021). However, the realization of the planting area remains low, at approximately 4,355 ha in 2023 with an average productivity of 2 tons per hectare, far below the target of 40,000 ha (Coordinating Ministry for Economic Affairs of the Republic of Indonesia, 2022). In fact, the potential area for sorghum development in Indonesia is estimated to exceed 100,000 ha across several provinces (Ministry of Investment of the Republic of Indonesia, 2023).

Increasing sorghum production strongly depends on the availability of high-quality seeds. Seeds play a direct role in determining uniform emergence, early seedling vigor, and yield potential in the field (Safitri et al., 2025). In Indonesia, sorghum seed availability is still dominated by the Breeder Seed class, making the involvement of seed growers essential to produce Foundation Seed, Stock Seed, and Certified Seed to

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ensure sustainable seed supply for farmers (Rochmadi, 2022). Seed quality is a key factor in cultivation success because it influences germination capacity and the ability of seedlings to adapt during the early growth stages (Copeland & McDonald, 1999). Seed quality evaluation is commonly conducted using the standard germination test. However, this method requires a relatively long time, approximately 4 to 10 days, making it less efficient for rapid decision-making in seed production and distribution systems (ISTA, 2021; Matthews & Powell, 2011).

As an alternative to accelerate seed quality testing, the radicle emergence method has been introduced as a rapid vigor test recommended by ISTA since 2014. This method evaluates radicle protrusion within a short time as an early indicator of seed growth potential (Khusna et al., 2021; Budiman et al., 2024). In Indonesia, this method has been developed and applied to rice, maize, and soybean with much shorter observation times than the standard method through Circular Letter No. 84/LB.010/C.3/8/2022 issued by BBPPMBTPH.

Radicle emergence testing in sorghum seeds can be conducted using the top of paper and between paper methods, which differ in aeration and moisture stability (ISTA, 2021). These factors directly affect oxygen and water availability, thereby influencing the rate and uniformity of radicle emergence. In wheat seeds, the between paper method has been reported to produce more consistent radicle emergence and germination data than the top of paper method (Bhuker et al., 2020). Similar findings have been reported in other food crops, such as maize and barley, where greater moisture stability in the between paper method is associated with more uniform germination (Abadia et al., 2024; Sedghi et al., 2010). However, scientific information on the application of these methods to sorghum seeds remains limited. Most studies on sorghum seed quality still focus on conventional germination parameters, while the use of radicle emergence as an early indicator of seed vigor has received little attention (Lazim, 2025; Muui et al., 2020). Therefore, further research on radicle emergence testing across different sorghum varieties in Indonesia is required to strengthen its scientific basis and to support the development of sorghum as a strategic food crop for improving productivity and promoting food diversification.

The radicle emergence test in sorghum seeds can be conducted using the top of paper and between paper methods, which differ in seed placement and media characteristics. The top of paper method provides better aeration that supports early embryo respiration, but the moisture conditions tend to fluctuate more rapidly because the paper surface is directly exposed to air (ISTA, 2021). In contrast, the between paper method maintains more stable moisture because the seeds are

sandwiched between paper sheets, allowing more uniform and continuous water uptake. This condition is critical during the imbibition phase, which strongly influences the speed and uniformity of radicle emergence. Studies on wheat have shown that the between paper method produces more uniform radicle emergence and germination compared to the top of paper method, particularly during early observation periods (Bhuker et al., 2020). Similar results have been reported in other cereal crops, where media moisture stability plays a key role in germination uniformity (Bewley et al., 2013 (Bewley et al., 2013); Marcos-filho, 2015). However, the response of sorghum seeds cannot be directly equated with other species due to differences in seed size, testa thickness, and water imbibition dynamics, which affect radicle emergence patterns.

Based on this information gap, this study aims to evaluate the effects of between paper and top of paper germination methods on radicle emergence test results in several sorghum varieties. The study also analyzes varietal differences in the rate of radicle emergence and assesses the ability of the radicle emergence test to provide an early estimation of sorghum seed germination capacity compared with the standard germination test.

Research on the application of the radicle emergence test in sorghum seeds is still limited, particularly in determining the optimal observation time as an early indicator of seed quality. Scientific information on optimal radicle emergence timing under between paper and top of paper methods is not yet available. The novelty of this study lies in identifying the optimal radicle emergence time for different sorghum varieties and comparing the effectiveness of both methods in predicting germination. The results are expected to fill existing knowledge gaps and support the development of a rapid radicle emergence testing standard for sorghum seeds to accelerate seed quality assessment and promote sorghum development in Indonesia.

Method

Research Location and Period

The research was conducted in the laboratory and greenhouse of the Technical Implementation Unit of the Seed Inspection and Certification Agency for Food, Horticultural, and Plantation Crops of Bali Province. The study took place from October to November 2025.

Materials and Tools

The materials used in this study included sorghum seeds, CD paper, sand, polyethylene plastic, distilled water, well water, labels, and markers. The equipment used consisted of trays, tweezers, a germinator, testing

boxes, a digital thermometer, a timer, a camera, a ruler, a purity table, an analytical balance, a divider, plastic dishes, a grinder, aluminum dishes, a spoon, an oven, brushes, a watering can, a sprayer, and Microsoft Excel software.

Experimental Design

This study employed a Nested Design, in which the germination method served as the main factor (main plot) and sorghum variety as the nested factor (sub plot). The germination method consisted of two levels, *Between Paper* (BP) and *Top of Paper* (TP). The variety factor consisted of five levels, Mandau, Super 1, Bioguma 1, Bioguma 2, and Bioguma 3. These factors were combined to obtain ten treatment combinations, namely BP-Mandau, BP-Super 1, BP-Bioguma 1, BP-Bioguma 2, BP-Bioguma 3, TP-Mandau, TP-Super 1, TP-Bioguma 1, TP-Bioguma 2, and TP-Bioguma 3. Each combination was replicated five times, resulting in a total of 50 experimental units.

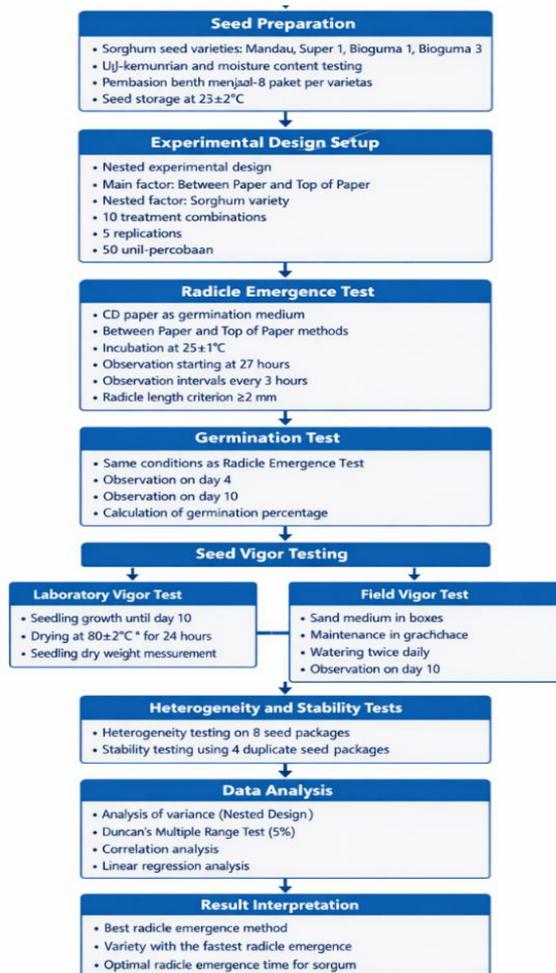


Figure 1. Research workflow

Experimental Procedures

Before testing, sorghum seeds from five varieties (Mandau, Super 1, Bioguma 1, Bioguma 2, and Bioguma

3) were prepared by ensuring uniformity and quality. Seed purity and moisture content were assessed, then the seeds were divided using a divider into eight packages. Four packages were used for testing and four were kept as reserves. All seeds were stored in a controlled-temperature room at 25±2°C until testing.

The radicle emergence (RE) test followed the procedures of the International Seed Testing Association. CD paper moistened with distilled water to optimal moisture served as the germination medium. In the *Between Paper* (BP) method, seeds were placed between two layers of CD paper, rolled, and enclosed in plastic. In the *Top of Paper* (TP) method, seeds were arranged on CD paper in a transparent box. The media and seeds were placed in a germinator set at 25±1°C. Observations began 27 hours after the start of germination and continued at three hour intervals until no additional radicles emerged. Seeds with radicles of at least 2 mm were counted as germinated to calculate the RE percentage.

The germination percentage (GP) also followed the International Seed Testing Association procedures. The medium and procedures were the same as in the RE test. Observations were made on day 4 and day 10 after sowing. Normal seedlings were counted according to International Seed Testing Association criteria to determine the germination percentage.

Seed vigor testing was carried out in both laboratory and field conditions. The laboratory vigor test used CD paper with the same germination conditions as the GT. On day 10, normal seedlings were dried in an oven at 80±2°C for 24 hours to determine seedling dry weight. The field vigor test used sand media placed in boxes that were moistened and kept in a greenhouse. Watering was carried out twice daily and observations were made on day 10 using the same assessment criteria.

Heterogeneity and stability tests were performed to ensure consistency of seed quality. Heterogeneity was evaluated through germination testing on eight packages of seeds from each variety. Stability was assessed by comparing the germination percentage results of four duplicate seed packages with those of the main test.

Data Analysis

Data from the radicle emergence (RE) and germination percentage (GP) were analyzed using analysis of variance based on the Nested Design to determine the effects of germination method and sorghum variety on the observed parameters. When significant effects were detected, Duncan’s Multiple Range Test at a 5% significance level was applied to compare treatments. Correlation and linear regression analyses between RE and GT values were conducted to

assess the strength of the relationship and the ability of the rapid RE test to predict sorghum seed germination.

Result and Discussion

Effect of Germination Methods and Varieties on the Rate of Radicle Emergence in Sorghum

a. Radicle Emergence (%)

Analysis of variance (ANOVA) showed that the germination method had a highly significant effect on radicle emergence at 30 to 48 hours ($p < 0.01$), a significant effect at 27 hours ($p < 0.05$), and no significant effect at 51 and 54 hours ($p > 0.05$). The variety factor within the method (sub plot) had a highly significant effect at all observation times ($p < 0.01$). The 5% Duncan's Multiple Range Test (Table 1) indicated significant differences between the *Top of Paper* (TP) and *Between Paper* (BP) methods during the early germination phase.

At 27 to 33 hours, seeds in the TP method showed faster radicle emergence than BP. At 33 hours, radicle emergence in TP reached 59%, while BP reached 35%. This difference persisted until 42 hours, when TP exceeded 80% and BP remained lower. After 45 to 51 hours, the difference declined, and at 51 hours both methods reached nearly equal emergence at approximately 94%. This indicates that TP was more efficient for detecting early germination, while both methods were equally effective for assessing seed viability. The faster emergence in TP was likely due to better aeration and stable moisture on the seed surface, supporting imbibition and rapid metabolic activation, consistent with Zhang et al. (2020) and Sghaier et al. (2022).

Differences among varieties were also significant at all observation times. In the early phase (27 to 30 hours), Bioguma 3 showed the highest radicle emergence (13.9 to 32.5%), followed by Super 1 and Mandau (5.9 to 26.3% and 3.5 to 25.6%). Bioguma 1 (4.4 to 20.6%) and Bioguma 2 (0.6 to 4.4%) were slower, indicating the highest early vigor in Bioguma 3 (Diaguna et al., 2024). In the mid-phase (33 to 39 hours), Super 1 increased sharply from

60.3% to 93.8%, which was significantly higher than other varieties. Bioguma 3 (58.4 to 85.3%) and Mandau (53.5 to 84.2%) formed an intermediate group, while Bioguma 1 (45.0 to 79.1%) and Bioguma 2 (18.1 to 65.9%) showed moderate growth. This pattern indicates higher metabolic efficiency in Super 1 during imbibition and radicle elongation.

In the later phase (42 to 45 hours), Super 1 remained highest (96.3 to 97.7%). Mandau (89.9 to 92.2%) and Bioguma 3 (90.0 to 91.3%) were intermediate, while Bioguma 1 (85.9 to 88.1%) and Bioguma 2 (78.1 to 83.7%) were lower. Toward the end of observation (48 to 54 hours), varietal differences decreased as all viable seeds had produced radicles. At 51 hours, Super 1 was highest (98.5%), significantly different from Bioguma 1 (91.7%) and Bioguma 2 (91.1%), but not significantly different from Mandau (95.5%) and Bioguma 3 (94.7%). At 54 hours, all varieties exceeded 92%, indicating good viability (Afriansyah et al., 2021).

Super 1 demonstrated high physiological vigor with active metabolism during early imbibition, allowing faster mobilization of food reserves to support embryo elongation (Afriansyah et al., 2021). Bioguma 3 responded rapidly in the early phase but grew more slowly than Super 1 in later stages, likely due to genetic differences affecting respiration and protein synthesis (Maulana, 2019). Bioguma 1 showed moderate growth with good viability (Andayani & Rosanti, 2023). Mandau was slower in the early phase but increased steadily, indicating moderate vigor and good physiological adaptation to the medium (Afriansyah et al., 2021). Bioguma 2 was the slowest in the early phase, likely due to higher initial moisture content (12.9%), which reduced membrane stability and enzymatic synchronization during imbibition (Hartawan & Nengsih, 2012).

These results confirm that the time and percentage of radicle emergence are sensitive indicators for assessing seed responses to testing conditions and are important predictors of seed germination and vigor (Diaguna et al., 2024).

Table 1. Effect of Between Paper and Top of Paper Germination Methods on Radicle Emergence in Several Sorghum Varieties.

Treatment	Average radicle emergence (%)									
	27	30	33	36	39	42	45	48	51	54
Method germination										
<i>Between papers</i>	4.9 a	16.6 a	35.2 a	56.1 a	74.3 a	84.5 a	88.3 a	92.6 a	94.0	95.5
<i>Top of paper</i>	6.4 a	27.2b	59.0 b	82.5 b	89.0 b	91.6 b	92.9 b	94.2 b	94.6	95.6
Variety										
Mandau	3.5 b	25.6 c	53.5 c	72.6 c	84.2 c	89.9 c	92.2 c	95.2 d	95.5 b	96.4 d
Super 1	5.9 c	26.3 c	60.3 d	85.7 d	93.8 d	96.3 d	97.7 d	98.4 e	98.5 c	98.9 e
Bioguma 1	4.4 bc	20.6 b	45.0 b	65.7 b	79.1 b	85.9 b	88.1 b	91.0 b	91.7 a	92.8 a
Bioguma 2	0.6 a	4.4 a	18.1 a	47.2 a	65.9 a	78.1 a	83.7 a	88.9 a	91.1 a	94.3 b
Bioguma 3	13.9 d	32.5 d	58.4 d	75.3 c	85.3 c	90.0 c	91.3 c	93.5 c	94.7 b	95.4 c

b. Germination Percentage (%)

Analysis of variance (ANOVA) showed that varietal differences had a significant effect on sorghum seed germination, while the germination method did not have a significant effect. The 5% Duncan’s Multiple Range Test (Table 2) indicated that both the Top of Paper (TP) and Between Paper (BP) methods produced high germination percentages and were not significantly different, at 94.44% and 93.96%, respectively. This result suggests that both methods were able to provide optimal microenvironmental conditions for germination, including adequate moisture, sufficient aeration, and stable seed-water contact, consistent with Faisal et al. (2022).

Significant differences were observed in the variety factor. Super 1 had the highest germination percentage at 99.2%, which was significantly different from the other varieties. This indicates that nearly all seeds developed into normal seedlings with high vigor, maintained embryo integrity, and efficiently mobilized energy reserves during early germination (Saputra et al., 2024). Mandau also exhibited a high germination percentage (97.5%), placing it in the superior group with stable performance. Bioguma 3 ranked in the intermediate group (93.9%), indicating that a small proportion of seeds experienced delayed germination. Bioguma 1 reached 91.2%, showing good germination but not as high as the superior varieties. Bioguma 2 had the lowest value (89.2%), significantly different from the other varieties, suggesting that some seeds had low vigor or experienced physiological constraints during germination.

Table 2. Effect of Between Paper and Top of Paper Germination Methods on Germination Power in Several Sorghum Varieties.

Treatment	Average germination power (%)
Germination method	
<i>Between papers</i>	93.96
<i>Top of paper</i>	94.44
Variety	
Mandau	97.5 d
Super 1	99.2 e
Bioguma 1	91.2 b
Bioguma 2	89.2 a
Bioguma 3	93.9 c

Germination percentage is a key indicator of physiological seed quality because it reflects the ability of seeds to develop into normal seedlings under optimal conditions. High values indicate effective physiological processes such as imbibition, respiration, and enzymatic activity. The results showed that TP was slightly higher, likely due to greater exposure of the seed surface, which allowed optimal oxygen supply while maintaining

moisture, although the difference from BP was not significant.

Varietal performance also showed clear variation. Super 1 exhibited high vigor from early imbibition, faster mobilization of food reserves, and a stable germination rate, as reported by (Saputra et al., 2024). Mandau showed a similar pattern, although slightly lower, indicating good physiological capacity in responding to testing conditions. In contrast, Bioguma 2 germinated more slowly, likely related to its higher initial moisture content (12.9%), which may have increased respiration during storage, accelerated physiological aging, reduced membrane integrity, and inhibited metabolic activation during imbibition (Pirredda et al., 2024; Gebregergis et al., 2024). This suggests that delayed germination in Bioguma 2 was more closely linked to physiological imbalance than to genetic quality.

All varieties had germination percentages above 85%, meeting seed quality standards under Minister of Agriculture Regulation No. 465 of 2023. Super 1 showed superior performance approaching 100%, indicating optimal physiological capability on paper-based media. These findings complement previous studies emphasizing post-storage or vigor-enhancement variation among sorghum genotypes, but few have compared varietal performance using paper-based germination methods (Maksum et al., 2020; Afriansyah et al., 2021). The superior performance of Super 1 in this study provides important information regarding the genetic potential of this variety under paper-based testing conditions.

c. Vigor Index

The analysis of variance (ANOVA) showed that varietal differences had a highly significant effect on the vigor index of sorghum seeds. Observations in Figure 2 indicate that the sand medium produced the highest vigor index compared with the Between Paper (BP) and Top of Paper (TP) methods. This result indicates that balanced aeration and moisture support early seedling growth more effectively. The sand medium allows better root development because of a wider growth space similar to natural soil conditions (De Silva et al., 2022).

Bioguma 3 showed the highest vigor index in the sand medium (8.25). This indicates the strongest and most efficient early growth capacity among the tested varieties. In BP and TP, this variety recorded vigor index values of 0.61 and 0.63, demonstrating a more responsive performance to media conditions resembling the natural environment. Super 1 ranked next, with a vigor index of 7.05 in sand, while BP and TP recorded values of 0.67 and 0.80. This reflects more optimal early growth in the sand medium. Bioguma 1 showed a value of 5.21 in sand, with BP and TP values of 0.52 and 0.58,

indicating relatively stable physiological performance despite sensitivity to media changes. Bioguma 2 recorded a vigor index of 4.52 in sand, with BP and TP values of 0.50 and 0.35, indicating lower early growth capacity but still benefiting from the sand medium. Mandau showed the lowest value in sand (4.30), with BP and TP values of 0.31 and 0.56, indicating lower vigor, possibly related to genetic factors or physiological conditions such as initial moisture content and seed maturity at harvest.

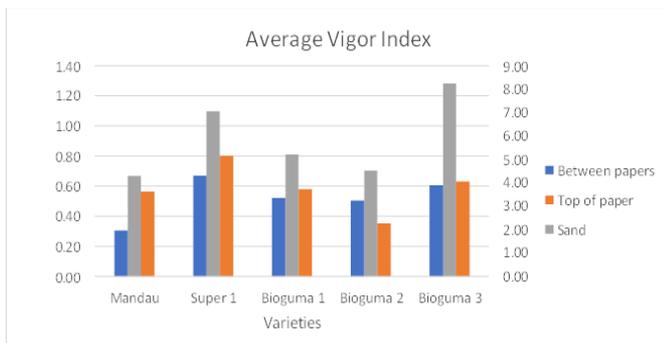


Figure 2. Average vigor index of several sorghum varieties using the between paper, top of paper, and sand methods

The vigor index reflects the ability of seeds to initiate early growth, which is related to physiological efficiency from imbibition to radicle development (ISTA, 2021). The sand medium, which provides balanced aeration and moisture, enables more optimal mobilization of food reserves. This makes vigor differences among varieties more clearly observable than in paper-based media (De Silva et al., 2022). These differences are also related to morphological and physiological factors, including seed size and food reserves. Large-seeded varieties such as Bioguma 3 possess greater starch and protein reserves, supporting stronger early growth (Tarakanov et al., 2021). In contrast, small-seeded varieties such as Mandau have more limited energy reserves, resulting in slower early growth despite low initial moisture content (9.7%). The higher moisture content in Bioguma 2 (12.9%) may reduce membrane stability during storage and decrease enzymatic activity at the onset of imbibition, leading to slower early growth (Zhang et al., 2020).

d. Emergence Uniformity (%)

The analysis of variance showed that sorghum variety had a highly significant effect on seed emergence uniformity, whereas the germination methods between paper and top of paper had no significant effect. The DMRT follow-up test at the 5% level (Table 3) confirmed that the mean emergence uniformity obtained using the between paper method at 92.64% and the top of paper

method at 93.00% did not differ statistically. These results indicate that both methods provide adequate basic conditions for germination, and that differences in emergence uniformity are primarily determined by varietal genetic factors.

Table 3. Effect of Between Paper and Top of Paper Germination Methods on Emergence Uniformity in Several Sorghum Varieties.

Treatment	Average Emergence Uniformity (%)
Germination method	
<i>Between papers</i>	92.64 a
<i>Top of paper</i>	93.00 a
Variety	
Mandau	95.8 d
Super 1	97.8 e
Bioguma 1	89.9 b
Bioguma 2	87.9 a
Bioguma 3	92.7 c

The effect of variety on emergence uniformity was clearly observed. The Super 1 variety showed the highest value at 97.8% and differed significantly from the other varieties. The Mandau variety exhibited relatively high uniformity at 95.8%, followed by Bioguma 3 with a moderate value of 92.7%. In contrast, Bioguma 1 and Bioguma 2 showed lower emergence uniformity, at 89.9% and 87.9%, respectively. These differences reflect variations in physiological seed quality and morphological uniformity among varieties.

The top of paper method tended to produce slightly higher emergence uniformity than the between paper method. This condition is associated with better oxygen availability because the seeds are not completely covered by wet paper, allowing aerobic respiration to proceed more optimally. In addition, stable surface moisture supports more uniform water imbibition and the activation of hydrolytic enzymes, particularly α -amylase, which plays a key role in starch breakdown to provide energy for embryo growth (De Silva et al., 2022). This physiological mechanism reduces variation in the timing of radicle emergence among seeds.

From the varietal perspective, the high emergence uniformity observed in Super 1 indicates greater physiological stability and more uniform seed size. Relatively large seeds with well-developed embryos allow more even distribution of endosperm reserves during the early stages of germination. In contrast, Mandau and some Bioguma varieties showed lower emergence uniformity, which is likely related to variation in seed size and initial moisture content. Smaller seeds have a higher surface-to-volume ratio, resulting in rapid imbibition but increasing the risk of internal moisture fluctuations that may disrupt physiological stability (Sakti et al., 2024). In larger-

seeded varieties, high initial moisture content may stimulate excessive early respiration and reduce metabolic efficiency, consistent with the findings of Maksum et al. (2020) regarding the effect of genotype on sorghum seed viability after storage.

e. Growth Rate (% per day)

The analysis of variance showed that germination method and sorghum variety had a highly significant effect on seed growth rate. The DMRT follow-up test at the 5% level (Table 4) indicated that the top of paper method produced the highest growth rate at 31.47% per day, whereas the between paper method resulted in a lower value of 23.14% per day. These results confirm that differences in the microenvironment created by germination methods play an important role in determining the early growth rate of seedlings.

Table 4. Effect of Between Paper and Top of Paper Germination Methods on the Rate of Growth in Several Sorghum Varieties

Treatment	Average Growth Rate (% per day)
Germination method	
Between papers	23.14 a
Top of paper	31.47 b
Variety	
Mandau	29.74 d
Super 1	29.53 d
Bioguma 1	25.23 b
Bioguma 2	24.66 a
Bioguma 3	27.35 c

The superiority of the top of paper method is associated with more favorable physiological conditions. Seed placement on the surface of the medium allows more stable moisture balance without water saturation and provides better oxygen availability compared with the between paper method. These conditions support aerobic respiration and accelerate the activation of hydrolytic enzymes, particularly α -amylase, in the mobilization of starch reserves into energy for embryo growth, as reported by De Silva et al. (2022). This environment promotes faster cell elongation and increases the daily growth rate of seedlings.

Regarding varietal effects, Mandau and Super 1 exhibited the highest growth rates, at 29.74% and 29.53% per day, respectively, followed by Bioguma 3 with a moderate value of 27.35% per day. Bioguma 1 and Bioguma 2 showed lower growth rates. These differences reflect the role of genetic factors in controlling seed vigor and early physiological responses during germination. This finding is consistent with reports by Susanto et al. (2022) and Pramono et al. (2024), which stated that differences among sorghum genotypes result in significant variation in seed viability and vigor.

Lower growth rates observed in some varieties may also be influenced by seed physical conditions, particularly initial moisture content. Varieties with higher growth rates in this study had relatively low initial moisture content of about 9 to 10%, which supports more stable hydration and early metabolic activation. In contrast, varieties with moisture content close to 12% may experience reduced membrane integrity during storage, thereby inhibiting early physiological responses, in accordance with the findings of Maksum et al. (2020).

Ability of the Radicle Emergence Test to Estimate Sorghum Seed Germination Percentage

Based on the observations, the Top of Paper (TP) method was the most effective in the radicle emergence (RE) test, with an optimal observation time at 48 hours after incubation. To evaluate the relationship between RE and seed viability, a correlation analysis was conducted between RE values obtained from the TP method and germination percentage (GP) as the final parameter. The relationship is presented in Figure 3.

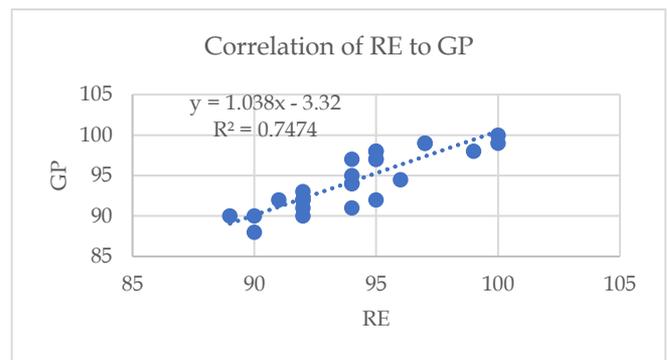


Figure 3. Correlation graph of RE against GP

The regression analysis produced the equation $y = 1.038x - 3.32$ with a coefficient of determination (R^2) of 0.7474. This R^2 value indicates that approximately 74.7% of the variation in GP can be explained by changes in RE. The relationship was strongly positive, as the data points followed an upward regression trend. The regression coefficient of 1.038 shows that every 1% increase in RE was followed by an increase of approximately 1.038% in GP. The relatively tight clustering of data points around the regression line indicates a consistent relationship, although slight variation was influenced by factors such as physiological seed condition, embryo viability, and uniformity of maturity.

The RE-to-GP conversion table (Table 5) showed a consistent linear trend. As RE increased from 70% to 81%, GP increased from 76% to 87%. At RE levels of 82–93%, GP increased from 88% to 100%. Each 1% increase in RE was followed by a 1–2% increase in GP, indicating a proportional and predictive relationship. RE values

below 75% corresponded to GP values of 76–81%, indicating that some seeds had not completed germination. RE values above 85% were associated with GP values of 92–93%, while RE values above 90% indicated that nearly all seeds reached maximum germination.

Table 5. Results of RE conversion to GP

RE (%)	GP (%)	RE (%)	GP (%)
70	76	82	88
71	77	83	89
72	78	84	91
73	79	85	92
74	80	86	93
75	81	87	94
76	82	88	95
77	83	89	96
78	84	90	97
79	85	91	98
80	86	92	99
81	87	93-100	100

The rapid appearance of the radicle serves as an early indicator of embryo physiological activity, including imbibition, activation of respiration, and hydrolytic enzyme activity, which determine successful normal germination. Assessing RE is faster than waiting for final GP, providing practical benefits for vigor screening and predicting seed lot germination (Diaguna et al., 2024; Catão & Hurtado, 2023).

The positive relationship between RE at 48 hours and GP can be physiologically explained. Seeds that rapidly produced radicles had efficiently passed through imbibition, mobilization of internal reserves, and activation of hydrolytic enzymes. This reflects the embryo's readiness to develop into a normal seedling, which is expressed in high GP values. This phenomenon aligns with the concept of seed vigor as the ability to grow rapidly and uniformly, a key factor in ensuring viability and successful germination (Saputra et al., 2024).

Significant variation among varieties was observed. Varieties with larger endosperm reserves and optimal pre-test physiological conditions tended to have higher RE and GP. Akbar et al. (2024) reported that sorghum varieties with larger seed size or better storage conditions exhibited superior vigor performance. However, an R^2 value of approximately 0.75 indicates that around 25% of the variability was influenced by other factors, including heterogeneity in seed size, initial moisture content, testa thickness, and prior storage conditions that affect enzymatic activity and membrane integrity (Catão & Hurtado, 2023).

Overall, these findings confirm that RE observed at 48 hours can be used as a rapid indicator to estimate the physiological quality of sorghum seeds, showing a

strong linear relationship with final germination percentage.

Conclusion

The Top of Paper (TP) method was the most effective for the radicle emergence (RE) test, with an optimal observation time at 48 hours, showing a positive and linear relationship with germination percentage (GP) of sorghum seeds ($R^2 = 0.7474$). The Super 1 variety exhibited the best performance, followed by Bioguma 3, with the highest RE and GP values, while Mandau and Bioguma 2 showed lower values. These results confirm that RE observation at 48 hours can be used as a rapid and accurate indicator for assessing sorghum seed viability and supporting the selection of superior varieties in seed production practices.

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Author Contributions

All authors have contributed to the completion of this manuscript. They have read and agreed to the published version of the manuscript

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Conflict of Interest

The authors declare no conflict of interest.

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