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AMARANTH (*AMARANTHUS HYPOCHONDRIACUS* L.) cv. Krepysh SEED GERMINATION AND GROWTH RESPONSE TO DIFFERENT SOWING DEPTHS ACROSS SEED FRACTIONS

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SUMMARY

Amaranth (*Amaranthus hypochondriacus* L.) is a promising crop because of its maximum nutritional values and ability to adapt to different soil and environmental conditions. Since amaranth has small seeds, it is crucial to sow the seeds at the optimal soil depth to ensure uniform germination and healthy seedlings, which eventually influence crop productivity. In this study, the sowing of amaranth cultivar Krepysh seeds with different sizes and specific gravity occurred in quartz sand at various depths (1, 2, 3, 4, and 5 cm). Examining the relationship between sowing depth and initial growth intensity of amaranth seedlings was the goal of this research. The results showed a decline in the number of viable and healthy seedlings as sowing depth increased. Additionally, heavy seeds sown at 1–2 cm depth demonstrated relatively high emergence rates. Conversely, the optimal sowing depth appeared to be 2–3 cm for medium and light seed fractions. Sowing at less than 2 cm depth resulted in insufficient moisture in the upper soil layer, while seeds sown deeper than 4 cm led to a delayed and non-uniform germination and healthy seedling. The study concludes a sowing depth of 2–3 cm emerged as the most suitable for amaranth, as it improves seed germination and helps prevent drought stress.

Keywords: *Amaranthus hypochondriacus* L. cultivar Krepysh, friendliness and simultaneity of seedlings, sowing depth, seedling viability

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Key findings: The optimal sowing depth for *Amaranthus hypochondriacus* L. cultivar Krepysh varied by seed fraction—heavy seeds perform best at 1–2 cm, while medium and light seeds do better at 2–3 cm. Sowing deeper than 4 cm notably delays emergence and diminishes seedling vigor across all seed types.

INTRODUCTION

Amaranth (*Amaranthus hypochondriacus* L.) is visibly increasing as a strategic alternative crop due to its high nutritional content, resilience to climate, and ability to grow in marginal environments. Its grains contain high-quality protein, essential amino acids, bioactive compounds, and minerals, making them suitable for food, animal feed, and functional products (Foley *et al.*, 2011; Mukuwapasi *et al.*, 2024; Toimbayeva *et al.*, 2025). In Russia, especially outside the chernozem region, amaranth is recognizably a promising crop for diversifying cereal production and improving food security (Nahi and Siankevich, 2023). However, successful cultivation in temperate continental climates depends on optimizing early growth stages, particularly seed germination and seedling establishment.

Seed germination and uniform seedling emergence are essential for maximizing crop productivity. In amaranth, the small seed size makes it highly sensitive to factors like sowing depth, soil texture, and moisture levels. Poor soil preparation, uneven planting depth, and insufficient moisture can adversely affect germination, seedling vigor, and uniformity, ultimately lowering yields (Gomes *et al.*, 2023; Wasay *et al.*, 2024). Shallow sowing can cause seeds to lose surface moisture quickly, especially in light soils, while sowing too deeply may delay emergence due to reduced oxygen access and increased resistance to root growth (Wang *et al.*, 2020; Talaee *et al.*, 2024). Similarly, understanding interactions among soil type, seed source, and seed burial depth is critical for optimizing seed germination and seedling establishment (Dar *et al.*, 2026; Stapleton *et al.,* 2025).

The Moscow Region experiences a temperate continental climate, with early-season temperatures that are often low with unpredictable rainfall in late May and early June. These conditions mostly lead to surface soil drying in light-textured soils outside the chernozem zone. Consequently, amaranth seedlings can show poor uniformity and weaker early growth. One effective strategy is adjusting the sowing depth, which helps reduce drought stress early in the season by improving moisture retention and ensuring proper soil aeration.

Previous research has explored how sowing depth affects amaranth emergence across different environmental settings. Webb *et al*. (1987) observed the highest emergence at shallow depths (1.3 cm) under controlled temperature gradients. Cao *et al*. (2015) found that sowing depth significantly alters plant height, biomass, and yield, with 2 cm as the optimal depth in their experiments. Basu *et al*. (2016) noted a decreased germination at deeper planting depths in *Amaranthus tricolor*. Nevertheless, most studies mainly addressed general germination success and yield, with limited focus on (i) how seed size fractions within a cultivar respond differently, (ii) early seedling growth activity, and (iii) adaptation to the specific agro-climatic conditions of Russia's non-chernozem zone.

Amaranth inflorescences generate seeds that vary in size, fullness, and density. Within a single cultivar, seed fractions (heavy, medium, and light) may differ in germination potential and vigor due to physiological maturity and reserve accumulation. Nonetheless, the interaction between seed fraction and sowing depth, especially on light-textured substrates with controlled moisture, remains poorly studied. Gaining insights into this interaction is crucial to optimizing seed placement depth and ensuring uniform stand establishment, particularly in areas with early-season moisture fluctuations.

This study examined how sowing depth (1–5 cm) affects germination rate and potential, seedling emergence time, hypocotyl length, fresh biomass, and the viability index of *Amaranthus hypochondriacus* L. cultivar Krepysh. The experiment happened in controlled conditions using quartz sand to mimic light-textured soils typical of the non-chernozem zone, with the moisture kept at 75% of water-holding capacity and temperatures at 22 °C–24 °C to simulate early-season field conditions in the Moscow Region. The study aimed to analyze the response of heavy, medium, and light seed fractions to different sowing depths, identifying the best sowing depth for each seed group to improve germination energy and seedling vigor. Likewise, an evaluation sought to measure initial seedling growth as an indicator of adaptability to light-textured soils with moderate moisture and offer agronomic suggestions to enhance amaranth stand establishment in temperate continental climates. These results will help improve agronomic practices for growing amaranth cultivation in regions with light soils and unstable early-season moisture regimes.

MATERIALS AND METHODS

Amaranth variety and seed preparation

The experiment employed seeds of the *Amaranthus hypochondriacus* L. cultivar Krepysh, registered in Russia in 2004 and developed by the Federal Scientific Vegetable Center (FSBSI). This cultivar shows adaptability to temperate continental climates in the non-chernozem zone. It is a recognized variety for producing consistent yields and uniform grain quality under standard farming practices. Before sowing, the seeds underwent cleaning and calibration in accordance with Russian State Standards (GOST 12038–84; GOST 12037–81). The calibration process involved two stages. The first was mechanical sieving using laboratory sieves to eliminate impurities and sort seeds by size. The second was density separation with an airflow seed separator to divide the seeds into three fractions based on specific gravity and seed fullness. The heavy fraction includes fully developed, high-density seeds with ample reserves. The medium fraction contains seeds of intermediate size and density, while the light fraction consists of smaller, lower-density seeds with fewer nutrient reserves.

Seeds received visual inspection to verify physiological maturity, ensure intact seed coats, and confirm the absence of mechanical damage or infection. Additional quality indicators included a thousand-seed weight and visual uniformity. Fractionation enabled analysis of how seed mass interacts with sowing depth, thereby affecting germination energy, seedling vigor, and early growth. Given that amaranth exhibits heterogeneous seed size due to extended flowering, commercial seed lots often contain seeds of varying sizes. Examining all fractions helped determine if optimal sowing depth can offset smaller seed reserves, especially in light-textured soils typical of the non-chernozem zone.

Sowing and initial growth intensity

The planted amaranth seeds in pots had the same size, measuring 20 cm in height and 15 cm in diameter, following the methodology described by Bome *et al.* (2011). Seeding depths included 1 cm (D1), 2 cm (D2), 3 cm (D3), 4 cm (D4), and 5 cm (D5). Quartz sand with a hardness of 1.50 g cm^{-3} was the soil employed for germination. It underwent the process of washing, calcination, and sieving through a 1.0 mm sieve. Then, the dry quartz sand filled the pots before irrigating with the same amount of water, maintained at 75% relative moisture before sowing, with the bottom of each pot lined with a tray to prevent water loss.

The selection of amaranth seeds from three fractions succeeded in ensuring their maturity, intactness, natural drying, and uniformity in shape and size. The seeds sustained an even sowing on the surface of the quartz sand with the depths of 1, 2, 3, 4, and 5 cm, before immediately covering with layers of quartz sand. Each pot contained a total of 100 seeds, with the experiment performed in triplicate. Seeds sown at a depth of 1 cm served as the control. The pots with seeds, after covering with glass plates, entailed germination in the light at temperatures of 22 °C–24 °C. Removing the first shoots reaching the glass took place, with the initial growth of seedlings assessed on the tenth day.

Moisture capacity of sand

The study used the method of Bome *et al.* (2011) to measure the moisture capacity of the quartz sand. Briefly, using a metal cylinder with a mesh bottom (height 30 cm, diameter 8 cm), it received a circle of moistened filter paper at the bottom of the cylinder, followed by weighing the cylinder. After filling the cylinder with three-quarters of its volume of calcined sand, its weighing continued. Placing a cylinder of sand in a vessel filled with water enabled the water level to match the surface of the sand. When the surface of the sand was evidently wet, removing the cylinder from the vessel followed, allowing the excess water to drain. The vessel's drying by filter paper from the bottom and sides preceded final weighing. The following formula served to calculate moisture capacity (A) in ml.

Moisture capacity (A)

$$A = \frac{100\,(c - b)}{(b - a)}$$

Where a = the mass of the empty cylinder (g), b = the mass of the cylinder with sand before its immersion in water (g), and c = the mass of the cylinder with sand after its saturation with water (g). The moisture capacity of the quartz sand used in this experiment reached its calculation as 24.14%. A strong positive correlation emerged between the sand moisture content and amaranth seed germination percentage (Pearson's $r = 0.91$, $p < 0.001$), indicating that moisture availability is a dominant driver of germination in sandy substrates.

Seedling initial growth intensity formulation

On the tested day, the seedlings emerging on the surface incurred flush cutting with the substrate surface, counting, and weighing immediately. At the end of the analysis, the percentage determination was (Ellis and Roberts, 1980; Finch-Savage and Leubner-Metzger, 2006; Beribe *et al*., 2025) as follows:

$$\text{Germination (\%)} = \frac{\text{Number of normally germinated seeds}}{\text{Number of seeds sown}} \times 100$$

$$\text{Germination potential (\%)} = \frac{\text{Number of normally germinated seeds on day-4}}{\text{Number of seeds sown}} \times 100$$

$$\text{GP (\%)} = \frac{N_{d4}}{N_s} \times 100$$

(where N_{d4} = normally germinated seeds on day 4, N_s = seeds sown).

$$\text{Seedling friendliness (\%)} = \frac{\text{Average seedling length}}{\text{Standard deviation of seedling length}} \times 100$$

The expression of results of the intensity of initial growth of seedlings was as follows (Bai *et al*., 2014; Yao *et al*., 2021; Kanno *et al*., 2025):

Time of seedling emergence/day = Σ ([*ni* × *di*]/*n*)

Where *ni* = the number of seeds germinated on day *i*, *di* = the time of emergence of seedlings per day, and *n* = the total number of germinated seeds.

Length of hypocotyls of amaranth seedlings

Fresh weight of seedlings in terms of 100 seedlings in grams followed the formulas below:

$$\text{Coefficient of fresh weight gain} = \frac{\text{Total fresh seedling weight}}{\text{Seedling length}}$$

$$\text{Seedling viability index} = \frac{\text{Stem thickness}}{\text{Seedling length}} + \text{Total fresh seedling weight}$$

Statistical analysis

All the recorded data based on various variables underwent analysis using Microsoft Excel 2016 and SPSS 12.0 software.

RESULTS

Sowing depth effect on seed germination

Seed germination and germination potential are crucial traits for evaluating germination percentage and seedling uniformity, which can eventually influence the seedling emergence and growth in the field. The seeds' germination potential reflects the proportion of seeds capable of developing into healthy plants under suitable environmental conditions (Peng *et al*., 2025). Uniformity in seed sowing depth often directly and indirectly affects grain yield and mostly served as a key measure of population growth and development in seedling studies (Khan *et al*., 2022; Alireza and Aritz, 2023). The results on how sowing depths influenced the germination, germination potential, and seedling health in amaranth (*A. hypochondriacus* L.) cultivar Krepysh are available in Figure 1.

Sowing depths significantly alter the germination, germination potential, and seedling friendliness of amaranth (Figure 1), which also aligns with the past study by Tyrus (2025). The inhibitory effect increases with more sowing depths: germination, germination potential, and seedling health in all seed fractions tend to decrease gradually. For heavy seed fraction, sowing depths of 3, 4, and 5 cm resulted in a reduction in germination (51.16%, 58.14%, and 88.37%, respectively), compared with D1 (the control). However, the sowing depth of D2 enhanced the germination by 10.42%. For the medium seed fraction, sowing depths of D2, D3, D4, and D5 decreased the germination by 14.89%, 29.79%, 42.55%, and 55.32%, respectively, compared with D1. For the light seed fraction, sowing depths of D2, D3, D4, and D5 reduced the germination percentage by 4.35%, 10.87%, 21.74%, and 21.74%, respectively, versus D1.

The sowing depth effect on germination potential was significantly (p < 0.05) greater than the germination percentage. In contrast, the germination potential of the heavy fraction of amaranth seeds was 10.34%, 68.97%, 68.97%, and 100.00% lower in treatments D2, D3, D4, and D5, respectively, compared with the control (D1). The germination potential in the medium fraction seeds with sowing depths of D2, D3, D4, and D5 decreased by 27.27%, 59.09%, 63.64%, and 90.91%, respectively, compared with D1. Similarly, the germination potential of seeds from the light fraction of amaranth seeds at sowing depths of D2, D3, D4, and D5 was 14.81%, 33.33%, 66.67%, and 70.37% lower than that in D1.

The difference in sowing depths also caused the remarkable variations in seedling friendliness. For the heavy fraction of amaranth seeds, seedling friendliness at sowing depths of D2, D3, D4, and D5 decreased by 1.30%, 33.37%, 65.66%, and 73.46%, respectively, compared with D1. Likewise, for the medium fraction, sowing depths of D2, D3, D4, and D5 reduced the seedling friendliness by 11.95%, 40.94%, 75.02%, and 82.96%, respectively, versus D1. For the light fraction, the seedling friendliness at sowing depths of D2, D3, D4, and D5 also decreased by 14.14%, 45.12%, 53.87%, and 59.60%, respectively, compared with the control (D1).

With sowing depths of D1 to D2, seedlings appear simultaneously, while seedling emergence displayed a notable reduction at sowing depths of D3, D4, and D5. The highest and lowest germination rates among the variants resulted in the heavy fraction of amaranth seeds sown at depths of D2 and D5, respectively. The fastest emergence of healthy seedlings occurred in the medium fraction of seeds sown at the depth of D1.

The effect of sowing depth on seedling emergence time appears in Figure 2. The time taken by amaranth seedlings to emerge tends to be delayed as sowing depth increases. At sowing depths, from D1 to D5, the seedling emergence ranged from three to six days. The shortest emergence time was evident with D1 (3.07 days), while the longest was at D5 (5.50 days). On average, seedling emergence delay was at 0.93 days for every 1 cm increase in sowing depth in the heavy seed fraction of amaranth seeds sown above D3. The average delay in time was 0.21 days in the medium

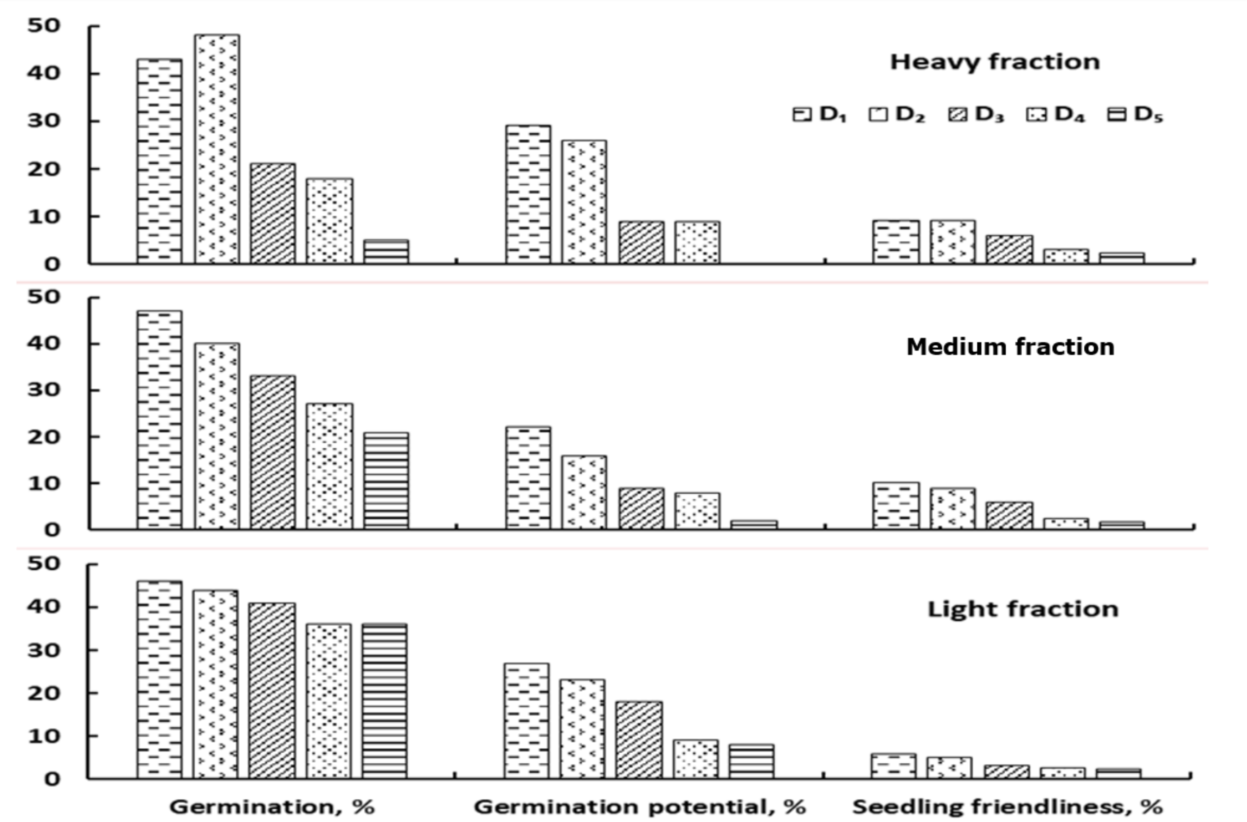

Figure 1. Effects of sowing depth on seed germination and seedling emergence in *Amaranthus hypochondriacus* L.

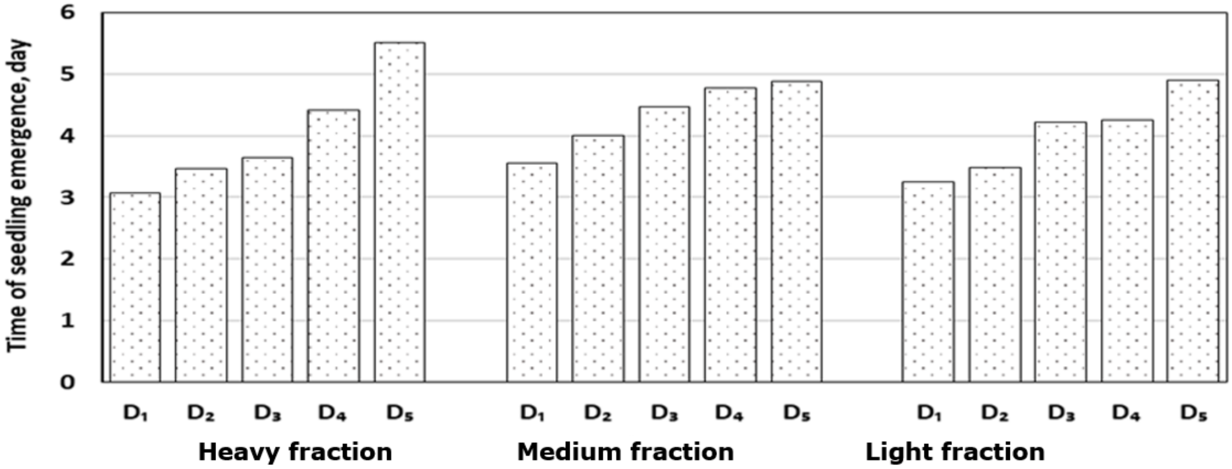

Figure 2. Effects of sowing depth on seedling emergence time in *Amaranthus hypochondriacus* L.

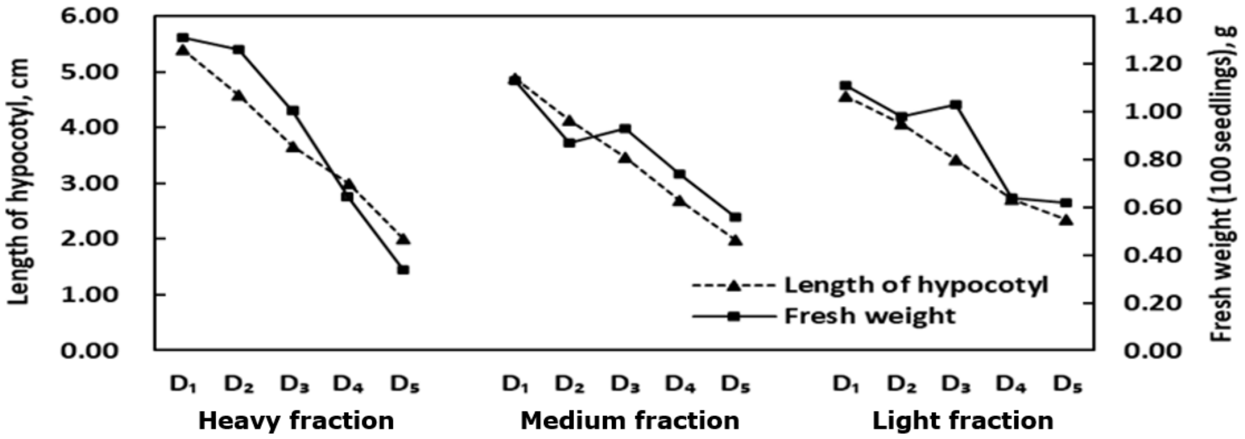

Figure 3. Effects of sowing depth on morphological traits of *Amaranthus hypochondriacus* L. seedlings.

seed fraction, and 0.34 days for each 1 cm increase in sowing depth in the light seed fraction.

Sowing depth effect on seedling biomass

The length of the hypocotyl is one of the relatively stable indicators of the morphological characteristics of *A. hypochondriacus* L. seeds, which mainly has the control of the genotype genetic makeup. However, hypocotyl length often receives influences from external environmental factors (Lkhamkhuu *et al*., 2020; Wasay *et al*., 2024). The effect of sowing depths on hypocotyl length and the fresh weight of amaranth seedlings occurs in Figure 3. The sowing depths significantly affected the hypocotyl length and the fresh weight of amaranth seedlings. Hypocotyl length consistently decreased as the sowing depth increased. The fresh weight of seedlings in the medium and light fractions initially reduced and then increased, while these traits declined with sowing depths of D4 and D5. In the heavy fraction of amaranth seeds, hypocotyl length reduced by 15.34%, 32.53%, 44.55%, and 63.03% with sowing depths of D2, D3, D4, and D5, respectively, compared with the control (D1). In the medium fraction, the reductions were 15.37%, 28.89%, 44.67%, and 59.43%, and in the light fraction, they were 10.75%, 25.00%, 40.35%, and 48.68%, respectively, compared with D1. On average, the hypocotyl length of amaranth seedlings decreased by 0.66 cm for every 1 cm increase in sowing depth.

The fresh weights of seedlings sown at planting depths of D2 to D5 were 8.40%, 23.66%, 51.15%, and 74.05% lower than those at the sowing depth of D1 in the heavy fraction of amaranth seeds. It was 23.01%, 15.38%, 34.51%, and 50.44% lower in the medium fraction, and 11.71%, 7.20%, 42.34%, and 44.14% lower in the light fraction, respectively. However, it was important to note that in the medium seed fraction, the fresh weight of seedlings was 6.90% higher at the sowing depth of D3 than of D2. In the light seed fraction, the seedlings' fresh weight was also 5.10% higher at D3 than at D2.

Sowing depth effect on growth traits

The coefficient of fresh weight gain and viability index can be effective to some extent as indicators of the quality and growth of amaranth seedlings and their adaptability to diverse environmental conditions (Onwubiko and Enwereji, 2023). The effect of sowing depths on these important traits in amaranth seedlings occurs in Figure 4. For the heavy fraction of amaranth seeds, the coefficient of fresh weight gain and the viability index tended

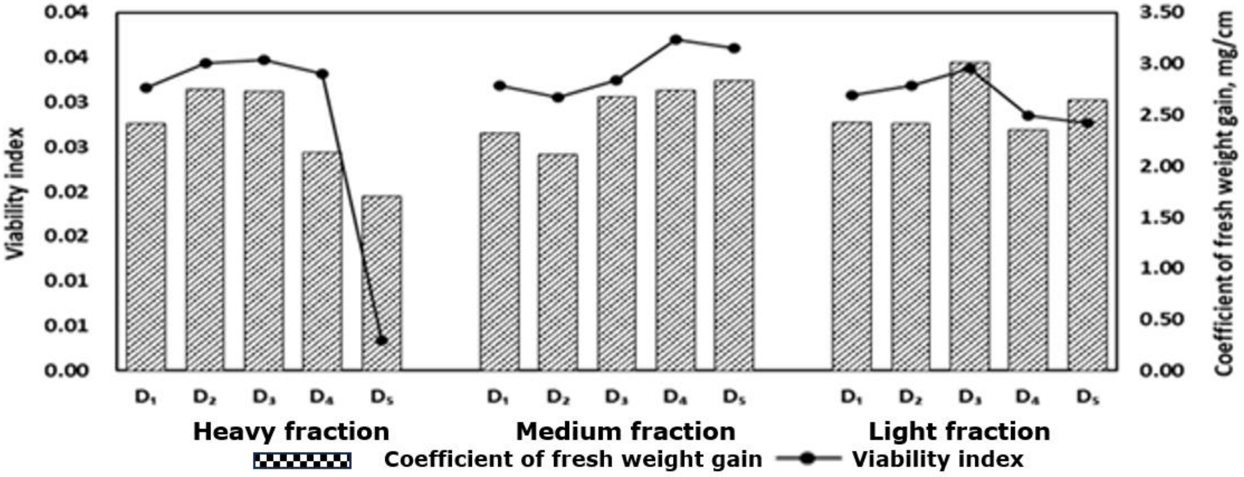

Figure 4. Effects of sowing depth on the coefficient of fresh weight gain and the viability index of *Amaranthus hypochondriacus* L. seedlings.

to increase and then decrease as the sowing depth increased. The coefficient of fresh weight gain in the heavy seed fraction reached a maximum of 2.75 mg/cm at sowing depth D2 and a minimum of 1.70 g/cm at D5. Compared with the control (D1), the coefficient of seedling fresh weight gain at sowing depths of D2, D3, D4, and D5 was 12.00%, 12.81%, -18.98%, and -29.75%, respectively. The highest viability index of amaranth seedlings was 0.0347 at a sowing depth of D3, with an increase of 9.81% observed over D1. Viability indices at sowing depths of D2, D4, and D5 were 8.86%, 4.75%, and -89.24% lower, respectively, versus D1.

For the medium fraction of amaranth seeds, the coefficient of fresh weight gain tended to decrease and then increase as sowing depth increased. In contrast, the viability index of amaranth seedlings generally declines, then rises, and decreases again with deeper sowing depths. The coefficient of fresh weight gain for amaranth seedlings with the medium fraction at sowing depths of D2, D3, D4, and D5, compared with D1, was -9.05%, 15.52%, 18.10%, and 21.98%, respectively. The viability index of amaranth seedlings at these depths was -4.09%, 1.89%, 16.35%, and 13.21%, respectively, versus D1 (control). For the light fraction of amaranth seeds, the coefficient of fresh weight gain and the viability index of amaranth seedlings reached their maximum levels (3.01 mg/cm and 0.0337) at a sowing depth of D3. The coefficient of fresh weight gain increased by -0.82%, 23.87%, -3.29%, and 9.05% at sowing depths of D2, D3, D4, and D5, compared with D1. Sowing depths of D2, D3, D4, and D5 raised the viability index of amaranth seedlings by 3.57%, 9.42%, -7.47%, and -10.39%, respectively, relative to the control (D1).

In all three fractions of amaranth seeds, the seedling viability index was relatively low at the sowing depth of D1. In contrast, shallow sowing often affects root growth under unfavorable soil moisture conditions, which further reduces the seedling viability. At a sowing depth of D5, the viability index was also relatively low. The likely reason was that deep sowing causes seedling retention and excessive nutrient depletion.

DISCUSSION

Uniform germination and strong early seedling growth are vital for amaranth yields, especially in temperate continental regions where moisture and temperature fluctuate early in the season. Consistent with earlier studies showing that sowing depth significantly affects germination and emergence (Webb *et al.,* 1987; Cao *et al*., 2015; Talaee *et al.,* 2024), this research confirms that planting too deep reduces germination rates, delays sprouting, and hampers seedling biomass development. Importantly, the study also reveals the optimal sowing depth varies with seed fraction (mass and density), highlighting a notable interaction between seed physiological quality and burial depth.

Earlier research primarily assessed sowing depth effects on entire seed lots (Basu *et al.,* 2016; Wang *et al.,* 2020; Wasay *et al.,* 2024). In contrast, this study separated heavy, medium, and light seed fractions and examined their distinct responses under controlled quartz-sand conditions that mimic light-textured soils typical of the non-chernozem zone. The results reveal that heavy seeds, which have larger reserves, tolerate moderate burial depths of 1–2 cm better, while medium and light seeds perform best at 2–3 cm. These findings support the idea that seed mass impacts early vigor and the ability to overcome mechanical resistance during emergence (Reed *et al.,* 2022; Lkhamkhuu *et al.,* 2020).

Consistent with earlier research indicating that shallow sowing results in rapid seed moisture loss (Brown and Wilson, 2019; Wasay *et al.,* 2024), our findings show reduced viability at 1 cm depth in controlled settings. Conversely, sowing at depths greater than 4 cm notably delayed germination, supporting the idea that excessive depth limits oxygen flow and increases the energy required for hypocotyl elongation (Wang *et al.,* 2020; Talaee *et al.,* 2024). Interestingly, sowing at a moderate depth of 2–3 cm improved seedling growth and viability, suggesting a better moisture-oxygen balance. Similar depth-related effects have reached documentation in other crops under different soil moisture conditions (Nemergut *et al.,* 2021; Sarwar *et al.,* 2024).

A key contribution of this study is the use of seedling growth intensity and viability indices combined as indicators of adaptive potential. Given that reports on germination percentage are common (Ellis and Roberts, 1980; Finch-Savage and Leubner-Metzger, 2006), combining it with biomass recovery and emergence timing provides a more comprehensive evaluation of early establishment. This approach is particularly relevant in areas with light-textured soils, where early drought stress often disrupts stand uniformity (Li et *al.,* 2023; Gomes *et al.,* 2023).

From an applied perspective, the findings provide cultivar-specific agronomic recommendations for *A. hypochondriacus* cv. Krepysh. The sowing of heavy seed fractions is best at 1–2 cm, whereas medium and light fractions' sowing is better at 2–3 cm to maximize emergence uniformity and seedling vigor. These recommendations are directly applicable to production systems in the non-chernozem zone and similar temperate agroecological regions. By demonstrating that optimal depth is not universal but rather fraction-dependent, the study provides practical guidance for seed-grading strategies and precision sowing management. Although further field validation under varying rainfall and temperature regimes would strengthen extrapolation, the presented work provides a novel framework for integrating seed physiological heterogeneity with depth management to improve early crop establishment.

CONCLUSIONS

The pioneering study suggested that differences in sowing depth significantly affect the germination percentage, germination potential, and seedling vigor of amaranth (*A. hypochondriacus* L.) cultivar Krepysh seedlings obtained from the seeds with various sizes. As the sowing depth increased, an inhibitory effect on seed germination occurred, delaying seedling vigor and germination potential. The seed size influenced these parameters when sowing occurred at the same depth. Based on various traits in this research work, the optimal sowing depth for heavy fraction seeds of *A. hypochondriacus* was 1–2 cm, while for medium and light fractions, the depth was 2–3 cm. By integrating germination percentage with seedling growth and viability indices, the study provides a more comprehensive assessment of early establishment than traditional germination tests.

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