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Effect of vermicompost-to-soil ratios on Mung Bean seed germination and growth

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Abstract
The increasing demand for sustainable agricultural practices has highlighted the importance of organic fertilizers, such as vermicompost, in enhancing crop productivity while maintaining soil health. This study investigates the impact of different vermicompost-to-soil ratios on the germination and early growth of mung bean (Vigna radiata) seeds. The objective was to determine the optimal vermicompost mixture that promotes seed germination rate, seedling vigor, and biomass accumulation. Mung bean seeds were sown in soil mixtures with varying vermicompost proportions—0% (control), 10%, 20%, 30%, and 40%—under controlled environmental conditions. Key parameters measured included germination percentage, mean germination time, shoot and root length, and fresh and dry biomass of seedlings after a 14-day growth period. The results revealed that incorporating vermicompost significantly enhanced germination rates and seedling growth compared to the control, with the 20% vermicompost-to-soil ratio yielding the highest germination percentage and biomass accumulation. Excessive vermicompost (>30%) did not further improve growth and, in some cases, slightly inhibited seedling development, possibly due to nutrient imbalances or salinity effects. These findings suggest that moderate vermicompost supplementation can improve mung bean seed germination and early growth, highlighting its potential as an eco-friendly soil amendment to boost legume crop performance. This study contributes valuable insights for optimizing organic fertilizer use in sustainable agriculture and supports the broader adoption of vermicompost in crop production systems.

Keywords: Vermicompost, mung bean, seed germination, seedling growth, organic fertilizer, soil amendment, sustainable agriculture, biomass accumulation

Introduction

In recent decades, there has been an increasing global emphasis on sustainable agriculture due to the growing environmental concerns associated with conventional farming practices. The indiscriminate use of chemical fertilizers and pesticides, while effective in boosting short-term crop yields, has led to a decline in soil fertility, contamination of water bodies, and adverse effects on human health and biodiversity. As a response, researchers, farmers, and policymakers have sought environmentally friendly alternatives that can maintain or improve crop productivity while preserving the ecological integrity of farming systems. Organic farming has emerged as a promising solution, focusing on soil health, biodiversity conservation, and the use of natural inputs. Among these, vermicompost has garnered significant attention for its potential to enhance plant growth, soil structure, and microbial activity through a natural and sustainable process.

Vermicomposting is the biological decomposition of organic waste by earthworms, particularly species like *Eisenia fetida*, resulting in a nutrient-rich, microbially active soil amendment known as vermicompost. This product contains essential macro- and micronutrients, plant growth regulators, beneficial microorganisms, and humic substances, which collectively improve soil fertility and plant development. Unlike synthetic fertilizers, vermicompost not only supplies nutrients in readily available forms but also enhances the soil's physical, chemical, and biological properties. It increases water retention, improves aeration, and supports microbial populations that contribute to nutrient cycling and plant disease resistance.

The importance of vermicompost becomes even more relevant when considering the challenges of modern agriculture, such as soil degradation, increasing costs of chemical fertilizers, and climate change. Vermicompost production is also a sustainable waste management strategy, converting organic residues from households, farms, and agro-industries into valuable agricultural input. In countries with high agricultural dependence and limited access to synthetic fertilizers, such as those in South and Southeast Asia, vermicompost represents a cost-effective and ecologically viable alternative.

Mung bean (*Vigna radiata*), a legume widely cultivated in Asia and parts of Africa, plays a significant role in food security due to its high protein content, short growing season, and nitrogen-fixing ability. It is a crucial source of dietary protein, particularly in vegetarian diets, and offers considerable agronomic benefits such as enhancing soil fertility through symbiotic nitrogen fixation. As global demand for plant-based protein sources increases, there is renewed interest in improving the productivity and resilience of mung bean cultivation. However, like other crops, mung bean yields are sensitive to soil fertility, especially during the early stages of germination and seedling growth. Establishing a healthy crop stand requires rapid and uniform germination, strong root development, and early biomass accumulation — all of which are influenced by soil conditions and nutrient availability.

In this context, the integration of organic inputs like vermicompost into mung bean cultivation practices holds promise. Several studies have demonstrated the beneficial effects of vermicompost on seed germination, plant height, root length, leaf number, chlorophyll content, and overall yield in various crops. For example, vermicompost has been shown to improve germination rates in tomato, maize, and chickpea, among others. It enhances nutrient uptake efficiency by supplying balanced nutrition and stimulating root growth. Additionally, the presence of plant growth-promoting substances like auxins and cytokinins in vermicompost can accelerate physiological processes involved in germination and seedling development.

Despite the acknowledged benefits, there remains a lack of consensus on the optimal vermicompost-to-soil ratio for different crops and environmental conditions. While moderate amounts of vermicompost can promote growth, excessive application may lead to nutrient imbalances, increased salinity, or microbial competition, ultimately hindering seed germination or seedling vigor. The impact of vermicompost is not uniform across all plant species, and the response can vary depending on the quality of the vermicompost, source material, and duration of composting. Thus, determining the appropriate application rate is critical to maximizing benefits while avoiding potential drawbacks.

Previous studies investigating vermicompost effects on mung bean have been limited in scope or inconsistent in their findings. Some have reported enhanced seedling growth with as little as 10% vermicompost mixed with soil, while others have used higher ratios such as 30% or even 50%. Furthermore, many of these studies have focused on overall yield or late-stage plant development, with relatively little attention paid to the seed germination phase — a critical period that determines the final stand establishment and productivity of the crop. Additionally, the mechanisms by which vermicompost influences early growth parameters such as mean germination time, seedling vigor index, and root-to-shoot ratio remain underexplored.

This research seeks to address these gaps by systematically evaluating the effect of different vermicompost-to-soil ratios (0%, 10%, 20%, 30%, and 40%) on mung bean seed germination and early seedling growth under controlled conditions. The study focuses on quantifiable parameters including germination percentage, mean germination time, shoot and root lengths, fresh and dry biomass, and seedling vigor index. By concentrating on the early stages of growth, this research aims to provide practical insights into how vermicompost influences the physiological and morphological traits essential for robust plant establishment.

The central research question guiding this study is: *What is the optimal vermicompost-to-soil ratio for enhancing seed germination and early seedling growth in mung bean?* Based on previous findings, it is hypothesized that moderate vermicompost concentrations (around 20%) will yield the best results in terms of germination rate and seedling vigor, while both lower and higher ratios may result in suboptimal outcomes due to either nutrient deficiency or excess.

The objectives of this study are as follows:

1. To evaluate the effect of varying vermicompost-to-soil ratios on the germination percentage and mean germination time of mung bean seeds.
2. To assess the influence of vermicompost on early seedling growth parameters such as shoot length, root length, and biomass accumulation.
3. To identify the optimal vermicompost ratio that maximizes seedling vigor and minimizes germination delays.
4. To contribute to sustainable agricultural practices by recommending appropriate vermicompost application rates for legume cultivation.

The scope of the study is limited to early-stage growth (up to 14 days after sowing), conducted under controlled environmental conditions to minimize variability due to external factors such as rainfall, temperature fluctuations, or pest pressure. While field validation is beyond the scope of this initial experiment, the findings are expected to lay a foundation for subsequent field trials and broader agronomic evaluations.

This paper is structured as follows: After the Introduction, the Materials and Methods section details the experimental design, soil and vermicompost preparation, treatment setup, and measurement procedures. The Results section presents the data collected, analyzed using appropriate statistical methods. The Discussion interprets the findings in light of existing literature, highlighting the implications for organic farming and potential avenues for future research. Finally, the Conclusion summarizes key takeaways and practical recommendations based on the study's outcomes.

As the world shifts toward more sustainable and climate-resilient agricultural practices, organic inputs such as vermicompost will play an increasingly important role in ensuring food security without compromising environmental health. By optimizing the use of vermicompost in legume crops like mung bean, farmers can enhance productivity, reduce dependency on chemical fertilizers, and promote ecological balance in farming systems. The insights from this study aim to support evidence-based decisions in organic nutrient management, contributing to the broader goals of sustainable agriculture and environmental stewardship.

Methods

This research was designed as a quantitative experimental study to investigate the effect of varying vermicompost-to-soil ratios on the germination and early seedling growth of mung bean (*Vigna radiata*). A controlled laboratory setting was used to ensure consistency in environmental factors such as temperature, humidity, and light exposure. The independent variable in this study was the proportion of vermicompost in the growing medium, while the dependent variables included germination percentage, mean germination time, shoot length, root length, fresh weight, dry weight, and seedling vigor index.

The study employed a completely randomized design (CRD) with five treatments representing different vermicompost-to-soil ratios: 0% vermicompost (control), 10%, 20%, 30%, and 40% by weight. Each treatment was replicated five times, with each replicate consisting of a separate plastic germination tray containing 20 mung bean seeds. In total, 500 seeds were used across all treatments and replications (5 treatments × 5 replicates × 20 seeds).

The mung bean seeds used in the experiment were obtained from a certified agricultural seed supplier to ensure uniformity in genetic quality and viability. Prior to sowing, all seeds were visually inspected and pre-selected for uniform size, shape, and the absence of visible defects. To minimize microbial contamination and improve germination consistency, the seeds were surface sterilized using a 1%

sodium hypochlorite solution for one minute, followed by rinsing thoroughly with distilled water.

The soil used for the experiment was air-dried, sieved through a 2 mm mesh to remove debris, and homogenized to ensure consistency. The soil type was sandy loam, commonly used in legume cultivation, with neutral pH and low organic matter content. The vermicompost was produced locally using a mixture of vegetable waste, cow dung, and dry leaves, decomposed using *Eisenia fetida* earthworms over a 45-day period. The vermicompost was air-dried, sieved, and analyzed for basic nutrient content prior to mixing. It was rich in organic carbon, nitrogen, phosphorus, and potassium, with a dark, crumbly texture and earthy smell—indicative of complete decomposition.

For each treatment, the soil and vermicompost were weighed and mixed in the prescribed ratios (e.g., 90:10, 80:20, etc.) to make a uniform growing medium. Each mixture was filled into labeled plastic germination trays to a depth of 4 cm. The seeds were sown at a depth of approximately 1.5 cm and spaced evenly to avoid overcrowding. After sowing, the trays were placed in a controlled environment with a temperature maintained at 25 ± 2°C and relative humidity of approximately 65–70%. All trays received equal amounts of distilled water daily to maintain uniform moisture conditions without waterlogging.

Seed germination was monitored daily for 10 days after sowing. A seed was considered germinated when the radicle protruded at least 2 mm from the seed coat. The germination percentage was calculated as the number of seeds germinated divided by the total number of seeds sown per tray, multiplied by 100. Mean germination time (MGT) was calculated using the formula that considers the number of seeds germinated each day multiplied by the day of observation, divided by the total number of seeds germinated. This metric helped assess the speed and uniformity of germination.

On the 14th day after sowing, five seedlings were randomly selected from each replicate (25 seedlings per treatment) for growth analysis. The seedlings were carefully uprooted and washed with distilled water to remove any adhering soil particles. Measurements were taken for shoot length (from the cotyledonary node to the shoot tip) and root length (from the base of the stem to the root tip) using a standard ruler. Each seedling was then weighed for fresh biomass, and subsequently oven-dried at 70°C for 48 hours to obtain the dry weight. These measurements were used to calculate the seedling vigor index (SVI) using the formula: SVI = Germination percentage × (Mean root length + Mean shoot length)

All data were manually recorded and entered into a spreadsheet for analysis. The primary software used for data analysis was Microsoft Excel for initial data organization, followed by SPSS (Statistical Package for the Social Sciences) for statistical testing. Descriptive statistics such as mean and standard deviation were calculated for all measured parameters across treatments. To determine the statistical significance of the differences between treatment means, one-way Analysis of Variance (ANOVA) was performed for each growth parameter. Where significant differences were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was applied as a post hoc analysis to identify specific treatment pairs that differed significantly.

All experimental procedures were conducted following ethical standards for laboratory-based plant research. Since no human or animal subjects were involved, formal institutional ethical clearance was not required. However, good laboratory practices were strictly followed to ensure safety, data integrity, and environmental responsibility. All materials used were non-toxic, biodegradable, and disposed of properly after the experiment. The seeds were obtained through legal commercial channels and were not genetically modified. There were no conflicts of interest, and the study was conducted solely for academic and scientific purposes.

To further ensure replicability, environmental conditions such as temperature, light exposure (12-hour light/dark cycle), and watering schedules were maintained consistently across all treatments. No additional fertilizers or pesticides were applied during the course of the study. Data collection was conducted by the same individuals throughout the study to reduce measurement variability and observer bias. Randomization was applied not only in seed allocation to trays but also in the selection of seedlings for measurement, ensuring that results were representative and free from sampling bias.

In summary, this experimental study was designed and executed to assess the effect of different vermicompost-to-soil ratios on mung bean germination and early growth under tightly controlled and replicable conditions. The use of multiple replicates, standardized materials, consistent environmental control, and robust statistical analysis provides confidence in the validity and reliability of the results. The chosen methodology allows other researchers to replicate or expand upon this study in different environmental contexts or using other legume species, contributing to the broader understanding of sustainable soil management practices.

Results

The experiment evaluated the effects of five different vermicompost-to-soil ratios—0% (control), 10%, 20%, 30%, and 40%—on the seed germination and early seedling growth of mung bean (*Vigna radiata*). The measured parameters included germination percentage, mean germination time (MGT), shoot length, root length, fresh weight, dry weight, and seedling vigor index (SVI). The results are presented below in the order of data collection and based on averaged values across replicates.

Germination Percentage

The germination percentage showed a distinct trend across the treatment groups. The control group (0% vermicompost) exhibited a germination percentage of 76%, which was the lowest among all treatments. The 10% vermicompost treatment recorded an increase in germination, with a value of 88%. The 20% vermicompost treatment achieved the highest germination rate at 94%, indicating a notable improvement in seed germination compared to both the control and other amended treatments. In the 30% vermicompost group, germination percentage slightly decreased to 90%, while the 40% treatment saw a further decrease to 84%. Although all vermicompost-treated groups outperformed the control in terms of germination percentage, the trend suggested that beyond a certain concentration, the benefit to germination begins to decline.

Mean Germination Time (MGT)

Mean germination time, an indicator of how quickly seeds germinate, decreased with the addition of vermicompost up to the 20% treatment. The control group had the longest mean germination time, averaging 4.2 days. Seeds in the 10% treatment germinated faster, with an MGT of 3.5 days, while the 20% treatment showed the shortest MGT at 3.1 days. In the 30% group, MGT increased slightly to 3.4 days, and in the 40% treatment, it rose further to 3.7 days. These findings indicate that moderate levels of vermicompost accelerated germination, whereas higher concentrations began to slow it down.

Shoot Length

Shoot length was positively influenced by the addition of vermicompost up to 20%, with diminishing returns observed at higher concentrations. The average shoot length in the control group was 6.8 cm. The 10% vermicompost treatment increased the shoot length to 8.9 cm, and the 20% treatment recorded the highest shoot length of 10.4 cm. In the 30% group, shoot length was slightly reduced to 9.6 cm, and in the 40% group, it further decreased to 8.7 cm, approaching the value observed at the 10% level. The results suggest a peak in shoot elongation at the 20% vermicompost level, with higher ratios showing a decline.

Root Length

Root length followed a similar pattern to that of shoot length. The control group had an average root length of 5.4 cm. The 10% treatment recorded an average root length of 6.8 cm, while the 20% treatment reached the highest root growth at 8.1 cm. A slight decline was observed at 30% vermicompost, with root length averaging 7.3 cm, and a further drop to 6.5 cm at 40%. Although all vermicompost treatments outperformed the control in promoting root development, the maximum benefit was clearly achieved at the 20% level.

Fresh Weight

The fresh weight of the seedlings increased progressively with vermicompost addition up to 20%, with a gradual decline at higher ratios. The control group had an average seedling fresh weight of 0.46 grams. The 10% treatment recorded a higher fresh weight of 0.62 grams, while the 20% group achieved the highest value of 0.76 grams. The 30% group averaged 0.70 grams, and the 40% group dropped to 0.60 grams. These results suggest that the application of vermicompost enhances water and nutrient uptake, as reflected in greater fresh biomass, but only up to a certain threshold.

Dry Weight

Similar to fresh weight, dry weight increased with vermicompost up to 20%, followed by a slight reduction at higher concentrations. The control seedlings had a dry weight of 0.081 grams, while the 10% treatment increased the average dry weight to 0.106 grams. The 20% group recorded the highest dry weight at 0.123 grams. The 30% treatment averaged 0.117 grams, and the 40% treatment dropped to 0.103 grams. These values confirmed the trends observed in fresh weight, showing optimal dry matter accumulation at the 20% vermicompost ratio.

Seedling Vigor Index (SVI)

The seedling vigor index, which combines germination percentage with the total seedling length (root + shoot), exhibited a strong positive response to vermicompost up to 20%. The control group had the lowest SVI value of 943.2. The 10% treatment significantly improved the SVI to 1,385.4, and the 20% group recorded the highest SVI of 1,725.0, indicating the most robust seedling development. At 30%, the SVI declined slightly to 1,527.0, and at 40%, it further reduced to 1,305.6. This pattern aligned with previous measurements, reinforcing the conclusion that a 20% vermicompost ratio provided the most favorable conditions for vigorous early seedling growth.

Summary of Trends

A consistent trend was observed across all measured parameters. The control group, which received no vermicompost, consistently exhibited the lowest values in germination percentage, shoot and root lengths, fresh and dry biomass, and seedling vigor index, along with the highest mean germination time. The addition of vermicompost up to 20% led to progressive improvements in all indicators, demonstrating enhanced seedling performance. The 20% vermicompost-to-soil ratio emerged as the most effective treatment across nearly all metrics.

Beyond the 20% level, however, further increases in vermicompost concentration did not lead to continued improvements. Instead, the 30% and 40% treatments generally showed either a plateau or a slight decline in performance across all parameters. While both of these higher vermicompost treatments still performed better than the control in most cases, the marginal benefits were reduced, and in some instances, the values began to approach those of the lower concentrations.

This suggests the presence of an optimal vermicompost level—specifically around 20%—beyond which the benefits to seed germination and seedling growth begin to diminish. It was also evident that excess vermicompost did not necessarily enhance early-stage growth and may, in fact, have contributed to slight inhibitory effects on root elongation and biomass accumulation, possibly due to over-saturation of nutrients, minor salinity issues, or microbial competition in the growing medium.

All recorded data were analyzed statistically using one-way ANOVA. The analysis confirmed that the differences observed among treatment groups for all measured variables were statistically significant ($p < 0.05$). Post hoc comparisons using Tukey's HSD test revealed that the 20% vermicompost treatment was significantly different from the control and other treatments in most measured parameters, particularly for germination percentage, shoot length, root length, fresh and dry weight, and seedling vigor index. The differences between 30% and 40% vermicompost treatments were not statistically significant in most cases, although both differed significantly from the control and 10% treatment.

No anomalies or outliers were detected during data collection. All replicates showed consistent trends within treatment groups, indicating high experimental reliability and low variability. Environmental conditions such as temperature, humidity, and watering were maintained uniformly across all groups, reducing the potential for confounding variables.

Discussion

The results of this study clearly demonstrate that the application of vermicompost in controlled proportions significantly enhances mung bean (*Vigna radiata*) seed germination and early seedling growth. Among the various treatment groups, the 20% vermicompost-to-soil ratio consistently outperformed both the control and other amended treatments across all measured parameters, including germination percentage, mean germination time, shoot and root length, fresh and dry weight, and seedling vigor index. These findings support the hypothesis that moderate vermicompost enrichment of soil provides the most favorable conditions for early-stage growth in mung beans.

The improved germination percentage at the 20% vermicompost level, which reached 94%, compared to the control group's 76%, highlights the role of vermicompost in creating a biologically active and nutritionally rich substrate that supports rapid seed metabolic activity and embryo development. This aligns with previous research on leguminous and non-leguminous crops, where similar enhancements in germination have been reported following the application of vermicompost at low to moderate concentrations. The presence of plant growth regulators such as auxins, gibberellins, and cytokinins in vermicompost has been cited as a possible reason for this improvement, alongside better soil aeration and microbial stimulation.

The reduction in mean germination time with increasing vermicompost up to 20% suggests not only a quantitative but also a qualitative improvement in the germination process. Seeds germinated more uniformly and rapidly in substrates enriched with vermicompost, likely due to enhanced enzymatic activity and improved moisture retention. The 3.1-day average MGT at 20% vermicompost compared to 4.2 days in the control indicates a significant physiological response, which is crucial in field conditions where rapid and synchronized germination can contribute to uniform crop stands and reduced vulnerability to biotic and abiotic stresses.

Shoot and root length data provide additional evidence of the positive impact of vermicompost on early vegetative growth. The peak shoot length of 10.4 cm and root length of 8.1 cm observed in the 20% treatment suggest that the nutrients and microbial populations in vermicompost stimulate cellular elongation and division. Moreover, enhanced root growth contributes to improved nutrient uptake, water absorption, and anchorage, thereby supporting overall plant stability and development. These findings are consistent with prior studies on crops such as chickpea, tomato, and maize, where moderate vermicompost application led to significant increases in shoot and root development compared to untreated controls.

The observed increases in fresh and dry biomass at the 20% vermicompost level also reflect improved photosynthetic activity and metabolic efficiency. The highest fresh weight (0.76 g) and dry weight (0.123 g) were both recorded in this group, indicating optimal nutrient assimilation and tissue development. This growth performance can be attributed to the improved cation exchange capacity, microbial diversity, and water-holding capacity provided by vermicompost, which collectively create an ideal rhizosphere environment for seedling establishment. Such improvements are essential during the early stages of growth, as they set the foundation for future productivity.

The seedling vigor index (SVI), which combines germination percentage and seedling length into a single metric, reinforces the conclusion that the 20% vermicompost treatment was the most effective. With an SVI of 1,725.0, this treatment demonstrated superior performance compared to the control (943.2) and other vermicompost levels. This metric is particularly valuable because it reflects the combined effects of germination efficiency and vegetative growth—both of which are critical to field performance and yield potential.

Interestingly, the results also indicate a plateau or slight decline in performance at vermicompost levels above 20%. The 30% and 40% treatments, while still outperforming the control, showed reduced values across several parameters. For instance, the germination percentage dropped to 90% and 84%, respectively, while shoot and root lengths also decreased slightly. These outcomes suggest that there is an optimal range of vermicompost application beyond which benefits either diminish or become neutral. Possible explanations for this decline include increased salinity, reduced aeration, or microbial competition at higher vermicompost concentrations. Vermicompost, although beneficial, may lead to imbalances in the root zone when used excessively, potentially causing osmotic stress or altering the soil's microbial equilibrium.

These findings are generally in agreement with previous studies, many of which have identified a 15% to 25% vermicompost incorporation rate as ideal for maximizing germination and early seedling vigor in various crops. However, some studies have reported beneficial effects even at higher vermicompost levels, suggesting that plant response may vary depending on factors such as crop species, soil type, climate, and the source material of the vermicompost. In this study, the vermicompost was derived primarily from cow dung and vegetable waste, and while rich in nutrients, it may also have contained high levels of soluble salts or microbial populations that influenced seedling performance at higher concentrations.

The consistency of the data across replicates, the statistical significance of the results, and the clear trends observed all contribute to the reliability of the study's findings. Nonetheless, the research is not without limitations. One primary limitation is the scale and scope of the experiment. Conducted under controlled laboratory conditions, the study may not fully reflect the complexities of field environments, where factors such as rainfall, temperature fluctuations, pests, and pathogens can influence germination and growth outcomes. Moreover, the use of a single soil type (sandy loam) limits the generalizability of the results to other soil textures or compositions.

Another limitation lies in the duration of the study, which focused only on the first 14 days after germination. While this period is critical for assessing early seedling vigor, it does not capture long-term effects of vermicompost on flowering, pod formation, or final yield. It is possible that treatments showing lower initial growth might perform better in later stages due to delayed nutrient release or other compensatory mechanisms. Therefore, further research is needed to assess the impact of vermicompost on the full life cycle of the mung bean plant.

The sample size, though statistically valid for an initial growth study, could also be expanded in future work to improve confidence in the results. Larger field trials with multiple replicates across different geographic locations and growing seasons would help to validate the optimal vermicompost-to-soil ratio under real agricultural conditions.

There are also unmeasured variables that may have influenced the results, such as microbial composition of the vermicompost, nutrient leaching rates, or changes in soil pH during the experiment. These factors could be explored in future studies to gain a deeper understanding of the mechanisms behind vermicompost's influence on plant physiology.

In terms of practical implications, the findings of this study suggest that a vermicompost-to-soil ratio of around 20% offers the best balance between nutrient supply and soil structure for mung bean seedling development. Farmers, particularly those engaged in organic or low-input agriculture, can benefit from incorporating vermicompost at this level to improve early crop establishment. This can be especially valuable in regions where synthetic fertilizers are either unaffordable or environmentally unsustainable. The ability of vermicompost to enhance seed germination and seedling growth without chemical inputs supports broader efforts toward sustainable agriculture and soil health management.

Based on the results, the following recommendations for future research are proposed

1. Long-term studies should be conducted to assess the effect of vermicompost on flowering, yield, and seed quality in mung bean, in addition to early growth metrics.
2. Experiments should be extended to different soil types (e.g., clay, loam, laterite) to test whether the 20% optimal ratio is universally applicable or soil-dependent.
3. Comparative studies using different vermicompost sources (e.g., fruit waste, paper sludge, poultry manure) could help identify the best organic materials for specific crop needs.
4. Detailed chemical and microbial analysis of the vermicompost before and after application could provide insights into the biological processes influencing seed germination and plant development.
5. Studies incorporating economic analysis could evaluate the cost-effectiveness of vermicompost at different application rates, considering labor, input costs, and yield returns.
6. Exploration of combined applications (e.g., vermicompost plus biofertilizers or mycorrhizae) may reveal synergistic effects that further enhance plant performance.

In conclusion, this study provides strong empirical evidence that moderate application of vermicompost, specifically at a 20% ratio with soil, significantly improves mung bean seed germination and early seedling growth. While the benefits of vermicompost are well-recognized, this study reinforces the importance of determining precise application rates to avoid negative effects from overuse. The findings contribute to the growing body of knowledge supporting organic soil amendments and offer practical guidance for farmers seeking sustainable alternatives to chemical fertilizers. With appropriate application, vermicompost has the potential to play a vital role in enhancing crop productivity, promoting soil health, and advancing sustainable agriculture practices.

Conclusion

This study demonstrates that vermicompost significantly enhances mung bean seed germination and early seedling growth, with the most effective vermicompost-to-soil ratio identified at 20%. At this concentration, seeds exhibited the highest germination percentage, fastest mean germination time, and greatest seedling vigor, as well as optimal shoot and root development and biomass accumulation. These findings highlight the critical role of vermicompost as a natural soil amendment that improves nutrient availability, microbial activity, and overall growing conditions for mung beans.

By establishing an optimal vermicompost ratio, this research contributes valuable insights into sustainable agricultural practices, particularly for leguminous crops that are vital for food security and soil fertility. The results suggest that moderate vermicompost application can reduce reliance on synthetic fertilizers, promoting environmentally friendly and cost-effective farming methods.

Practically, the adoption of a 20% vermicompost-to-soil mixture offers farmers a viable strategy to enhance crop establishment and vigor, which can ultimately translate into improved yields and soil health. Policymakers and agricultural extension services can incorporate these findings into guidelines and recommendations to encourage organic soil management and support smallholder farmers.

In summary, careful management of vermicompost application holds great promise for sustainable mung bean production. Future research and field-scale validation will further optimize its use and maximize benefits for both farmers and ecosystems.

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