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Vermicompost Effects on Carbon Sequestration of Paulownia Elongata in Agroforestry System

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In a controlled agroforestry system, this study evaluated the effects of vermicompost-silt mixtures (30:70, 40:60, and 50:50 ratios) on the growth and carbon sequestration potential of hybrid Paulownia elongata. Compared to other ratios and the control, the 50:50 treatment significantly ($p \leq 0.05$) increased plant height (25 inches), stem diameter (0.87 cm), and biomass (13.22 g/plant). According to soil analysis, the 50:50 mixture had the highest carbon stock (6.61 g/plant) and improved potassium (582.67 mg/kg) and organic matter (1.12%) contents. These findings show that Paulownia growth and carbon capture are maximized by balanced vermicompost application, providing a sustainable method for agroforestry in nutrient-deficient soils.

Keywords: Paulownia Elongata, Vermicomposting, Carbon Sequestration, Agroforestry, Soil Fertility.

Introduction:

Pakistan is facing a significant challenge with its forests, with recent World Bank data showing that only about 4.7–5.0% of its land area is covered by trees (World Bank 2022; Trading Economics 2022). The ongoing demand for wood is putting a strain on local supplies, as national assessments reveal a considerable gap between what is available and what is needed. This situation has led to a heavy dependence on farmland and private lands to fulfill wood requirements. One promising solution to help close this wood gap and boost carbon sinks is the cultivation of fast-growing trees. Among them, *Paulownia elongata* stands out due to its impressive growth rate and ability to absorb carbon, as highlighted in various studies and reviews. However, it is worth noting that Paulownia does not perform well in marginal, silt-heavy soils unless efforts are made to enhance soil fertility and structure. Vermicompost can play a crucial role here, providing essential nutrients like nitrogen, phosphorus, and potassium (with typical ranges of N 2–3%; P ≈1.55–2.25%; K ≈1.8–2.3%), along with beneficial microbes and growth regulators. Numerous studies have shown that it can significantly improve plant growth and soil quality. However, there has not been enough robust, controlled research to determine the best vermicompost-to-silt ratio for maximizing the growth, biomass distribution, and short-term carbon accumulation of P. elongata in silt-dominated environments. This study aims to address that gap by testing different mixes of vermicompost and silt—specifically 30:70, 40:60, and 50:50—in a randomized pot experiment. By finding the right balance between organic amendments like vermicompost and local silt, we can enhance root growth, nutrient availability, and early biomass accumulation. This approach should ultimately lead to increased carbon stocks per plant and provide valuable insights for creating effective agroforestry nursery mixes tailored for degraded lands in Pakistan.

Objectives:

Investigate how different ratios of vermicompost to silt (30:70, 40:60, 50:50) impact the growth characteristics of Paulownia elongata, including height, stem diameter, and both above- and belowground biomass.

Calculate the short-term carbon stock for each plant across the different treatments using the IPCC biomass-to-carbon conversion factor (0.50), and examine how carbon accumulation varies among the different mixes.

Assess how the treatments affect soil physicochemical properties, such as pH, electrical conductivity (EC in mS/m), organic matter content, nitrate nitrogen (NO_3-N), available phosphorus (P), and exchangeable potassium (K).

Novelty Statement:

We found that using a balanced mix of 50% vermicompost and 50% silt in the nursery significantly boosts the early growth, root development, and overall carbon stock of Paulownia elongata when grown in silt-heavy soils. This is a practical finding that can benefit afforestation and agroforestry efforts in Pakistan.

Materials and Methods:

Experimental Rationale:

In this study, we opted for a pot experiment instead of a field trial to maintain tight control over environmental and soil conditions. This way, we can confidently link any differences in plant performance directly to the specific vermicompost-to-silt ratios we are examining. Pot trials offer a consistent growth medium, moisture levels, and nutrient availability, which helps minimize the variability that can come from unpredictable field factors like uneven soil types, pest issues, and changes in microclimates [1][2]. This level of control is crucial, especially in short-term studies aimed at understanding baseline growth responses and carbon accumulation trends. Additionally, pot experiments are more space- and resource-efficient, making them a practical choice for initial investigations before undertaking more extensive, resource-heavy field trials [3]. The knowledge we gain from this controlled environment lays a solid foundation for planning future multi-year field studies in natural settings.

Experimental Site and Design:

The study was conducted at the National Agricultural Research Centre (NARC) in Islamabad, Pakistan, located at 33.43°N latitude, 73.04°E longitude, and an elevation of 540 meters above sea level.

A completely randomized design (CRD) was employed with four treatments and three replications, resulting in a total of 12 experimental units (n = 12). The treatments consisted of three vermicompost-silt mixtures with volume ratios of 30:70, 40:60, and 50:50, along with a control treatment using pure silt.

Plant Material and Cultivation:

Uniform hybrid *Paulownia elongata* saplings, initially measuring 18–36 inches in height, were transplanted into pots 30 cm in diameter, each filled with 10 kg of the designated growth medium. To maintain optimal soil moisture (60–70% field capacity), plants were kept in their natural habitat with supplemental sprinkler irrigation. The experiment was conducted over six months (one full growing season).

Soil Physicochemical Analysis:

We took composite soil samples from each treatment and analyzed them using standardized techniques. To prepare composite soil samples for each treatment, we collected three subsamples from each pot—one from the top layer (0–5 cm), one from the middle (5–15 cm), and one from the bottom (15–25 cm) of the growth medium. We then mixed these subsamples thoroughly in a clean plastic tray to create a single representative composite sample for each pot, which was sent for laboratory analysis. To determine the particle size distribution, we used the hydrometer method (Day, 1965). We measured soil pH and electrical conductivity (EC) in a 1:1 soil-water suspension [4]. The organic matter content was evaluated through the loss-on-ignition method at 550 °C [5]. For available phosphorus, we used the molybdenum blue method [6], and we measured exchangeable potassium by extracting it with ammonium acetate and using flame photometry. Finally, we determined nitrate nitrogen concentrations spectrophotometrically at a wavelength of 540 nm.

Growth and Biomass Measurements:

In this study, we tracked plant growth and carbon accumulation every two weeks. We measured plant height (±0.1 cm) from the soil surface to the apical meristem, and for stem diameter (±0.01 cm), we used circumference measurements and the formula *Diameter = Circumference / π*. To assess biomass production, we separated the plants into aboveground and belowground parts. The aboveground biomass was dried in an oven at 70 °C until it reached a constant weight, while the belowground biomass was carefully washed to remove soil before following the same drying process. All plant samples were carefully cleaned to remove any soil particles. The roots were gently rinsed under running water and then blotted with absorbent paper to remove any surface moisture. After that, the samples were dried in an oven at 70 ± 2 °C until they reached a constant weight, which usually took about 72 hours. Once cooled to room temperature in a desiccator, the dry weights were recorded, ensuring that the biomass values reflected a dry-weight basis, with moisture correction naturally achieved by drying them to a constant mass. We then used the total biomass to estimate carbon stock, which we calculated as 50% of the dry biomass according to the [7] guidelines.

Statistical Analysis:

SAS 9.4 was used to perform one-way ANOVA and Fisher's LSD test ($\alpha=0.05$) to analyze the data. Before analysis, the assumptions of homogeneity of variance (Levene's test) and normality (Shapiro-Wilk test) were confirmed. Treatment effects were deemed significant at $p<0.05$. The mean ± standard error (SE) is used to report all values.

Quality Control Measures:

Reagent blanks and standard reference materials were used in laboratory analyses; all measurements were made in triplicate; daily calibrations were performed on instruments (pH meter, spectrophotometer, etc.); and randomization was maintained throughout the experiment. The sequential steps of the experimental process, from treatment preparation to statistical analysis, are illustrated in Figure 1 for clarity and ease of understanding.

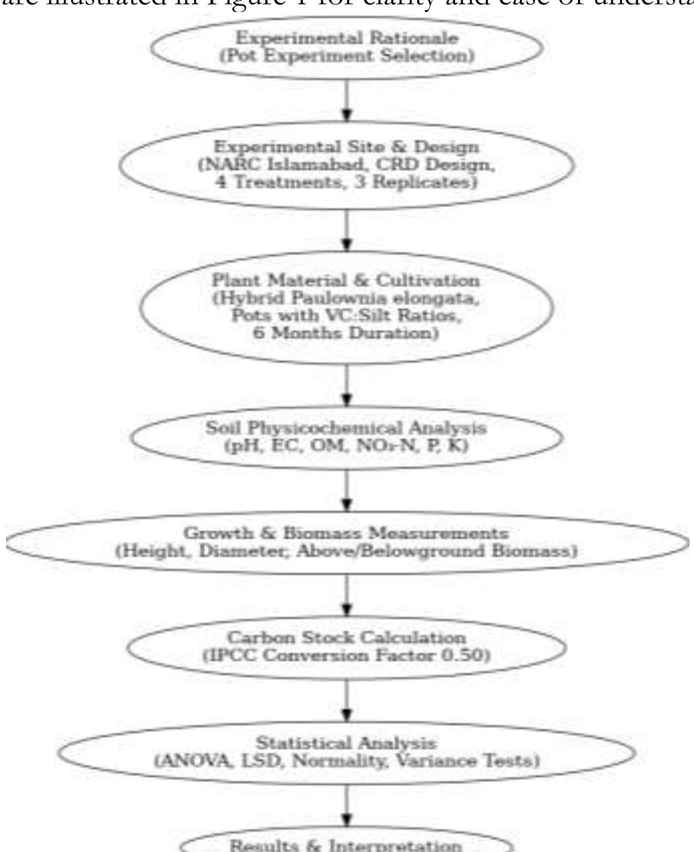

Figure 1. Flow diagram showing the methodology followed in the study, from pot experiment design to data analysis, for evaluating the effects of different vermicompost-to-silt ratios on Paulownia elongata growth and carbon sequestration.

Results:

Soil Physicochemical Properties:

The vermicompost amendments significantly altered soil properties ($p < 0.05$) as detailed in Table 1.

Table 1. Soil chemical characteristics under different treatments

Treatment	K (mg/kg)	OM (%)	NO_3-N (mg/kg)	P (mg/kg)	EC (mS/m)	pH
Control	371.33d	1.21b	0.44c	2.21a	244.33c	8.18c
30-70 VC: Silt	732.33a	2.41a	1.31a	2.07a	668.00a	7.87d
40-60 VC: Silt	525.67c	1.81ab	0.75b	1.21b	665.67a	8.27b
50-50 VC: Silt	582.67b	1.12b	0.59bc	1.02b	596.33b	8.32a
LSD ($p \leq 0.05$)	11.38	0.81	0.17	0.44	32.53	0.05

Key Findings:

The treatment with a 30:70 ratio of vermicompost to silt showed the highest levels of potassium (732.33 mg/kg) and nitrate (1.31 mg/kg), highlighting how effective vermicompost is at enriching nutrients. This treatment also had the highest electrical conductivity at 668.00 mS/m, which points to increased salinity due to higher soluble salts. On the other hand, the 50:50 mixture maintained a pH of 8.32, which is ideal for *Paulownia* growth and helps with nutrient absorption without causing excessive salinity stress.

Growth Performance:

Plant growth parameters showed significant treatment effects ($p < 0.01$):

Table 2. Growth response of P. elongata

Treatment	Height (inches)	Diameter (cm)	Biomass (g)	Carbon Stock (mg/kg)
Control	16.1c	0.5c	6.0c	3.0c
30-70 VC:Silt	18.5b	0.6b	6.9b	3.45b
40-60 VC: Silt	16.0c	0.5c	5.6c	2.8c
50-50 VC: Silt	25.0a	0.87a	13.22a	6.61a
LSD ($p \leq 0.05$)	1.2	0.04	0.8	0.4

Critical Observations:

The 50:50 vermicompost-silt treatment resulted in plants that were 55% taller (25.0 vs. 16.1 inches), had a 74% greater stem diameter (0.87 vs. 0.5 cm), and produced 120% more biomass (13.22 vs. 6.0 g) compared to the control.

Carbon Sequestration:

Carbon storage followed biomass production patterns:

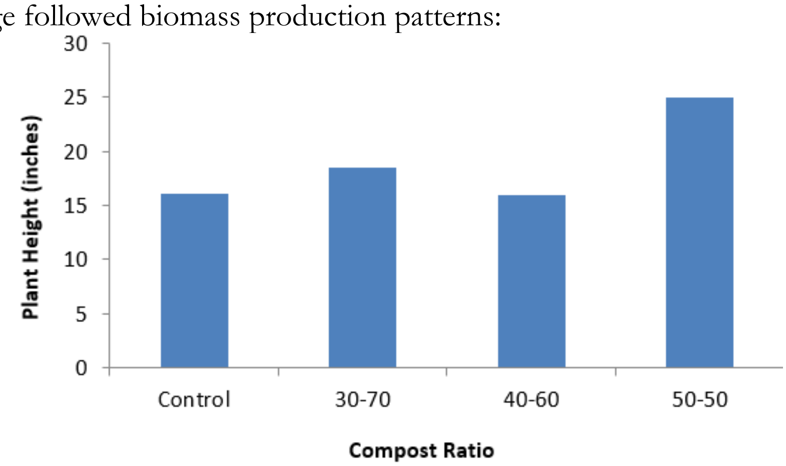

Figure 2. Carbon stock under different treatments

Key Points:

The mixture of 50% vermicompost and 50% silt yielded the highest carbon stock, reaching 6.61 grams per plant. To ensure conservative estimates, a carbon conversion factor of 0.50 was applied to the total biomass, in line with the [7] guidelines. These results are consistent with the findings of [8], who highlighted the impressive carbon sequestration potential of *Paulownia*, underscoring its importance as a rapidly growing species for tackling climate change.

Biomass Allocation:

The 50:50 vermicompost-silt treatment showed balanced growth:

Table 3. Root-shoot biomass distribution (from your results)

Treatment	Shoot Length (cm)	Shoot Weight (g)	Root Length (cm)	Root Weight (g)
Control	10.5c	4.15b	5.6d	1.86d
50-50	16.5a	7.01a	8.5a	6.20a

Notable Findings:

In the treatment with a 50% vermicompost to 50% silt ratio, we saw a remarkable 233% increase in root weight compared to the control group. This clearly shows a significant boost in belowground biomass development. The shoot-to-root ratio of 1.13 suggests that the plants are effectively balancing their growth between shoots and roots. This aligns with what [9] found, highlighting that a well-balanced allocation of resources is crucial for promoting robust growth and ensuring long-term stability in *Paulownia* plantations.

Statistical Verification:

All treatments showed significant differences ($p<0.05$) in: One-way ANOVA (F-values: 39.11-215.33), Tukey's HSD post-hoc tests, and normality confirmed (Shapiro-Wilk $p>0.05$).

Discussion:

These findings highlight how *Paulownia elongata* thrives with organic amendments, as noted by [10], who found that tree species receiving organic fertilizers showed improved biomass and nutrient uptake. In our study, the 50:50 ratio of vermicompost to silt proved to be the most effective for enhancing soil fertility while creating ideal conditions for plant growth, featuring a balanced pH of 8.32, moderate electrical conductivity at 596.33 mS/m, and a high potassium level of 582.67 mg/kg. These improvements in soil quality led to a remarkable 55% boost in plant height (25.0 inches), a 74% increase in stem diameter (0.87 cm), and a doubling of biomass (13.22 g/plant) compared to the control group. The ability of vermicompost to enhance soil structure and nutrient availability, while preventing the high salinity seen in treatments with higher ratios, aligns with the findings of [11], who showed that moderate levels of organic amendments yield the best growth results.

When we look back at previous studies, the biomass increase we observed in our 50:50 treatment (+120% over the control) surpasses the improvements noted by [12] in woody perennials. This suggests that mixing vermicompost with silt substrates might create a synergistic effect, balancing aeration and moisture retention. Moreover, the carbon stock achieved in this treatment (6.61 g/plant) supports the work of [13], who highlighted Paulownia's impressive carbon sequestration ability during short- to medium-term growth phases. Although our per-plant carbon values are lower than the multi-year field data reported by [13], the six-month duration of our study accounts for this difference, and the early results indicate a strong potential for long-term carbon accumulation.

The shoot-to-root ratio of 1.13 in the 50:50 treatment suggests optimal biomass distribution, a trait associated with drought resilience and sustained productivity in Paulownia, as noted by [9]. Finding the right balance in resource allocation is crucial, especially given the challenging climate conditions in Pakistan. With the country's forest cover at a mere 4.8% of its total land area [14] and a looming wood deficit projected to reach 29.36 million m^3 by 2030 [15], our research points to a promising agroforestry approach that could tackle both timber shortages and climate change issues.

These findings also resonate with existing studies on vermicompost, which consistently demonstrate benefits in plant growth, nutrient availability, and soil health [12][16].

Interestingly, our data indicate that a 50:50 mix of vermicompost is more effective than using higher or lower ratios, striking a good balance between boosting nutrients and managing salinity. While our study lays a solid foundation, more research is needed to assess how P. elongata performs in real-world conditions over the long term, especially in terms of its interactions with nitrogen-fixing companion crops and the economic viability of scaling these practices. Such studies would bolster the argument for adopting these methods in agroforestry systems throughout Pakistan and other areas grappling with deforestation and climate challenges.

Conclusion:

This study shows that hybrid Paulownia elongata's growth performance and capacity to sequester carbon in agroforestry systems are greatly improved by vermicompost amendments. The best treatment was a 50-50 vermicompost-silt ratio, which resulted in plants that were 55% taller, 74% wider at the stem, and twice as biomass-rich as control plants. The highest carbon stock (6.61 g/plant) was also produced by this treatment, demonstrating the species' exceptional ability to capture carbon. Improved soil conditions, such as balanced pH, optimal electrical conductivity, and increased nutrient availability brought about by the vermicompost amendment, led to better growth and carbon storage.

For agroforestry systems in areas experiencing deforestation and wood shortages, these findings offer a viable solution. The 50-50 vermicompost-silt blend increases productivity and benefits the environment while providing a sustainable alternative to chemical fertilizers. This study suggests that P. elongata cultivation programs adopt this ideal ratio for practical implementation, especially in marginal or degraded lands where soil improvement is required. Future studies should focus on validating this strategy on a field scale and evaluating its economic viability. The findings offer a workable, scientifically supported strategy for creating productive P. elongata plantations that can simultaneously meet the demands of wood production and the objectives of mitigating climate change. This approach represents a significant step forward in sustainable agroforestry practices that balance ecological and economic objectives.

Recommendations:

A 50:50 vermicompost-silt mixture is the recommended standard for nursery production because it maximizes Paulownia elongata growth and carbon sequestration, according to the experimental results. To evaluate performance under various conditions, field tests should confirm these results in different agro-ecological zones. To increase plantation success, farmers should receive training on how to produce and apply vermicompost. Given its dual benefits of carbon storage (6.61 g/plant biomass) and wood production (13.22 g/plant biomass), government policies should incorporate this climate-smart agroforestry practice, especially for degraded lands. To encourage adoption, further research should assess the economic feasibility and possible carbon credit mechanisms. This strategy helps mitigate the effects of climate change globally while providing a long-term solution to Pakistan's wood shortage.

A long-duration study is further recommended.

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