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POT SIZE MATTERS IN SCREENHOUSE STUDIES ON COWPEA (*VIGNA UNGUICULATA* L.)

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Abstract

Pot size plays a crucial role in cowpea (Vigna unguiculata L.) growth and development under controlled conditions. In this screenhouse study, we compared small (4 L) and large (10 L) pots across 20 replicates using the IT90K-76 genotype. Plants in larger pots consistently outperformed those in smaller ones, showing 40.9% more leaves, 52.5% greater leaf area, and 55.5% heavier seeds, all statistically significant ($P < 0.05$). Root biomass nearly doubled, reinforcing the importance of soil volume for healthy root development. Interestingly, traits such as pod length and seed count per pod remained unchanged, suggesting genetic stability. These findings highlight how pot size can skew experimental outcomes and offer practical guidance for designing more reliable screenhouse trials, especially in legume breeding and pre-breeding programs.

Keywords
crop management, cowpea, legume, pot size, screenhouse experiment, soil volume

Introduction

Cowpea (*Vigna unguiculata* [L.] Walp.) is a climate-resilient legume of immense nutritional, economic, and ecological value, particularly across Sub-Saharan Africa. In Ghana, it serves as a cornerstone of food and nutrition security, contributing significantly to household incomes and national GDP (Agriculture in Africa Media (AfricaagMedia), 2020). Its adaptability to marginal soils, short growth cycle, and ability to fix atmospheric nitrogen make it a strategic crop for smallholder farmers navigating increasingly erratic rainfall and declining soil fertility (Nataline et al., 2018; Singh et al., 2017). Beyond its role as a protein-rich staple, cowpea is also used as fodder, green manure, and a cover crop, reinforcing its multifunctionality in sustainable farming systems (Owusu et al., 2021).

As breeding programs intensify efforts to develop high-yielding, climate-resilient cowpea varieties, screenhouse experiments have become indispensable. These controlled environments allow researchers to isolate specific variables, accelerate phenotyping, and generate reproducible data for early-generation selection (Fageria et al., 2014; Poorter et al., 2012). However, a critical yet often underappreciated factor in such studies is the size of the pots used to grow experimental plants. Pot size directly influences root development, water and nutrient availability, and ultimately, plant performance (Poorter et al., 2012; Sinclair et al., 2017). When pot volume is insufficient, it can constraints root expansion, induce stress responses, and skew physiological traits leading to misleading conclusions about genotype potential (Cassiano et al., 2025; Neumann and George, 2009).

Despite the widespread use of pot experiments in legume research, there is a surprising lack of consensus on optimal pot sizes, particularly for cowpea. Studies in other crops have shown that increasing pot volume can significantly enhance biomass accumulation, photosynthetic efficiency, and reproductive output (Aragão et al., 2020; Ghosh et al., 2019). Yet, few studies have systematically quantified these effects in cowpea, and even fewer have linked pot-induced constraints to implications for breeding or agronomic scaling. Moreover, some traits such as pod length and seed number per pod may be less responsive to pot size, suggesting a complex interplay between genetic control and environmental modulation (El-Sharkawy et al., 2022).

This study addresses that critical gap by evaluating how pot size influences cowpea growth, yield, and root architecture under screenhouse conditions. Using the improved genotype IT90K-76 and a completely randomized design with 20 replicates per treatment, we compared two commonly used pot sizes (4 L and 10 L) to assess their effects on above-ground and belowg-round traits. We hypothesize that larger pots will significantly enhance vegetative growth, reproductive output, and root biomass by improving resource availability and reducing physical constraints. By grounding our findings in robust statistical analysis and linking them to broader agronomic implications, we aim to inform best practices for controlled-environment experimentation and support more accurate phenotyping in legume improvement programs.

Materials and Methods

Study Site and Experimental Design

The experiment was conducted under screenhouse conditions at the CSIR-Crops Research Institute, Fumesua, Ghana (0°43'N, 10°36'W; 186 m above sea level), located within the semi-deciduous rainforest agro-ecological zone. The site experiences a bimodal rainfall pattern, with major and minor cropping seasons commencing in March and September, respectively. Trials were conducted in both 2024 seasons to validate the findings across various temporal conditions.

A completely randomized design (CRD) with 20 replicates per treatment was used. Two pot sizes served as treatments: a small pot (4 L) and a large pot (10 L), representing commonly used volumes in screenhouse trials. The improved cowpea genotype IT90K-76, sourced from the International Institute of Tropical Agriculture (IITA), was used for uniformity. Each pot was filled with homogenized loamy soil, two seeds were sown, and the seedlings were thinned to 1 per pot to ensure consistent plant density. Standard agronomic practices were followed. Plants were irrigated to field capacity as needed, and foliar fertilizer (NPK 20:20:20) was applied in two splits at 2 and 4 weeks after planting. Insect pests were managed with a registered pyrethroid-organophosphate formulation, and hand weeding was performed periodically. At physiological maturity, plants were harvested for yield and biomass assessments.

Data Collection

Phenological traits recorded included days to first flowering, 50% flowering, first podding, 50% podding, and physiological maturity. The measured growth parameters were plant height, stem girth, number of leaves, and leaf dimensions. Leaf area per plant was estimated using standard length-width approximations.

Yield-related traits included the number of pods per plant, pod length, pod weight, number of seeds per pod, and total seed weight. Root traits were assessed post-harvest, including root length, width, angle, and counts of primary and secondary roots. Fresh and dry root biomass were recorded, with dry weights obtained after oven-drying at 50°C for 24 hours.

Root traits, including root length, width, and angle, were also assessed. Root length was measured as the total distance from the root tip to the base of the plant, indicating the plant's ability to access water and nutrients from deeper soil layers. Root width (root diameter) was measured to assess root thickness, which is associated with structural support and enhanced water and nutrient uptake (Comas et al., 2013). Root angle, defined as the orientation of roots relative to the soil surface, was evaluated to determine adaptation to soil conditions, with a steeper angle indicating deeper soil penetration and a shallower angle indicating enhanced surface nutrient acquisition (Uga et al., 2013).

The number of primary and secondary roots was documented. Primary roots, the first to emerge from the seed during germination, are the main support system and foundation for lateral root growth. A higher number of primary roots can indicate better anchorage and initial nutrient uptake efficiency (Wasson et al., 2012). Secondary roots, also known as lateral roots, develop from primary roots and significantly enhance the root system's ability to explore soil resources, thereby improving soil penetration and water absorption (Gruber et al., 2013). The total number of roots was calculated as the sum of all primary and secondary roots, providing an estimate of the plant's soil exploration capacity and nutrient uptake potential (Rich and Watt, 2013).

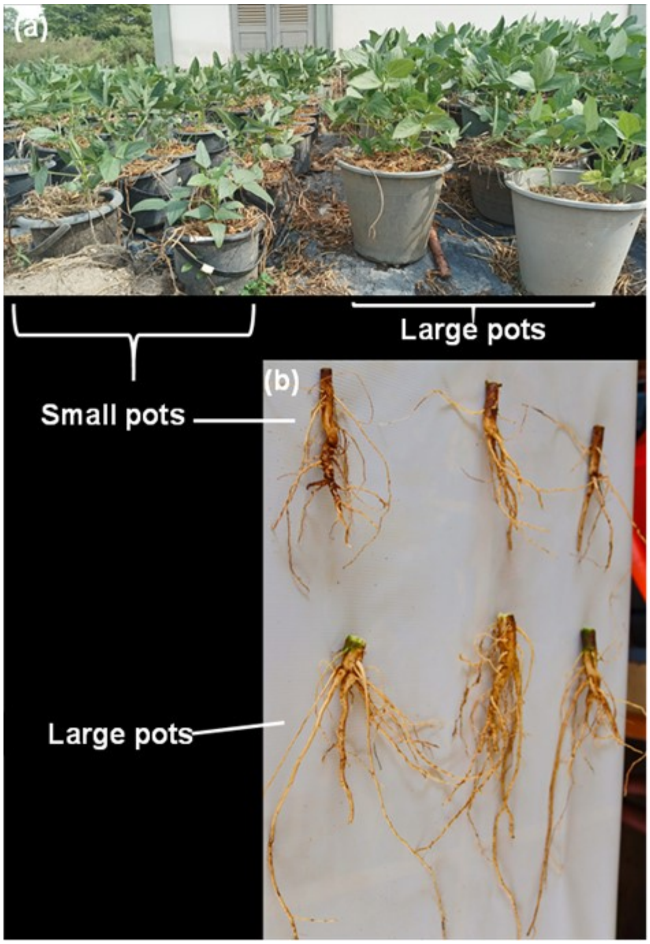

Figure 1. Cowpea plants (above-ground biomass) growing in large and small pot sizes in the upper panel. The lower panels compare cowpea root development in large and small pots.

Biomass measurements included fresh and dry root biomass. Fresh biomass weight was recorded as the total mass of the roots immediately after harvesting, including water content, to provide insights into the overall growth and vigour of the root system under specific environmental conditions (Roumet et al., 2006). The dry biomass weight was obtained by drying the roots in a 50°C oven for 24 hours, providing a stable indicator of root growth efficiency and resource allocation (Poorter et al., 2012).

Statistics

All data were analyzed using JASP Team (2025) version 0.19.3. Before analysis, normality and homogeneity of variance were confirmed using Shapiro–Wilk and Levene's tests, respectively. A Student's t-test was used to compare trait means between the two pot sizes, with significance set at $P \leq 0.05$. Pearson correlation analysis was also conducted to explore relationships between above-ground and below-ground traits. Results are presented as means ± standard error (SE). Visual comparisons of plant and root development

Table 1. Aboveground traits and characteristics of cowpea in different pot sizes

Trait	Treatment	Mean	rank	SD	SE	CV	df	T-Test
Plant Height (cm)	Large pot	41.715	a	5.993	1.340	0.144	38.000	0.030
	Small pot	36.855	b	7.561	1.691	0.205		
Stem Girth (mm)	Large pot	7.598	a	1.846	0.413	0.243	38.000	0.046
	Small pot	6.338	b	2.006	0.448	0.316		
Leaf Number	Large pot	14.650	a	6.548	1.464	0.447	38.000	0.027
	Small pot	10.400	b	5.051	1.130	0.486		
Leaf Width (cm)	Large pot	6.272	a	2.182	0.488	0.348	38.000	0.021
	Small pot	4.905	b	1.304	0.292	0.266		
Leaf Length (cm)	Large pot	7.420	a	1.352	0.302	0.182	38.000	0.098
	Small pot	8.260	a	1.755	0.392	0.212		
Estimated Leaf Area / Plant (cm^3)	Large pot	502.238	a	307.276	68.709	0.612	38.000	0.045
	Small pot	329.168	b	211.745	47.348	0.643		
Number of seeds per pod	Large pot	16.400	a	4.627	1.035	0.282	38.000	0.327
	Small pot	15.000	a	4.292	0.960	0.286		
Pod Length (cm)	Large pot	12.926	a	2.006	0.449	0.155	38.000	0.354
	Small pot	12.257	a	2.480	0.555	0.202		
Number of pods per plant	Large pot	17.400	a	5.679	1.270	0.326	38.000	0.042
	Small pot	13.650	b	5.613	1.255	0.411		
Pod Weight (g)	Large pot	19.585	a	7.954	1.779	0.406	38.000	0.037
	Small pot	14.955	b	5.333	1.193	0.357		
Seed Weight (g)	Large pot	12.560	a	5.708	1.276	0.454	38.000	0.003
	Small pot	8.080	b	2.494	0.558	0.309		
Days to maturity	Large pot	65.000	nan	0.000	0.000	0.000	NaN	NaN[a]
	Small pot	72.000	nan	0.000	0.000	0.000		

across treatments are shown in Figure 1.

Results and Discussion

Results

Above-ground traits and characteristics of cowpea in different pot sizes

The experiment employed a T-test to assess differences in measured traits, comparing cowpea growth and yield performance grown in small pots (4 L) and large pots (10 L). The results indicate significant variations in several key growth and reproductive parameters, demonstrating the influence of pot size on cowpea development and overall productivity (Fageria et al., 2014; Taiz et al., 2015) Table 1.

Cowpea plants grown in large pots exhibited significantly taller plants, averaging 41.72 cm, compared to 36.86 cm in small pots (P = 0.030), suggesting that a larger soil volume provided better access to nutrients and water, thereby promoting vertical growth (Table 1). Similarly, stem girth was significantly larger in large pots (7.60 mm) than in small pots (6.34 mm, P = 0.046), indicating that increased root space enhanced structural development and biomass accumulation (Ghosh et al., 2019) Table 1. The number of leaves per plant was also notably higher in large pots, averaging 14.65 leaves, compared to 10.40 in small pots (p = 0.027), suggesting that larger pots facilitated greater vegetative growth, likely due to improved root expansion and nutrient availability (Table 1). A similar trend was observed in leaf width, where plants in large pots had significantly broader leaves (6.27 cm) compared to those in small pots (4.91 cm, P = 0.021), which potentially contributed to higher photosynthetic efficiency (Table 1) as earlier reports by Zhang et al. (2016) and Li et al. (2021). However, leaf length did not differ significantly between treatments, with large pots averaging 7.42 cm and small pots 8.26 cm (p = 0.098), indicating that leaf expansion in length was not strongly influenced by pot size (Table 1). The estimated leaf area per plant was significantly higher in large pots, reaching 502.24 cm^2. In contrast, small pots recorded only 329.17 cm^2 (P = 0.045), reinforcing earlier observations that cowpea plants in large pots exhibited superior vegetative growth (Table 1). This finding aligns with previous studies indicating that larger root volumes support greater water uptake and nutrient availability, thereby increasing leaf expansion (Nour et al., 2020).

Yield-related traits showed similar patterns. The number of

Table 2. Belowground traits and characteristics of cowpea in different pot sizes

Traits	Treatment	Mean	Rank	SE	SD	CV	df	T-Test
Roots Length (cm)	Large pot	26.840	a	1.389	6.210	0.231	38.000	0.043
	Small pot	23.150	b	1.078	4.821	0.208		
Roots Width (cm)	Large pot	19.622	a	6.363	28.457	1.450	38.000	0.179
	Small pot	10.873	a	0.607	2.717	0.250		
Roots Angle (degrees)	Large pot	122.975	a	9.760	43.647	0.355	38.000	0.779
	Small pot	118.575	a	12.085	54.047	0.456		
Number of Primary Roots	Large pot	13.100	a	0.994	4.447	0.339	38.000	0.450
	Small pot	12.150	a	0.748	3.345	0.275		
Number of Secondary Roots	Large pot	3.700	a	0.193	0.865	0.234	38.000	0.839
	Small pot	3.600	a	0.450	2.010	0.558		
Total Number of Roots	Large pot	16.850	a	1.029	4.603	0.273	38.000	0.440
	Small pot	15.700	a	1.057	4.725	0.301		
Fresh Root Biomass Weight (g)	Large pot	350.925	a	44.230	197.802	0.564	38.000	0.001
	Small pot	178.625	b	19.581	87.568	0.490		
Dry Root Biomass Weight (g)	Large pot	84.075	a	10.585	47.336	0.563	38.000	0.005
	Small pot	48.375	b	5.752	25.723	0.532		

pods per plant was significantly greater in large pots, with an average of 17.40 pods, compared to 13.65 pods in small pots (P = 0.042), suggesting that increased root space enhanced reproductive success (Table 1). This indicates that the greater root expansion in large pots improved nutrient access, thereby enhancing flowering and pod development Kamara et al. (2018). However, pod length remained statistically unchanged, with large pots producing pods measuring 12.93 cm. In comparison, small pots recorded 12.26 cm (p = 0.354), indicating that although more pods were made in large pots, pod elongation was not influenced by pot size (Table 1). This suggests that soil volume influenced pod number but did not directly impact pod elongation, indicating potential genetic control over this trait (El-Sharkawy et al., 2022).

Regarding seed production, the number of seeds per pod did not differ significantly between treatments. Large pots averaged 16.40 seeds, and small pots averaged 15.00 seeds (p = 0.327), suggesting that seed count is relatively stable regardless of soil volume (Table 1). However, pod weight was significantly higher in large pots (19.59 g) than in small pots (14.96 g) (p = 0.037), suggesting that while the number of seeds per pod remained stable, individual pods in large pots had better grain filling (Table 1). This observation was further supported by the seed weight, which was significantly higher in large pots (12.56 g) compared to small pots (8.08 g) (P = 0.003), indicating that plants grown in larger soil volumes had better access to nutrients and water, leading to improved seed quality and overall yield (Table 1). The findings suggest that grain filling was enhanced by greater nutrient and water availability in larger pots (Ahmed et al., 2020). This substantial increase in seed weight further confirms that larger soil volume improves overall crop productivity and grain quality (Aliyu et al., 2019). Another key observation was the difference in the number of days to maturity. Small pot plants reached physiological maturity at 72 days. In contrast, those in large pots matured in 65 days, likely due to stress-induced delays resulting from restricted root growth and limited nutrient uptake in small pots (Table 1). The delayed maturity in small pots likely resulted from growth constraints and stress caused by limited root space, which restricted access to essential nutrients and water, thereby delaying physiological processes (Singh et al., 2017).

Below-ground traits and characteristics of cowpea in different pot sizes

A T-test was conducted to compare the below-ground traits of cowpea plants grown in small pots (4 L) and large pots (10 L). The results indicate that root development and biomass accumulation were significantly affected by pot size, highlighting the importance of soil volume in the expansion and function of the root system. Cowpea plants grown in large pots exhibited significantly longer roots, with an average root length of 26.84 cm, compared to 23.15 cm in small pots (p = 0.043). This suggests that greater soil depth enabled better root penetration and expansion, thereby enhancing water and nutrient uptake efficiency (Table 2). Regarding root width, plants in large pots had an average width of 19.62 cm, nearly double that of plants in small pots (10.87 cm); however, this difference was not statistically significant (P = 0.179). This indicates that while bigger pots facilitated greater lateral root spread, variability within treatments may have influenced the statistical outcome (Table 2).

The root angle, which determines the spatial orientation of the root system, averaged 122.98 degrees in large pots and

118.58 degrees in small pots. However, this difference was not statistically significant (P = 0.779), suggesting that pot size did not significantly alter root growth direction (Table 2). The number of primary roots also showed no significant difference, with large pots averaging 13.10 primary roots and small pots averaging 12.15 primary roots (P = 0.450), indicating that initial root branching may be more genetically controlled than influenced by pot size (Table 2). Similarly, the number of secondary roots did not differ between treatments, with large pots averaging 3.70 roots and small pots averaging 3.60 roots (P = 0.839), indicating that soil volume had a minimal effect on secondary root proliferation (Table 2). Although the total number of roots was slightly higher in large pots (16.85 roots) compared to small pots (15.70 roots), this difference was not statistically significant (P = 0.440), indicating that root initiation occurred at a similar rate across both treatments (Table 2).

However, root biomass accumulation was greatly influenced by pot size. The fresh root biomass weight was significantly higher in large pots, averaging 350.93 g, compared to only 178.63 g in small pots (P = 0.001). This suggests that larger pots provided better conditions for root growth, leading to more biomass accumulation (Table 2). Similarly, dry root biomass weight was significantly greater in large pots (84.08 g) than in small pots (48.38 g, P = 0.005), reinforcing the conclusion that larger root space facilitated better resource allocation and growth (Table 2).

Above-ground trait relatedness of cowpeas under different pot sizes

A t-test comparison of cowpea plants grown in small pots (4 L) and large pots (10 L) revealed significant differences in several growth and yield traits, demonstrating the influence of pot size on plant development. Furthermore, Pearson's correlation analysis (Figure 2) provides deeper insights into the relationships between these traits. Cowpea grown in large pots exhibited significantly greater plant height, averaging 41.72 cm, compared to 36.86 cm in small pots (P = 0.030). The positive correlation (r = 0.421, P = 0.007) between plant height and estimated leaf area per plant suggests that taller plants also developed larger canopies, likely due to improved root expansion and resource uptake in larger pots. Similarly, stem girth was significantly larger in large pots (7.60 mm) compared to small pots (6.34 mm) (P = 0.046), reinforcing the idea that increased soil volume enhances structural growth. The moderate correlation (r = 0.366, P = 0.020) between plant height and stem girth further supports this, as taller plants require stronger stems to sustain their biomass (Figure 2).

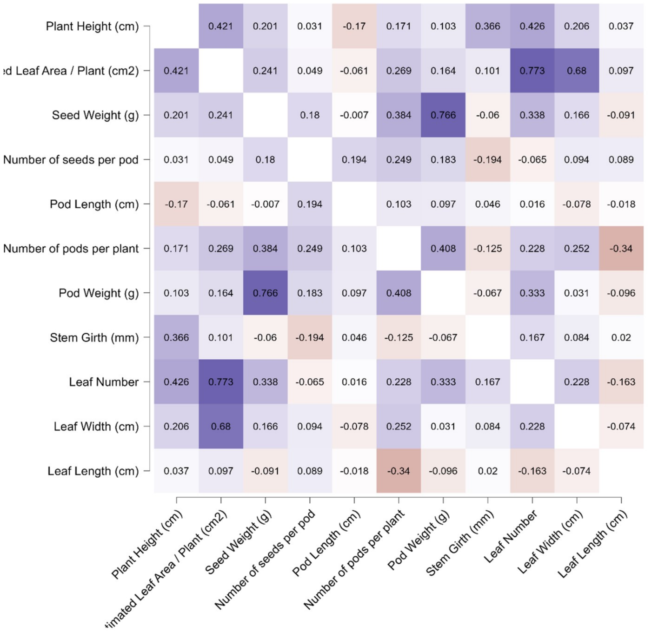

Figure 2. Pearson's correlations of above-ground cowpea traits growing in different pot sizes.

Leaf traits also showed apparent differences between treatments. The number of leaves per plant was significantly higher in large pots (14.65) than in small pots (10.40; P = 0.027), consistent with the strong positive correlation ($r = 0.773$, $p < 0.001$) between leaf number and estimated leaf area per plant (Figure 2). This suggests that plants with more leaves also had larger leaf surfaces, enhancing light capture and photosynthetic efficiency. Additionally, leaf width was significantly greater in large pots (6.27 cm) than in small pots (4.91 cm, P = 0.021). Furthermore, its correlation with estimated leaf area ($r = 0.680$, $P < 0.001$) suggests that increased leaf width contributed to a larger canopy. However, leaf length did not differ significantly between treatments (7.42 cm vs 8.26 cm, P = 0.098). It showed no strong correlation with key growth traits, indicating that pot size had minimal impact on this parameter. Regarding reproductive characteristics, the number of pods per plant was significantly higher in large pots (17.40) than in small pots (13.65; p = 0.042). This trait showed a moderate correlation with seed weight (r = 0.384, P = 0.014), indicating that pod production may influence final yield (Figure 2). Despite this, pod length remained statistically unchanged (12.93 cm vs 12.26 cm, P = 0.354), and the weak correlations with other traits (r = -0.170 to 0.194) suggest that this trait was largely independent of growth conditions. The number of seeds per pod did not differ significantly between treatments (16.40 vs 15.00, P = 0.327) and showed little correlation with overall productivity, highlighting its stability across pot sizes (Figure 2). Pod weight, however, was significantly greater in large pots (19.59 g) than in small pots (14.96 g, P = 0.037). The strong correlation between pod weight and seed weight ($r = 0.766$, $P < 0.001$) suggests that larger pods contributed directly to improved seed production. Similarly, seed weight was significantly higher in large pots (12.56 g) than in small pots (8.08 g; P = 0.003), reinforcing the observation that greater soil volume positively influences seed development. The lack of correlation between seed weight and pod length (r = -0.007, P = 0.964) suggests that pod size was not the primary factor determining variation in seed weight; instead, nutrient availability and resource allocation were more significant. Lastly, days to maturity differed between treatments, with plants in small pots taking longer (72 days) than those in large pots (65 days). This delayed maturity in small pots may be attributed to restricted root development, which limited access to essential nutrients and moisture. The negative correlation between the number of pods per plant and leaf length (r = -0.340, P = 0.032) suggests that plants with more significant reproductive investment allocate fewer resources to vegetative structures, resulting in trade-offs between growth and yield components (Figure 2).

Below-ground trait relatedness of cowpeas under different pot sizes

The Pearson correlation analysis of below-ground traits in cowpea plants grown in different pot sizes revealed varying relationships among root morphology and biomass traits. The results highlight key interactions between root length, width, angle, number of primary and secondary roots, total root number, and root biomass accumulation. Root length and width were positively correlated (r = 0.297, P = 0.063), although this association was not statistically significant at the 5% level (Figure 3). This suggests that as root length increased, root width also tended to increase, potentially indicating a general expansion of root architecture in response to the available soil volume. Root angle, which influences root spreading and nutrient acquisition, showed a weak positive correlation with root length (r = 0.261, P = 0.104) and root width (r = 0.219, P = 0.174), though neither relationship was statistically significant. This suggests that variations in root length and width did not strongly determine the angular spread of the roots (Figure 3).

The number of primary roots showed weak, statistically insignificant correlations with most root traits. It was negatively correlated with root length (r = -0.074, P = 0.650) and root angle (r = -0.064, P = 0.695), indicating that an increase in primary root count did not necessarily result in more pronounced or outwardly directed root growth. Similarly, the number of secondary roots showed no significant correlation with the number of primary roots (r = 0.248, P = 0.124) or with root length ($r = 8.682 \times 10^{-5}$, P = 1.000). However, the total number of roots exhibited a strong and highly significant correlation with the number of primary roots (r = 0.945, $P < 0.001$) and the number of secondary roots (r = 0.542, $P < 0.001$), confirming that root proliferation is dependent mainly on primary and secondary root formation (Figure 3). Root biomass traits were also evaluated with root morphological parameters. Fresh root biomass weight showed no significant correlation with root length (r = 0.096, p = 0.556), width (r = -0.038, P = 0.815), or total root number (r = 0.031, P = 0.849), suggesting that root size and biomass accumulation are influenced by factors beyond root elongation or branching alone. However, dry root biomass weight exhibited a strong and highly significant positive correlation with fresh biomass weight (r = 0.857, $P < 0.001$), confirming that fresh biomass is a strong predictor of final dry matter accumulation (Figure 3).

Figure 3. Pearson's correlations of below-ground cowpea traits growing in different pot sizes.

Discussion

Pot Size and Its Influence on Above-ground and Below-ground Growth in Cowpea

The present study confirms that pot size strongly influences cowpea growth and yield. Plants in larger pots attained greater height, thicker stems, larger leaf area, more pods, heavier pods, and heavier seeds (Table 1), suggesting that a larger root zone facilitates greater uptake of water and nutrients (Bonomelli et al., 2017). Smaller pots, by contrast, appear to impose spatial or hydraulic constraints that limit resource acquisition, consistent with meta-analytic evidence that doubling pot volume often increases biomass by $\sim$43% Poorter et al. (2012). However, it is essential to reflect on the inherent limitations of pot experiments. Passioura (2006) warned that potted systems are susceptible to artefacts, including edge effects, soil compaction, and microclimatic heterogeneity, which may distort physiological responses (e.g., hypoxia in poorly aerated zones and uneven moisture gradients). For example, in shallow or narrow pots, the soil near the edges may heat or dry more quickly, creating localized stress zones. Soil compaction or settling over time can reduce root penetration and aeration. Additionally, microclimate differences (e.g., between the pot surface and ambient air) may lead to deviations in vapour pressure deficit, boundary-layer conductance, or root-zone temperatures relative to field conditions (Passioura, 2006; Poorter et al., 2012).

The geometry and material of the pot may also bias results: non-porous plastic or dark pots absorb more heat, altering soil temperature and thus affecting root metabolic rates or water relations (Kawaletz et al., 2014; Poorter et al., 2012). The ratio of canopy size to soil volume may further exacerbate stress in small pots. As the canopy grows, transpiration demand increases, but limited soil volume may restrict the water supply, leading to stomatal closure, a reduced photosynthetic rate, and feedback suppression of growth. In extreme cases, root–shoot signalling (e.g., via abscisic acid and cytokinins) may shift under confinement, accelerating stress responses (Tardieu et al., 2010). Root restriction has been shown to trigger elevated ABA levels, thereby constricting stomatal conductance and reducing carbon assimilation (Tardieu et al., 2010). In addition, a limited root zone might hinder nutrient uptake kinetics, especially for mobile ions (e.g., nitrate, phosphate), whose depletion zones around roots are relatively small; thus, the competitive advantage of a larger soil mass is magnified (Dalling, 2013).

In our correlation analyses, the tight positive relationships among leaf area, pod weight, and seed weight (Figure 2) reflect coherent root–shoot integration, supporting the notion that greater root biomass and functional root surface area enable more robust carbon and nutrient fluxes. The significant interrelationships among root biomass traits emphasize the importance of below-ground carbon investment in sustaining above-ground yield (Table 2).

Effects of Pot Size on Reproductive Traits and Yield Components

Pot size significantly affected the number of pods, pod weight, and seed weight—mirroring the pattern that larger root zones better support reproductive sink strength. The enhanced assimilate supply resulting from larger soil volumes likely enabled more efficient grain filling. Although pod length and seeds per pod remained similar across treatments, the increased seed mass in large pots suggests superior resource allocation to grain development. This aligns with the literature, which indicates that root depth and nutrient access are critical determinants of cowpea yield (Iseki et al., 2021).

The observation that plants in small pots matured slightly later may reflect a compensatory delay under stress: restricted rooting may have induced subtle nutrient or water limitations, slowing developmental progression. This pattern is consistent with pot studies on legumes, where root confinement induces mild stress that slows reproduction (Sinclair et al., 2017).

Root Architecture and Below-ground Dynamics

Root system architecture is central to resource acquisition, and our results show that pot size profoundly influences root elongation and biomass. In larger pots, roots extended farther and accumulated more mass, reflecting fewer spatial constraints. These findings agree with broader patterns in leguminous and other crops (Poorter et al., 2012). Interestingly, traits such as root width, branching angle, and the count of primary or secondary roots remained relatively stable, implying that architectural branching patterns may be more genetically constrained than plastic in response to soil volume (Nkhoma et al., 2020).

Yet, soil compaction and restricted aeration in smaller pots may impose additional constraints: compacted zones reduce porosity, leading to hypoxic stress that hampers root respiration and nutrient uptake. These mechanical and physiological stresses amplify the pot-size effects on root efficiency (Lipiec et al., 2012). In addition, when root systems are constrained, the kinetics of nutrient uptake (especially for less mobile ions) may slow due to limited root length density and overlap in depletion zones (Dalling, 2013).

Practical Implications, Limitations, and Future Directions

These findings carry critical implications for greenhouse and controlled-environment experiments. The consistent underperformance of plants in small (4 L) pots suggests that many pot-based studies may systematically underestimate plant potential. This reinforces the call by Poorter et al. (2012) to ensure the plant biomass to pot volume ratio remains well under 1 g L^{-1} to avoid artefactual constraints (Poorter et al., 2012).

Nevertheless, pot experiments are valuable for controlled hypothesis testing and comparative screening—provided their inherent limitations are acknowledged and minimized (Passioura, 2006). Future work should integrate non-destructive root imaging, gas exchange measurements (including photosynthesis and stomatal conductance), chlorophyll fluorescence, and isotope tracing to disentangle the physiological pathways by which pot size affects performance. In parallel, field validation is indispensable to ensure that pot-derived insights scale to agronomic reality.

By openly acknowledging artefacts (edge effects, compaction, microclimate, pot material, root–shoot feedbacks) and combining physiological probes with field trials, researchers can enhance the robustness and translatability of pot-based findings for cowpea and other crops.

Conclusion

The findings demonstrate that pot size significantly affects cowpea growth and yield performance. The larger root volume in large pots enabled greater root expansion, resulting in higher plant height, stem girth, leaf area, pod number, pod weight, and seed weight. Traits such as leaf length, pod length, and number of seeds per pod remained unaffected, suggesting that these characteristics are more genetically determined and less influenced by soil volume constraints. The delayed maturity observed in small pots highlights the negative impact of restricted soil space on plant development. These results suggest that, for optimal cowpea growth and yield, providing a larger soil volume is beneficial, either by using larger pots or by growing in field conditions where root development is not restricted. Future studies should investigate nutrient dynamics, root architecture, and stress physiology to better understand the mechanisms underlying growth constraints in limited soil environments.

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