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Research Article

Growth and Yield of Lima Beans as Influenced by Population Density and Staking Alternatives

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Abstract: Lima bean (*Phaseolus lunatus* L.) remains an underutilized legume in Nigeria, partly due to limited agronomic recommendations for optimizing its productivity. The present study investigated the effects of staking methods and plant population density on some agronomic properties of two accessions of Lima bean. The experiment was conducted out at Institute of Agricultural Research and Training research station situated at Ikenne, Ogun state in 2023 and 2024. The treatment combinations consisted of two lima bean accessions (2005-012A and 2006-005A) planted at three population densities: 17777, 13333 and 10000 plant ha⁻¹ respectively and two staking alternatives (trellis staking and vertical staking) with no stakes as control. The experimental design was a split-split plot in a randomized complete block with accession, staking methods and population densities assigned as the main plot, sub-plot and sub-sub plot respectively. Data were analysed using ANOVA with mean separated at $\alpha=0.05$. Vertical staking consistently enhanced vine length, leaf production, biomass accumulation, pod parameters, and grain yield relative to trellis and no staking treatments. Grain yield ranged from 253.1 (10000 plants ha⁻¹) to 347.7 kg ha⁻¹ (13333 plants ha⁻¹). Accession 2006-005A outperformed 2005-012A in grain yield by 25%. No stakes resulted in delayed flowering and the lowest yield (225.14 kg ha⁻¹) compared to vertical (361.94 kg ha⁻¹) and trellis staking (313.08 kg ha⁻¹). The study recommends vertical staking combined with a plant population density of 13333 plants ha⁻¹ for improved lima bean productivity in the study area.

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1. Introduction

Lima beans (*Phaseolus lunatus* L. Walp.) are an important grain legume and source of protein in the diets of Nigerians. In Nigeria, lima bean is cultivated mainly for its dry seeds. Its biomass also helps to improve soil fertility (Abdulraheem et al., 2024).

Despite the potentials in lima beans, it is highly underutilized in Nigeria and it has not received much attention in terms of research studies on agronomic practices plant population densities as compared to cowpea and soybean which has been well researched. Saka et al., (2004) noted that the yield of lima bean is low being estimated at 271 kg ha⁻¹ in south west Nigeria with little or no

improvement targeted towards the production of the crop. In this regard, new production methods of this crop and cropping systems demand research interest.

Plant population density is a key agronomic factor that significantly influences the growth, development and yield of crops (Sher et al., 2017). In legumes, population density affects the competition for resources such as light, water, and nutrients, which in turn impacts plant growth and productivity (Iqbal et al., 2018; Gezahegn, 2019). Studies have shown that high densities often lead to increased competition for essential resources, which can reduce individual plant growth while lower densities may result in the underutilization of available resources, limiting overall yield potential (Ren et al., 2020). Optimal densities ensure efficient light interception and resource use, leading to enhanced growth and productivity (Chapepa et al., 2020; Slattery and Ort, 2021).

A maximum yield of a crop could be obtained mainly by providing the optimum plant population per unit area (Shrikanth et al., 2008). Adebisi et al., (2004) and Abdul-Rafiu (2015) reported that similarly spaced crops of different accessions would produce different yields and the physiological quality of seeds obtained may also differ. For lima bean specifically, the effects of plant population density on growth and yield are not well-documented. Hence, the need for this study.

Staking is also a common agronomic technique used in climbing or semi-climbing legumes such as lima bean to support plant growth, enhance light penetration, and reduce disease incidence. Several staking methods have been explored in the cultivation of different agronomic crops such as yam and cucumber including vertical staking, trellising, and the use of live stakes (Pradhan et al., 2021; Oshunsanya et al., 2022). Vertical staking, often achieved using wooden poles or bamboo sticks, provides direct upward support, reducing lodging and ensuring better light interception. Studies have shown that vertical staking improves fruit set in cucumber, enhances air circulation, and reduces disease pressure, particularly fungal infections that thrive in humid, poorly aerated conditions (Njoku, 2023; Wubetie and Wubetu, 2025). Trellising, another effective staking method, involves the use of a horizontal support system such as wires or ropes to facilitate vine climbing. This method has been reported to increase the total leaf area index, leading to enhanced photosynthesis and overall biomass accumulation (Nair et al., 1999; Kurhekar et al., 2015). The growth habit, canopy architecture, and reproductive pattern of lima bean differ considerably from those of other vining crops which implies there remains a paucity of empirical data specifically addressing staking systems for lima bean. Evaluating different staking methods for lima bean is therefore crucial to determine the most efficient support system for optimizing yield and pod quality, as well as the cost-effectiveness of staking materials and labour. This study aims to generate evidence-based recommendations for improving lima bean productivity, bridging the knowledge gap that exists relative to other well-studied climbing crops. A cultural practice in lima beans cultivation that will enhance staking efficiency, such as the use of a suitable staking method in the form of stakes or trellises, may contribute significantly to farmers' adoption and integration of the crop into their cropping system.

2. Materials and Methods

The experiment was conducted at the Ikenne research station of the Institute of Agricultural Research and Training (IAR&T) which is located on longitude 06°51.074' N and latitude 003°42.626' E (altitude 62 m above sea level) with mean annual rainfall of 1441mm. The experiment was carried out in May to October and June to November of 2023 and 2024 respectively. According to Nigerian Meteorological Agency (NiMet), Nigeria, the average rainfall during the evaluation period (June -Nov) in 2023 and 2024 in Ikenne was 225.95 mm and 316.10 mm, respectively. Temperature ranged from 22 to 33 °C in 2023 and 22 to 34 °C in 2024. Average relative humidity was 87% in 2023 and 89% in 2024.

2.1. Soil sampling

Soil samples were collected with a soil auger at four separate sites from the experimental plots at 0-15 cm depth before the commencement of land preparation.

Soil physiochemical composition of the experimental site determined prior to the experimentation was as follows: pH H₂O: 5.25; organic carbon: 0.62%; total N: 0.1%; P: 8.2 mg/kg; K: 0.33 cmol/kg; Ca: 1.73 cmol/kg; ECEC: 2.85 cmol/kg; sand: 79.80%; silt: 12.00%; clay: 8.20%.

2.2. Procedure, treatments and experimental design

In each of the two seasons, treatment combinations consisted of two lima bean accessions (2005-012A and 2006-005A) planted at three population densities (P): 17777, 13333 and 10000 plant ha⁻¹ (75 cm × 75 cm, 100 cm × 75 cm and 100 cm × 100 cm respectively) and two staking methods; trellis staking and vertical staking (Figure 1) with no stakes as control. In the plots with trellis, stakes were placed between rows of lima bean and equal number of lima bean stands on opposite sides of the stake trilled to it using ropes (Figure 1). The experimental design employed was a split-split plot in Randomized Complete Block Design (RCBD). The main plots consisted of 2 accessions of lima bean and the subplots were three staking methods and sub-sub plot with three plant population densities. Each sub-sub plot size was 6 m x 6 m (36 m²) separated by 2 m.



Figure 1. Pictorial view of the staking alternatives. A represents vertical staking and B represents trellis staking.

2.3. Cultural practices

Lima bean seeds were sown at 2 seeds per hole and later thinned to 1 plant per stand after 2 weeks. Stakes were placed using bamboo poles of about 1.5 m - 2 m long between 2-3 Weeks after Planting (WAP). Application of S-Metolachlor at a rate of 0.960 g ha⁻¹ was made immediately after planting using a knapsack sprayer for pre-emergence control of weeds. Subsequently, weeds were controlled manually every four weeks.

2.4. Data collection

Number of branches per shoot and number of leaves per plant were taken by counting all shoot branches and leaves on 5 sampled plants at 4, 8 and 12 weeks after planting; Vine diameter (mm) was measured using a vernier caliper by placing the caliper around the vine and the readings recorded; Terminal leaflet length and width were recorded by measuring the length and width of five fully grown healthy terminal leaflet at random. Above ground portions of plants were collected from a small portion of net plot at mid-podding. The plants were cut at ground level, weighed, dried at 70 °C and recorded as biomass weight using scale on the field as soon as possible after cutting. Days to 50% flowering is recorded as the number of days from seedling emergence to stage when 50% of plants have begun to flower. Pod length, width, seeds/pod weight, seeds/pod and seed weight/pod were recorded on 10 randomly selected pods. Pod length was measured from peduncle stalk end to pod beak end. Pods/plant and pods/peduncle per plant was recorded on 10 sampled plants at harvest. 100-seed weight (g) was recorded on 100 randomly selected seeds. Grain yield (kg ha⁻¹) was recorded from the total plot (36 m²) and converted to kilograms per hectare.

2.5. Data analysis

The data collected were subjected to analysis of variance using SAS software 9.0 while the treatment means were compared using Least Significant Difference (LSD)

3. Results

3.1. Effect of accession, staking methods and planting densities on vine length, number of leaves, number of main branches and vine diameter of two accessions of lima bean at 4 weeks after planting

Significantly longer vines (15.44 cm) were obtained in 2023 compared to 2024 (13.80 cm) as shown on Table 1. Accession 2005-012A produced longer vines (15.47 cm) than accession 2006-005A (13.71 cm). Vine length was not significantly influenced by the staking methods. However, the effect of plant population was significant on the vine length. Lima planted at 17777 plants ha⁻¹ (15.07 cm) and 13333 plants ha⁻¹ (15.54 cm) produced significantly longer vines than 10000 plants ha⁻¹ (13.24 cm). There was no significant effect of year, accession and staking methods on the number of leaves per plant. Plant populations 17777 plants ha⁻¹ (20.33 cm) and 13333 plants ha⁻¹ (20.07 cm) resulted in significantly higher number of leaves than 10000 plants ha⁻¹ (13.24 cm). Number of main branches of the crop was significantly higher in 2023 (6.16) than in 2024 (5.64). Vertical (6.17) and trellis staking (5.91) led to significantly more branches compared to no staking (5.61) (Table 1). Plant population, 17777 plants ha⁻¹ (6.18), followed by 13333 plants ha⁻¹ (6.03) recorded the highest number of main branches than 10000 plants ha⁻¹ being the lowest (5.47). Vine diameter was not significantly affected by year, accession and plant population. However, staking methods showed clear differences with vertical staking having the thickest vines (0.56 mm), followed by trellis staking (0.51 mm), while no staking produced significantly thinner vines (0.41 mm).

3.2 Effect of accession, staking methods and planting densities on vegetative growth of two accessions of lima bean at 8 weeks after planting

Year 2024 had significantly longer vines (134.76 cm) than 2023 (120.08 cm) (Table 1). Accession 2005-012A produced significantly longer vines (139.85 cm) than 2006-005A (114.98 cm). Staking method significantly influenced vine length with trellis staking resulting in the longest vines (142.60 cm) followed by vertical staking (134.03 cm) and no staking having significantly shorter vines (105.62 cm). Plant population did not significantly impact vine length. Vertical staking had significantly highest number of leaves (68.51). No significant differences were observed in the number of leaves recorded on no staking (62.87 cm) and trellis staking that had the lowest number of leaves (58.05). Years, accession and plant population did not significantly affect number of leaves. No significant effects were observed from year, accession, staking, or plant population on the number of main branches. Also, no significant differences were observed for year, staking methods and plant population for vine diameter at 8 WAP as shown on table 2. However, accession 2006-005A had significantly thicker vines (0.86 mm) compared to 2005-012A (0.80 mm).

3.3 Effect of accession, staking methods and planting densities on vegetative growth of two accessions of lima bean at 12 weeks after planting

Table 1 showed that year 2024 had significantly longer vines (158.02 cm) than 2023 (144.40 cm) at 12 WAP. Also, accession 2005-012A significantly produced longer vines (169.48 cm) than 2006-005A which was shorter (132.95 cm). Staking method had significant effects with vertical staking significantly having the longest vine length (181.04 cm) than trellis staking and no staking (113.30 cm). However, no significant difference were observed in the vine lengths observed from the different plant populations. Vertical staking resulted in the highest leaf number (76.96), significantly exceeding trellis staking (64.07) and no staking (68.28). Other factors such as year, accession and population did not significantly affect the number of leaves (Table 1). Vertical staking resulted in significantly more branches (10.17) compared to trellis staking (6.90) and no staking (7.81). Year, accession and population did not significantly influence this trait. Significant differences in vine diameter were not observed across treatment factors at 12 WAP.

3.4 Effect of accession, staking methods and planting densities on terminal leaf dimensions and biomass dry weight of two accessions of lima bean

Year 2023 had significantly longer leaves (9.21 cm) compared to 2024 (7.73 cm). Also, accession 2005-012A had significantly longer terminal leaves (9.18 cm) than 2006-005A (7.76 cm) (Table 2). Vertical staking resulted in a significantly higher length (8.60 cm) than no staking (8.45) but not significantly different from trellis staking. Plant density of 13333 plants ha⁻¹ resulted significantly in longer terminal leaves (8.64) than 10000 plants ha⁻¹ (8.30 cm) but no significant difference from density of 17777 plants ha⁻¹ (8.46 cm). In the same vein, year 2023 (5.39 cm) and accession 2005-012A (5.33 cm) produced significantly wider leaves compared to 2024 (3.93 cm) and 2006-005A (3.98 cm). No significant differences were observed among staking methods for terminal leaf width. Plant density of 13333 plants ha⁻¹ produced significantly wider terminal leaves (4.87 cm) than plant density of 17777 plants ha⁻¹ (4.66 cm) and 10000 plants ha⁻¹ (4.43 cm). Likewise, year 2023 and accession 2005-012A produced significantly greatest leaf area (37.77 cm² and 37.35 cm² respectively) than 2024 and 2006-005A (23.33 cm² and 23.76 cm² respectively) (Table 2). No significant differences were observed among staking methods for leaf area. Plant population influenced leaf area with 13333 plants ha⁻¹ (32.47 cm²) and 17777 plants ha⁻¹ (30.59 cm²) significantly exceeding 10000 plants ha⁻¹ (28.59 cm²). Vertical staking resulted in significantly higher biomass (1932.17 kg ha⁻¹) compared to trellis (1651.53 kg ha⁻¹) and no staking (1182.70 kg ha⁻¹). Accession 2005-012A had the highest biomass (1550.47 kg ha⁻¹), significantly exceeding 2006-005A (1360.46 kg ha⁻¹). Year effects were not significant on biomass dry weight. Plant population of 17777 plants ha⁻¹ produced significantly higher biomass over populations of 13333 plants ha⁻¹ and 10000 plants ha⁻¹ (Table 2).

3.5 Effect of accession, staking methods and population density on flowering, pod, and yield parameters of two accessions of lima bean

Year 2024 had significantly delayed flowering to 77.44 days compared to 2023 (74.32 days) (Table 3). Also, accession 2005-012A had significantly delayed flowering (77.87 days) relative to 2006-005A (74.02 days). Among staking methods, no staking significantly delayed flowering (82.22 days) compared to vertical and trellis staking which had shorter days to flowering (72.94 and 72.67 days). No significant differences were observed in the number of days to flowering. Year 2024 recorded significantly delayed 50% flowering (79.18 days) compared to 2023 (76.15 days). Accession 2005-012A had delayed flowering (79.5 days) compared to 2006-005A (75.80 days). No staking treated plot further delayed flowering (83.94 days), significantly higher than vertical staking (74.28 days).

In same vein, year 2024 had a significantly delayed podding (83.64 days) than 2023 (79.66 days). Accession 2005-012A showed delayed podding (83.37 days) compared to 2006-005A (79.93 days). No staking treated plot also took the longest time (87.56 days) to pod, while vertically staked plants produced pods in the shortest time (78.17 days) (Table 4.6). Year 2024 had significantly higher pod weight (0.58 g) than 2023 (0.42 g). Accession 2006-005A also had significantly higher pod weight (0.63 g) than 2005-012A (0.37 kg). Vertical staking significantly increased pod weight (0.86 g) compared to trellis (0.51 g) and no staking (0.14 g).

Plant density of 13,333 plants/ha produced significantly higher pod weight (0.69 kg) than 17777 plants ha⁻¹ (0.51 kg). Plant density of 10000 plants ha⁻¹ resulted in the significantly lowest pod weight (0.31 kg). 2023 recorded significantly longer pods (6.17 cm) than 2024 (5.65 cm). Accession 2006-005A had significantly longer pods (6.03 cm) relative to 2005-012A (5.78 cm). Vertical staking (6.12 cm) significantly exceeded trellis (5.86 cm) and no staking (5.75 cm). A similar trend was observed for pod width except that there was no significant year and staking treatment effect (Table 3).

Table 3 also showed that the year 2023 resulted in significantly higher grain yield (315.70 kg ha⁻¹) compared to 2024 (284.40 kg ha⁻¹). Accession 2006-005A produced more yield (333.70 kg ha⁻¹) than 2005-012A (266.41 kg ha⁻¹). Vertical staking significantly increased grain yield (361.94 kg ha⁻¹) compared to trellis staking (313.08 kg ha⁻¹), and no staking resulted in the lowest grain yield (225.14 kg ha⁻¹).

Table 1. Effect of accession, staking methods and planting densities on vegetative growth parameters of Lima bean at 4, 8, and 12 weeks after plankting

Treatments	Vine length (cm)	Number of leaves	Number of main branches	Vine diameter (mm)	Vine length (cm)	Number of leaves	Number of main branches	Vine diameter (mm)	Vine length (cm)	Number of leaves	Number of main branches	Vine diameter (mm)
	4 Weeks after planting				8 Weeks after planting				12 Weeks after planting			
Year												
2023	15.44a	19.77	6.16a	0.51	120.08b	64.24	5.98	0.85	144.40b	68.67	8.19	1.12
2024	13.80b	19.48	5.64b	0.48	134.76a	62.06	5.47	0.82	158.02a	70.87	8.40	1.09
LSD	1.35	0.73	0.29	0.05	7.34	6.59	0.58	0.04	11.3	7.01	1.95	0.06
Accession												
2005-012A	15.47a	19.84	5.96	0.50	139.85a	63.47	5.65	0.80b	169.48a	68.77	7.69	1.09
2006-005A	13.71b	19.40	5.83	0.48	114.98b	62.81	5.81	0.86a	132.95b	70.77	8.90	1.12
LSD	1.35	0.73	0.29	0.05	7.34	6.59	0.58	0.04	11.3	7.01	1.95	0.06
Staking method												
Vertical	15.48	19.58	6.17a	0.56a	134.03a	68.51a	6.13	0.83	181.04a	76.96a	10.17a	1.11
Trellis	14.21	19.66	5.91ab	0.51a	142.60a	58.05b	5.47	0.86	159.30b	64.07c	6.90ab	1.13
No staking	14.17	19.61	5.61b	0.41b	105.62b	62.87ab	5.59	0.81	113.30c	68.28b	7.81b	1.07
LSD	1.65	0.89	0.35	0.06	8.98	8.06	0.71	0.05	13.84	8.59	2.38	0.07
Plant population												
17777 plants ha⁻¹	15.07a	20.33a	6.18a	0.52	129.96	64.26	5.76	0.85	150.94	69.00	7.81	1.11
13333 plants ha⁻¹	15.54a	20.07a	6.03a	0.47	122.28	62.32	5.81	0.81	143.92	69.56	7.69	1.08
10000 plants ha⁻¹	13.24b	18.45b	5.47b	0.47	130.01	62.85	5.67	0.84	158.77	70.75	9.37	1.12
LSD	1.65	0.89	0.35	0.06	8.98	8.06	0.71	0.05	13.84	8.588	2.38	0.07
V × S	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
S × P	ns	ns	ns	ns	**	ns	ns	ns	***	ns	ns	ns
V × P	ns	ns	ns	ns	***	ns	ns	ns	**	ns	ns	ns
V × S × P	ns	ns	ns	ns	***	ns	ns	ns	***	ns	ns	ns

Means with same letter in a column is not significantly different (P<0.05); ns = not significant; *, **, *** significant at 0.05, 0.01 and 0.001 levels of probability respectively.

Plant population of 13333 plants ha⁻¹ caused significantly higher grain yield (347.65 kg ha⁻¹) than 17777 plants ha⁻¹ (299.41 kg ha⁻¹). Plant density of 10000 plants ha⁻¹ produced the significantly lowest grain yield (253.10 kg ha⁻¹). For pod yield, no significant year effect was observed. However, accession 2006-005A recorded higher pod yield (901.70 kg ha⁻¹) compared to 2005-012A (467.26 kg ha⁻¹). Vertical staking led to the greatest pod yield (690.87 kg ha⁻¹), significantly higher than trellis (470.03 kg ha⁻¹) and no staking (492.54 kg ha⁻¹). Plant population of 13333 plants ha⁻¹ resulted in significantly higher pod yield (850.85 kg ha⁻¹) than 17777 plants ha⁻¹ (767.76 kg ha⁻¹). Plant density of 10000 plants ha⁻¹ resulted in the significantly lowest grain yield (434.82 kg ha⁻¹).

Table 2. Effect of accession, staking methods and planting densities on terminal leaf dimensions and biomass dry weight

Treatments	Terminal Leaf Length (cm)	Terminal Leaf Width (cm)	Leaf Area (cm ²)	Biomass (kg ha ⁻¹)	Dry weight
Year					
2023	9.21a	5.39a	37.77a	1469.18	
2024	7.73b	3.93b	23.33b	1441.75	
LSD	0.15	0.16	1.54	99.34	
Accession					
2005-012A	9.18a	5.33a	37.35a	1550.47a	
2006-005A	7.76b	3.98b	23.76b	1360.46b	
LSD	0.15	0.16	1.54	99.34	
Staking method					
Vertical	8.60a	4.63	30.88	1932.17a	
Trellis	8.35ab	4.69	30.37	1651.53b	
No staking	8.45b	4.65	30.40	382.70c	
LSD	0.18	0.20	1.89	121.70	
Plant population					
17777 plants ha ⁻¹	8.46ab	4.66b	30.59a	1539.85a	
13333 plants ha ⁻¹	8.64a	4.87a	32.47a	1458.12ab	
10000 plants ha ⁻¹	8.30b	4.43c	28.59b	368.43b	
LSD	0.18	0.20	1.89	121.70	
V × S	**	**	**	ns	
S × P	***	***	***	ns	
V × P	***	***	***	ns	
V × S × P	***	***	***	ns	

Means with same letter in a column is not significantly different (P<0.05); ns = not significant; *, **, *** significant at 0.05, 0.01 and 0.001 levels of probability respectively.

Table 3. Effect of accession, staking methods and planting densities on flowering, pod and yield parameters

Treatments	Days to first flower	Days to 50% Flowering	Days to 50% Pod	Pod weight (g)	Pod length (cm)	Pod width (cm)	Grain Yield (kg/ha ⁻¹)	Pod yield (kg/ha ⁻¹)
Year								
2023	74.32b	76.15b	79.66b	0.42b	6.17a	1.23	315.70a	660.96
2024	77.44a	79.18a	83.64a	0.58a	5.65b	1.22	284.40b	707.99
LSD	2.111	2.124	2.097	0.09	0.19	0.03	22.31	144.80
Accession								
2005-012A	77.87a	79.5a	83.37a	0.37b	5.78b	1.21b	266.41b	467.26b
2006-005A	74.02b	75.80b	79.93b	0.63a	6.03a	1.25a	333.70a	901.70a
LSD	2.10	2.12	2.10	0.09	0.19	0.03	22.31	144.80
Staking method								
Vertical	72.94b	74.28b	78.167b	0.86a	6.12a	1.24	361.94a	890.87a
Trellis	72.67b	74.72b	79.222b	0.51b	5.86b	1.22	313.08b	670.03b
No staking	82.22a	83.944a	87.556a	0.14c	5.75b	1.23	225.14c	492.54c
LSD	2.59	2.60	2.57	0.11	0.24	0.04	27.32	177.40
Plant population								
17777 plants ha ⁻¹	75.56	77.44	81.56	0.51b	5.99	1.26a	299.41b	767.76a
13333 plants ha ⁻¹	76.72	78.06	81.39	0.69a	5.79	1.21b	347.65a	850.85a
10000 plants ha ⁻¹	75.56	77.44	82.00	0.31c	5.94	1.21b	253.10c	434.82b
LSD	2.59	2.60	2.569	0.11	0.24	0.04	27.32	177.40
V × S	ns	ns	ns	***	ns	ns	***	***
S × P	*	**	**	***	ns	ns	***	*
V × P	ns	ns	ns	ns	ns	ns	**	*
V × S × P	**	**	**	***	ns	ns	***	*

Means with same letter in a column is not significantly different (P<0.05); ns = not significant; *, **, *** significant at 0.05, 0.01 and 0.001 levels of probability respectively.

4. Discussion

The significantly longer vine length observed in 2024 compared to 2023 at 8 and 12 WAP may be attributed to more favourable climatic conditions such as higher early-season rainfall and moderate temperatures that promote vegetative elongation (Keller and Tarara, 2010; Geleta et al., 2024). This pattern supports findings by Danga et al. (2009), who reported that adequate soil moisture enhances stem extension in leguminous crops. The superior vine length recorded in accession 2005-012A suggests a genetic advantage in early vigour and internode elongation, traits considered desirable for rapid canopy coverage (Isa, 2016; Kelly, 2018). Vertical staking contributed to increased vine length and diameter, likely because mechanical support reduces lodging and optimizes light interception along the vine axis, consistent with the observations by Bhardwaj et al. (2025). Denser plant populations of 17777 plants ha⁻¹ resulted in longer vines and more main branches, potentially due to competitive light capture stimulating apical dominance and branching. This interaction between density and growth habit is comparable to previous reports in climbing legumes where closer spacing increased shoot biomass allocation (Benomar et al., 2012; Olawepo et al., 2020). Regarding the number of leaves, the lack of significant variation across years, varieties, and staking methods suggests that leaf initiation rate during early development was relatively stable under the tested conditions. Vine diameter was significantly greater under vertical staking, supporting the idea that mechanical support reduces mechanical stress and promotes vine growth. Similar results were noted by Takusewanya et al. (2017), who observed thicker stems in staked climbing beans compared to unsupported plants. The absence of significant effects of year and accession indicates that stem thickening was primarily a response to staking rather than environmental or genetic factors at this growth stage. The thinner stems under no staking may predispose plants to lodging and breakage, reducing early vigour.

The significant advantage conferred by trellis staking shows that lateral support structures can further stimulate vine length by distributing weight and reducing mechanical drag. This finding corroborates earlier studies indicating that trellis systems maximize vertical and horizontal growth potential (White, 2019; Massrie and Zewdie, 2025). The higher number of leaves recorded under vertical staking compared to trellis and no staking indicates that staking methods influence canopy development beyond simple mechanical support. Improved light distribution and airflow in vertically trained vines can delay senescence and promote sustained leaf expansion (Danko et al., 2024). The lack of significant differences between years and varieties suggests that leaf retention and initiation are largely driven by staking during this growth period. Similar findings have been reported by Asamoah (2022) who documented increased leaf area index in staked cucumber. The lower leaf number observed under trellis staking may result from greater shading within the canopy or mechanical damage to the petioles.

The significantly higher number of main branches observed under vertical staking indicates that staking not only supports axial growth but also encourages lateral branching. This response may be linked to reduced mechanical stress on nodes, facilitating bud break and branch extension (Guimond et al., 1996). The lack of significant varietal and year effects suggests that staking method is the primary driver of branching patterns during this period. The lower branch counts under trellis and no staking treatments could result from increased competition or shading that suppresses axillary bud development. This finding is consistent with Leduc et al., 2014, who emphasized the role of light quality and mechanical constraints in regulating branching. Higher leaf area in accession 2005-012A demonstrates the cumulative effect of longer and wider terminal leaves on overall canopy photosynthetic surface. This observation aligns with Krisnawati and Adie (2017), who reported that genetic differences in leaflet dimensions strongly influence total leaf area index. The higher leaf area recorded in vertical staking further emphasizes the importance of structural support in optimizing canopy development. Among plant populations, 13333 plants ha⁻¹ resulted in larger leaf area, suggesting that intermediate density can balance light interception and inter-plant competition. These results reinforce the need for integrated management combining appropriate accession, staking, and spacing to maximize leaf area.

Biomass dry weight was significantly higher under vertical staking, consistent with the improved leaf area and greater light interception in vertically trained plants. Similar results were documented by Umesh et al. (2023), who observed higher biomass accumulation in staked legumes due to enhanced photosynthetic efficiency. Accession 2005-012A produced greater biomass than 2006-005A, likely reflecting its superior vegetative vigour and leaf development. Plant population effects were less pronounced, though closer spacing tended to support higher biomass, perhaps due to greater

canopy coverage. The delayed flowering observed in 2024 compared to 2023 suggests that seasonal conditions such as lower temperatures or fluctuating rainfall extended the vegetative phase. This trend is consistent with findings by Nelson et al., 2010 who described delayed floral induction in legumes under suboptimal photothermal conditions. Accession 2005-012A also showed a tendency toward later flowering, indicating genetic variability in phenological responses. No staking significantly delayed flowering, likely due to increased shading and reduced light quality within dense, unsupported canopies (Gianoli, 2003). Such delays can impact synchronization of flowering and pod development, with potential yield loss. Pod weight was highest in 2024, suggesting that extended vegetative periods likely provided greater assimilate reserves for reproductive sinks (Noquet et al., 2004). This trend aligns with the observations by Beiküfner et al. (2019) who reported higher pod yield under longer vegetative growth durations. The superior pod weight in accession 2006-005A indicates genetic potential for pod filling and size. Vertical staking significantly enhanced pod weight, likely due to improved canopy structure that supports better light penetration and nutrient allocation to pods (Bhardwaj et al., 2025). As expected, no staking resulted in the lowest pod weight indicating that poor canopy management reduces reproductive allocation. Grain yield and pod yield were highest under vertical staking, demonstrating the cumulative benefit of staking on vegetative growth, phenology, and reproductive development. Similar findings were reported by Musoni et al. (2014), Mazina et al. (2014), and Kajura et al. (2019) who showed that staking significantly increases grain yield in climbing beans. The superior yields in accession 2006-005A shows its genetic potential under proper management. No staking resulted in the lowest yields, confirming the negative impact of lodging and poor canopy structure.

Conclusion

The study evaluated the effects of lima bean accession, staking method, and plant population density on growth, yield, and biomass production in southwestern Nigeria. Accession 2006-005A is recommended for grain production, while accession 2005-012A is suitable where biomass production is desired. Vertical staking should be adopted by farmers cultivating lima bean, as it consistently improved growth, yield, and biomass. A plant population density of approximately 13333 plants per hectare is recommended for optimal yield performance.

Ethical Statement

Ethical approval is not required for this study because no harm was done to the plant and environment.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of any images, figures, graphics, tables, or related titles.

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Author Contributions

The research concept and experimental design were formulated by author 1. The experiment was conducted under the supervision of Author 2, and data collection was carried out jointly by author 1 and author 3. The manuscript was written collaboratively by author 1 and author 2.

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