



INTERACTIVE EFFECTS OF NITROGEN, PHOSPHORUS AND CROPPING SYSTEM ON  
THE GROWTH PERFORMANCE OF POPCORN (*Zea mays* L. Everta) AND LABLAB  
(*Lablab purpureus* L. Rongai) INTERCROPPING

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ABSTRACT

The study evaluated the interactive effects of nitrogen, phosphorus, and cropping systems on the growth performance of popcorn (*Zea mays* var. *everta*) and lablab (*Lablab purpureus*) during the 2020–2022 wet seasons at Bayero University, Kano, Nigeria. Treatments consisted of five nitrogen levels (0, 30, 60, 90, and 120 kg N ha<sup>-1</sup>), three phosphorus levels (0, 30, and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>), and three cropping systems (alternate stand, alternate row, and alternate strip). The factors were factorially combined and arranged in a split–split plot design with three replications, where nitrogen was assigned to the main plots, cropping system to the subplots, and phosphorus to the sub-subplots. Nitrogen and phosphorus application significantly ( $p < 0.05$ ) improved plant height, number of leaves, stem girth, and biomass of both crops. The highest values were obtained with 120 kg N ha<sup>-1</sup> and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, indicating optimal nutrient availability without diminishing returns. Among the cropping systems, the alternate strip arrangement consistently produced superior growth and biomass accumulation, owing to better light interception, root complementarity, and efficient nutrient utilization. Significant N × P and N × cropping system interactions revealed synergistic effects between nutrient supply and spatial configuration. Integrating 120 kg N ha<sup>-1</sup> and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> with alternate strip intercropping optimized growth and resource-use efficiency, demonstrating a practical and sustainable approach for enhancing cereal–legume productivity and soil fertility restoration in the fragile sandy loam soils of the Sudan Savanna.

**Key words:** Biomass, Efficiency, Interaction, Nitrogen and Phosphorus

INTRODUCTION

Nigeria's rapidly growing population continues to increase the demand for food, creating pressure on agricultural systems to produce more with limited land and resources. Sustainable intensification through mechanization and improved agronomic practices is therefore essential to achieving food security (Ene *et al.*, 2025; Fatima & Ying, 2025). Among such practices, cereal–legume intercropping has proven effective in enhancing soil fertility, reducing input costs, and stabilizing yields under smallholder farming conditions (Ibrahim *et al.*, 2025).

Maize (*Zea mays* L.) remains one of Nigeria's most important cereals, both economically and nutritionally, contributing significantly to national food security and rural livelihoods (Erenstein *et al.*, 2022). Popcorn (*Zea mays* L. *everta*), a specialty maize variety, is gaining popularity due to its growing demand in the snack industry, yet remains under-researched in terms of agronomic optimization. Integrating popcorn with nitrogen-fixing legumes such as *Lablab purpureus* could enhance productivity and sustainability by improving nitrogen availability, suppressing weeds, and enhancing soil structure (Gopinath *et al.*, 2024).

Despite its potential, the Sudan Savanna of Nigeria is characterized by low soil fertility, erratic rainfall, and poor nutrient management, all of which contribute to low and unstable maize yields (Tofa *et al.*, 2022). While nitrogen and phosphorus applications are known to enhance crop growth, the optimal levels and interactions of these nutrients under popcorn–lablab intercropping systems remain poorly defined. Most existing research has focused on conventional maize rather than popcorn, limiting available recommendations for farmers seeking sustainable, high-yield production systems.

Integrating lablab into popcorn production systems could provide a cost-effective approach to improving soil fertility, crop performance, and overall farm profitability. Lablab's deep rooting system and nitrogen-fixing ability can enhance soil physical and chemical properties, while efficient nutrient use through intercropping can reduce fertilizer costs and minimize environmental impacts (Mthimunya *et al.*, 2021). Understanding how different nitrogen and phosphorus levels affect this system will help develop nutrient management strategies that optimize both yield and sustainability under Sudan Savanna conditions. The study aims to evaluate the effects of nitrogen and phosphorus levels and cropping systems on the growth, yield, and resource-use efficiency of popcorn and lablab under Sudan Savanna conditions.

## MATERIALS AND METHODS

### The study Area

A field experiment was conducted during the rainy seasons of 2020, 2021, and 2022 at the Teaching and Research Farm, Faculty of Agriculture, Bayero University, Kano, Nigeria (latitude 11°58' N, longitude 8°26' E, 475 m above sea level). The site is located within the Sudan Savanna ecological zone of Nigeria. Before the commencement of the experiment, composite soil samples were randomly collected from the experimental site at a depth of 0–30 cm using a soil auger. The samples were thoroughly mixed to obtain a uniform composite, which was analyzed to determine the physical and chemical properties of the soil following the standard procedures described by Black (1965).

The treatments consisted of five nitrogen levels (0, 30, 60, 90, and 120 kg N ha<sup>-1</sup>), three phosphorus levels (0, 30, and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>), and three cropping systems (alternate stand, alternate row, and alternate strip). These factors were factorially combined and arranged in a split-split plot design, with nitrogen assigned to the main plot, cropping system to the subplot, and phosphorus to the sub-subplot, and the treatments replicated three times. Meteorological data such as rainfall, relative humidity, and temperature were obtained from the Department of Soil Science, Bayero University Kano, throughout the experimental period.

Seeds of popcorn (*Zea mays* L. *everta*) and lablab (*Lablab purpureus* L. *rongai*) were obtained from the National Animal Production Research Institute (NAPRI), Shika, Zaria. Popcorn seeds, which are smaller than other maize varieties and capable of popping, have a maturity period of 85–95 days, while lablab seeds are brown and bean-like, with a maturity period of 90–120 days. The experimental field, which measured 96 m × 76 m (7,296 m<sup>2</sup>), was cleared, ploughed, harrowed, and ridged. It was divided into three replications separated by 2 m alleys, and further subdivided into main, sub-, and sub-subplots. Each sub-subplot measured 5 m × 6 m (30 m<sup>2</sup>), with a net plot area of 5 m × 3 m (15 m<sup>2</sup>) used for data collection.

Seeds of both crops were sown manually according to treatment specifications. Three seeds were placed per hole at a depth of 3 cm and spaced 25 cm apart between stands, and seedlings were thinned to two plants per stand seven days after sowing (DAS). Manual hoe weeding was carried out at 3, 6, and 9 weeks after sowing (WAS). Nitrogen fertilizer was applied in two equal splits at 2 and 6 WAS, while the full dose of phosphorus was applied at 2 WAS. Both fertilizers were applied by band placement. Pest and disease management were carried out using D.D. Force and Cypermethrin, applied with a knapsack sprayer at a rate of 20 mL per 10 L of water whenever infestation was observed.

Plant height was determined from the base to the apex using a meter rule, and stem girth was measured at mid-stem using a tape. The number of leaves per plant was counted, and stem girth was estimated using a standard measuring device. Relative growth rate was calculated as the rate of increase in fresh weight per unit of dry weight per unit of time.

Data collected on growth characters were subjected to analysis of variance (ANOVA) using Statistix 10 software, and treatment means that differed significantly were separated using the Student–Newman–Keuls (SNK) test at the 5% probability level.

## RESULTS AND DISCUSSION

### Physical and Chemical properties of Soil of the Experimental site at during the 2020, 2021 and 2022 rainy seasons

The physical and chemical properties of the soils at the experimental sites prior to treatment application are presented in Table 1. The soils were predominantly sandy in texture, with sand fractions exceeding  $640 \text{ g kg}^{-1}$ , silt ranging between  $190\text{-}220 \text{ g kg}^{-1}$ , and clay content between  $130\text{-}150 \text{ g kg}^{-1}$ . Based on these proportions, the soils were classified as sandy clay loam, typical of the Sudan Savanna zone. The soil reaction (pH 6.1-6.9) ranged from slightly acidic to near neutral, which is generally favorable for most field crops. Organic carbon content was low ( $< 0.5\%$ ), indicating poor organic matter status. Likewise, total nitrogen ( $0.04\%$ ) and available phosphorus ( $< 5 \text{ mg kg}^{-1}$ ) were below the critical levels required for optimal crop growth. Exchangeable bases ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^{+}$ ,  $\text{Na}^{+}$ ) were low, while cation exchange capacity ( $1.9\text{-}2.0 \text{ c mol kg}^{-1}$ ) was also limited. Micronutrient analysis showed adequate iron levels ( $285\text{-}336 \text{ mg kg}^{-1}$ ) but relatively low zinc concentrations ( $3\text{-}11 \text{ mg kg}^{-1}$ ).

**Table 1: Physical and Chemical properties of Soil of the Experimental site at during the 2020, 2021 and 2022 rainy seasons**

| Soil properties                                              | Season (0-30 cm) |            |            |
|--------------------------------------------------------------|------------------|------------|------------|
|                                                              | 2020             | 2021       | 2022       |
| <b>Physical (<math>\text{g kg}^{-1}</math>)</b>              |                  |            |            |
| Sand                                                         | 262.24           | 205.6      | 204.8      |
| Silt                                                         | 170.00           | 109.6      | 190.6      |
| Clay                                                         | 563.90           | 603.6      | 602.0      |
| Textural class                                               | Sandy loam       | Sandy loam | Sandy loam |
| <b>Chemical</b>                                              |                  |            |            |
| pH in ( $\text{H}_2\text{O}$ )                               | 6.4              | 6.5        | 6.3        |
| pH in ( $\text{CaCl}_2$ )                                    | 5.16             | 5.59       | 5.55       |
| OC ( $\text{g kg}^{-1}$ )                                    | 0.47             | 0.71       | 0.70       |
| Total Nitrogen ( $\text{g kg}^{-1}$ )                        | 0.04             | 0.03       | 0.04       |
| Available P ( $\text{mg kg}^{-1}$ )                          | 5.37             | 5.46       | 5.40       |
| <b>Exchangeable bases (<math>\text{cmol kg}^{-1}</math>)</b> |                  |            |            |
| $\text{Ca}^{++}$                                             | 1.83             | 1.70       | 1.71       |
| $\text{Mg}^{++}$                                             | 1.25             | 0.47       | 0.51       |
| $\text{K}^{++}$                                              | 0.20             | 0.19       | 0.20       |
| $\text{Na}^{++}$                                             | 0.12             | 0.07       | 0.09       |
| CEC                                                          | 4.57             | 2.42       | 2.41       |

### Plant Height of Popcorn and Vine Length of Lablab as influenced by Nitrogen, Phosphorus and Cropping System at BUK during the 2020, 2021 and 2022 Wet Seasons

Table 2 presents the influence of nitrogen, phosphorus, and cropping system on the plant height of popcorn and vine length of lablab across the 2020, 2021, and 2022 wet seasons at BUK. Nitrogen application significantly ( $p < 0.05$ ) influenced the plant height of popcorn in 2020 and 2021, though the effect was not significant in 2022. The tallest popcorn plants ( $134.69 \text{ cm}$ ) were recorded at  $120 \text{ kg N ha}^{-1}$  in 2020, while shorter plants ( $119.08\text{-}120.47 \text{ cm}$ ) were observed at lower nitrogen levels ( $0\text{-}60 \text{ kg N ha}^{-1}$ ). Similarly, vine length of lablab responded significantly to nitrogen in 2020 and 2021, with the longest vines ( $149.27\text{-}150.79 \text{ cm}$ ) recorded at  $90\text{-}120 \text{ kg N ha}^{-1}$ . However, in 2022, nitrogen had no significant effect ( $p > 0.05$ ) on vine length. These results indicate that nitrogen played a key role in promoting vegetative growth in both crops, particularly during the first two seasons.

In a similar trend, phosphorus application significantly ( $p < 0.05$ ) increased the plant height of popcorn in 2020 and 2021, but not in 2022. The tallest plants were recorded at  $60 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$  ( $149.94 \text{ cm}$  in 2020 and  $53.87 \text{ cm}$  in 2021). For lablab, phosphorus exerted a strong and consistent positive influence on vine length across all three seasons, with the highest mean values ( $168.70 \text{ cm}$  in 2020 and  $168.27 \text{ cm}$  in 2021) observed at  $60 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ , while the lowest vine lengths occurred

in the control plots ( $0 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ ). This consistent response suggests that phosphorus availability was crucial for vigorous vine growth in lablab throughout the study period.

Across the cropping systems, significant effects were also observed for both popcorn and lablab growth. Popcorn plant height varied significantly among systems in 2020 and 2021, with the alternate strip system producing the tallest plants (145.53 cm in 2020 and 51.14 cm in 2021), followed by the alternate row and alternate stand systems. Likewise, vine length of lablab was greatest under the alternate strip system across all three seasons, indicating that this spatial arrangement favored better growth performance compared to the other intercropping patterns. The interaction between experimental factors were significant and are presented in Table 3-5.

**Table 2: Plant Height of Popcorn and Vine Length of Lablab as influenced by Nitrogen, Phosphorus and Cropping System at BUK during the 2020, 2021 and 2022 Wet Seasons**

| Treatment                                                                | Popcorn             |                    |       | Lablab              |                     |                    |
|--------------------------------------------------------------------------|---------------------|--------------------|-------|---------------------|---------------------|--------------------|
|                                                                          | 2020                | 2021               | 2022  | 2020                | 2021                | 2022               |
| <b>Nitrogen (<math>\text{kg N ha}^{-1}</math>)</b>                       |                     |                    |       |                     |                     |                    |
| 0                                                                        | 120.47 <sup>c</sup> | 47.82              | 29.10 | 137.73 <sup>c</sup> | 139.23 <sup>b</sup> | 34.32              |
| 30                                                                       | 119.10 <sup>c</sup> | 48.00              | 29.23 | 135.64 <sup>d</sup> | 135.73 <sup>b</sup> | 34.62              |
| 60                                                                       | 119.08 <sup>c</sup> | 46.79              | 28.42 | 132.74 <sup>e</sup> | 136.32 <sup>b</sup> | 34.52              |
| 90                                                                       | 121.99 <sup>b</sup> | 48.44              | 33.89 | 139.89 <sup>b</sup> | 149.27 <sup>a</sup> | 34.95              |
| 120                                                                      | 134.69 <sup>a</sup> | 48.88              | 30.56 | 137.73 <sup>c</sup> | 150.79 <sup>a</sup> | 36.24              |
| P of F                                                                   | 0.000               | 0.050              | 0.125 | 0.000               | 0.010               | 0.698              |
| SE $\pm$                                                                 | 0.645               | 0.568              | 1.949 | 0.890               | 3.834               | 1.455              |
| <b>Phosphorus (<math>\text{kg P}_2\text{O}_5 \text{ ha}^{-1}</math>)</b> |                     |                    |       |                     |                     |                    |
| 0                                                                        | 73.31 <sup>c</sup>  | 41.03 <sup>c</sup> | 29.50 | 92.03 <sup>c</sup>  | 100.90 <sup>c</sup> | 38.65 <sup>a</sup> |
| 30                                                                       | 145.95 <sup>b</sup> | 49.06 <sup>b</sup> | 29.22 | 158.06 <sup>b</sup> | 157.63 <sup>b</sup> | 33.80 <sup>b</sup> |
| 60                                                                       | 149.94 <sup>a</sup> | 53.87 <sup>a</sup> | 32.00 | 168.70 <sup>a</sup> | 168.27 <sup>a</sup> | 32.34 <sup>b</sup> |
| P of F                                                                   | 0.000               | 0.000              | 0.135 | 0.000               | 0.000               | 0.000              |
| SE $\pm$                                                                 | 0.558               | 0.515              | 1.503 | 0.733               | 2.461               | 0.893              |
| <b>Cropping System (C)</b>                                               |                     |                    |       |                     |                     |                    |
| Alternate stand                                                          | 108.77 <sup>c</sup> | 45.83 <sup>c</sup> | 27.86 | 123.04 <sup>c</sup> | 123.28 <sup>c</sup> | 36.71 <sup>a</sup> |
| Alternate row                                                            | 114.89 <sup>b</sup> | 46.99 <sup>b</sup> | 31.55 | 134.46 <sup>b</sup> | 142.65 <sup>b</sup> | 35.23 <sup>a</sup> |
| Alternate strip                                                          | 145.53 <sup>a</sup> | 51.14 <sup>a</sup> | 31.31 | 161.29 <sup>a</sup> | 160.88 <sup>a</sup> | 32.85 <sup>b</sup> |
| P of F                                                                   | 0.000               | 0.000              | 0.067 | 0.000               | 0.000               | 0.001              |
| SE $\pm$                                                                 | 0.498               | 0.469              | 1.661 | 0.772               | 2.448               | 0.875              |
| <b>Interaction</b>                                                       |                     |                    |       |                     |                     |                    |
| N x C                                                                    | 0.000               | 0.006              | 0.416 | 0.000               | 0.011               | 0.443              |
| N x P                                                                    | 0.000               | 0.012              | 0.147 | 0.000               | 0.019               | 0.254              |
| C x P                                                                    | 0.000               | 0.000              | 0.191 | 0.000               | 0.000               | 0.000              |
| N x C x P                                                                | 0.000               | 0.003              | 0.093 | 0.000               | 0.000               | 0.026              |

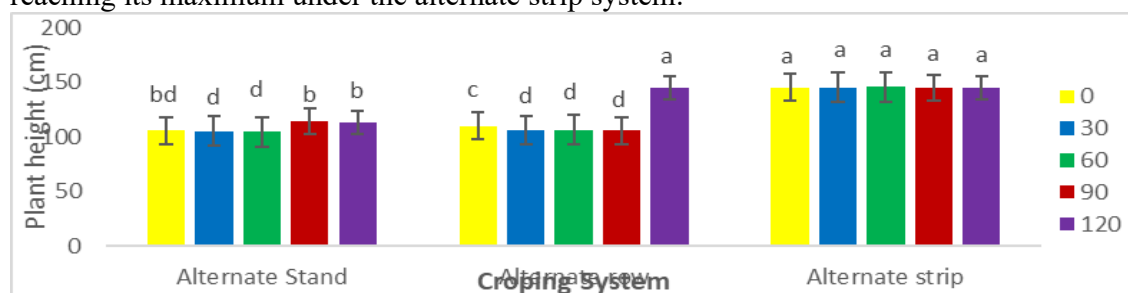
NB: Means within the same treatment column followed by different letters differ significantly using Student-Newman Keuls Test (SNK).

### Interaction Effects

The interaction between nitrogen and cropping system significantly ( $p < 0.05$ ) affected the plant height of popcorn at 10 WAS during the 2020 wet season is shown in Figure 1. The tallest plants (146.00 cm) were recorded under the combination of  $60 \text{ kg N ha}^{-1}$  and the alternate strip system, while the shortest plants (104.57 cm) occurred in the alternate stand system at the same nitrogen level. Plant height generally increased from the alternate stand to the alternate row and was highest under the alternate strip arrangement across nitrogen levels.

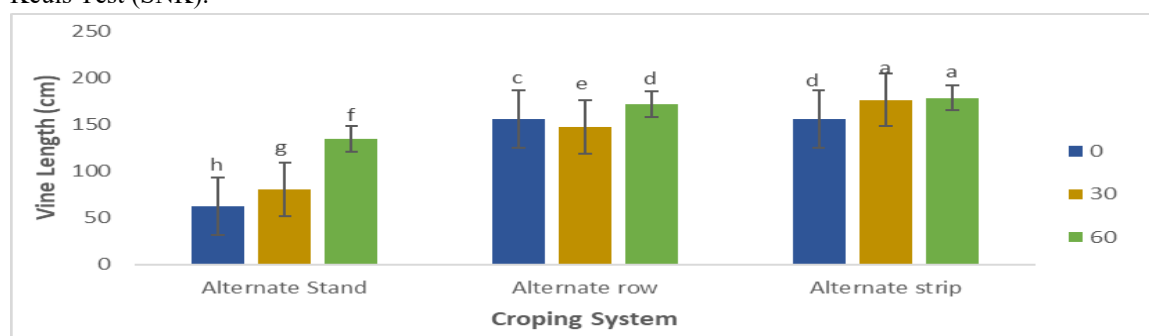
The interaction between phosphorus and cropping system significantly ( $p < 0.05$ ) influenced the vine length of lablab at 10 WAS during the 2020 wet season (Figure 2). The longest vines (178.36 cm) were obtained from the combination of 60 kg  $P_2O_5$   $ha^{-1}$  and the alternate strip system, while the shortest vines (62.11 cm) were observed under the alternate stand system without phosphorus application. Vine length increased progressively with phosphorus rate and cropping intensity.

During the 2021 wet season, the interaction between nitrogen and cropping system significantly ( $p < 0.05$ ) affected lablab vine length is shown in Figure 3. The combination of 90 kg N  $ha^{-1}$  and the alternate strip system produced the longest vines (161.22 cm), whereas the shortest vines (111.28 cm) were recorded under the alternate stand system at 60 kg N  $ha^{-1}$ . Vine length followed a similar trend as in 2020, increasing from the alternate stand to the alternate row and reaching its maximum under the alternate strip system.



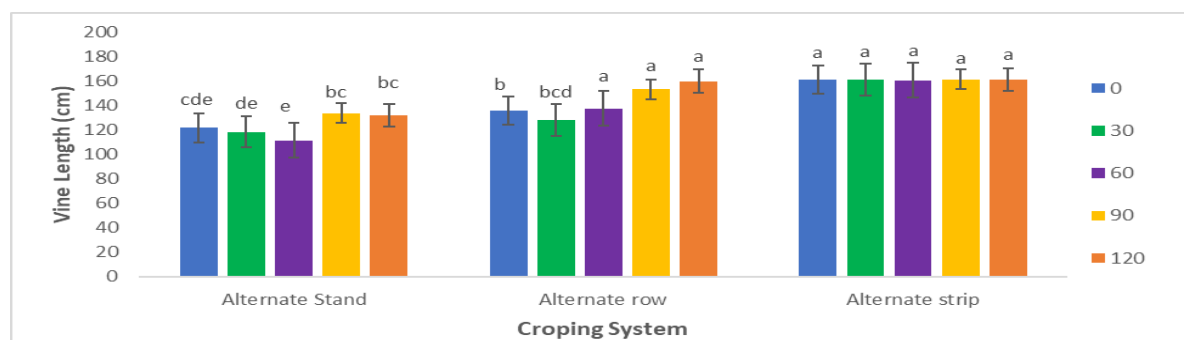
**Figure 1:** Interaction of Nitrogen and Cropping System on the Plant height of Popcorn at 10 WAS at BUK during the 2020 Wet Season

**NB:** Means with unlike letter(s) are significantly different at 5% level of probability using Student-Newman Keuls Test (SNK).



**Figure 2:** Interaction of Phosphorus and Cropping System on the Vine length of Lablab at 10 WAS at BUK during the 2020 Wet Season

**NB:** Means with unlike letter are different at 5% level of probability using Student-Newman Keuls Test (SNK).



**Figure 3:** Interaction of Nitrogen and Cropping System on the Vine Length (cm) of Lablab at 10 WAS at BUK During the 2021 Wet Season

**NB:** Means with unlike letter(s) are significantly different at 5% level of probability using Student-Newman Keuls Test (SNK)

### Number of leaves per plant

The influence of nitrogen, phosphorus, and cropping system on the number of leaves per plant of popcorn and vine length of lablab across the 2020, 2021, and 2022 wet seasons at BUK is presented in Table 3. Nitrogen application significantly ( $p < 0.05$ ) influenced the number of leaves per plant in both popcorn and lablab across the 2020-2022 wet seasons at BUK. In popcorn, the highest leaf numbers (7.19-7.30) were recorded at 120 kg N ha<sup>-1</sup>, while the lowest (6.52-6.59) occurred at 0-30 kg N ha<sup>-1</sup>. Similarly, lablab recorded the highest number of leaves (42.67-42.74) at 120 kg N ha<sup>-1</sup>, with the fewest leaves (38.82-39.48) observed at 0-30 kg N ha<sup>-1</sup>.

Phosphorus application also had a significant ( $p < 0.05$ ) effect on leaf production for both crops in all seasons. Popcorn plants produced more leaves (7.36-7.71) at 30-60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> compared to the control (5.31-6.04). Likewise, lablab showed higher leaf numbers (43.11-45.38) at 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> than at 0 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> (30.82-32.22).

Cropping system effects were also significant ( $p < 0.05$ ) for both species across all years. The alternate strip system consistently produced the highest leaf counts in popcorn (7.20-7.62) and lablab (44.56-44.69), followed by the alternate row and alternate stand systems. Several significant interactions were observed for both crops, particularly in 2020 and 2021, suggesting that nutrient response was influenced by the cropping arrangement and combined nutrient levels.

**Table 3: Number of Leaves Plant<sup>-1</sup> of Popcorn and Lablab as influenced by Nitrogen, Phosphorus and System at BUK During the 2020, 2021, and 2022 Wet Seasons**

| Treatments                                                        | Popcorn            |                    |                    | Lablab             |                    |                     |
|-------------------------------------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|
|                                                                   | 2020               | 2021               | 2022               | 2020               | 2021               | 2022                |
| <b>Nitrogen (kg N ha<sup>-1</sup>)</b>                            |                    |                    |                    |                    |                    |                     |
| 0                                                                 | 6.59 <sup>b</sup>  | 7.19 <sup>a</sup>  | 6.26 <sup>ab</sup> | 38.93 <sup>b</sup> | 39.44 <sup>c</sup> | 27.07 <sup>a</sup>  |
| 30                                                                | 6.52 <sup>b</sup>  | 6.96 <sup>ab</sup> | 6.22 <sup>ab</sup> | 38.82 <sup>b</sup> | 39.48 <sup>c</sup> | 26.85 <sup>ab</sup> |
| 60                                                                | 6.59 <sup>b</sup>  | 7.00 <sup>a</sup>  | 6.11 <sup>b</sup>  | 39.04 <sup>b</sup> | 38.48 <sup>c</sup> | 24.37 <sup>b</sup>  |
| 90                                                                | 6.81 <sup>ab</sup> | 7.04 <sup>a</sup>  | 6.44 <sup>a</sup>  | 40.30 <sup>b</sup> | 41.04 <sup>b</sup> | 28.93 <sup>a</sup>  |
| 120                                                               | 7.19 <sup>a</sup>  | 7.30 <sup>a</sup>  | 6.44 <sup>a</sup>  | 42.67 <sup>a</sup> | 42.74 <sup>a</sup> | 28.19 <sup>a</sup>  |
| P of F                                                            | 0.021              | 0.050              | 0.061              | 0.002              | 0.000              | 0.036               |
| SE±                                                               | 0.166              | 0.568              | 0.110              | 0.693              | 0.513              | 1.165               |
| <b>Phosphorus (kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>)</b> |                    |                    |                    |                    |                    |                     |
| 0                                                                 | 5.31 <sup>b</sup>  | 6.04 <sup>b</sup>  | 5.98 <sup>b</sup>  | 30.82 <sup>c</sup> | 32.22 <sup>c</sup> | 25.67 <sup>b</sup>  |
| 30                                                                | 7.56 <sup>a</sup>  | 7.71 <sup>a</sup>  | 6.40 <sup>a</sup>  | 43.73 <sup>b</sup> | 43.11 <sup>b</sup> | 26.82 <sup>b</sup>  |
| 60                                                                | 7.36 <sup>a</sup>  | 7.53 <sup>a</sup>  | 6.51 <sup>a</sup>  | 45.29 <sup>a</sup> | 45.38 <sup>a</sup> | 28.73 <sup>a</sup>  |
| P of F                                                            | 0.000              | 0.000              | 0.001              | 0.000              | 0.000              | 0.005               |
| SE±                                                               | 0.109              | 0.515              | 0.137              | 0.510              | 0.528              | 0.917               |
| <b>Cropping Systems (C)</b>                                       |                    |                    |                    |                    |                    |                     |
| Alternate stand                                                   | 6.38 <sup>b</sup>  | 6.84 <sup>b</sup>  | 5.89 <sup>b</sup>  | 36.49 <sup>c</sup> | 36.62 <sup>c</sup> | 25.04 <sup>b</sup>  |
| Alternate row                                                     | 6.64 <sup>b</sup>  | 6.82 <sup>b</sup>  | 6.42 <sup>a</sup>  | 38.80 <sup>b</sup> | 39.40 <sup>b</sup> | 27.60 <sup>a</sup>  |
| Alternate strip                                                   | 7.20 <sup>a</sup>  | 7.62 <sup>a</sup>  | 6.58 <sup>a</sup>  | 44.56 <sup>a</sup> | 44.69 <sup>a</sup> | 28.58 <sup>a</sup>  |
| P of F                                                            | 0.000              | 0.000              | 0.000              | 0.000              | 0.000              | 0.004               |
| SE±                                                               | 0.134              | 0.469              | 0.117              | 0.664              | 0.617              | 0.960               |
| <b>Interaction</b>                                                |                    |                    |                    |                    |                    |                     |
| N x C                                                             | 0.002              | 0.324              | 0.002              | 0.001              | 0.000              | 0.003               |
| N x P                                                             | 0.003              | 0.165              | 0.396              | 0.032              | 0.155              | 0.001               |
| C x P                                                             | 0.000              | 0.000              | 0.000              | 0.000              | 0.000              | 0.006               |
| N x C x P                                                         | 0.000              | 0.000              | 0.124              | 0.000              | 0.000              | 0.000               |

**NB: Means within the same treatment column followed by different letters differ significantly using Student-Newman Keuls Test (SNK).**

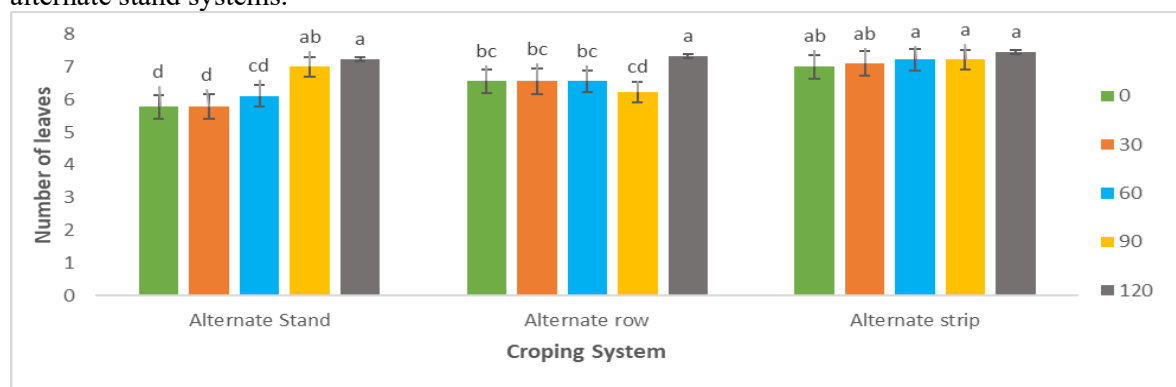
### Nitrogen × Cropping System Interaction for Popcorn and Lablab

The interaction between nitrogen and cropping system significantly ( $p < 0.05$ ) influenced the number of leaves per plant of popcorn at 10 WAS in 2020, as shown in Figure 4. The highest number

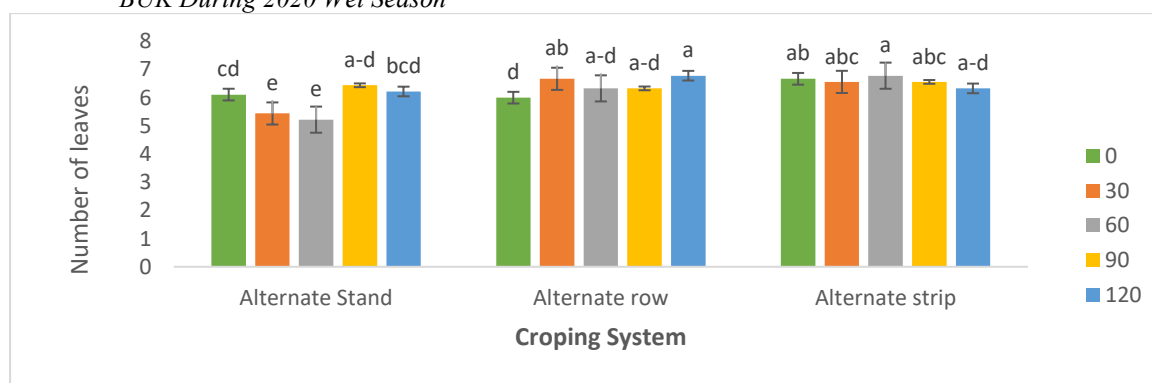
of leaves (7.44) was obtained from the combination of 120 kg N ha<sup>-1</sup> and the alternate strip system, which was statistically similar to other nitrogen levels within the same system (7.00-7.22), compared with the other interaction combinations that resulted in lower leaf counts.

Similarly, Figure 5 shows a significant ( $p < 0.05$ ) interaction between nitrogen and cropping system in 2021, where the combination of 120 kg N ha<sup>-1</sup> and the alternate row system produced the highest leaf number (6.78), followed closely by the alternate strip system at 60-90 kg N ha<sup>-1</sup> (6.56–6.78). The fewest leaves (5.22) were recorded in the alternate stand system at 60 kg N ha<sup>-1</sup>.

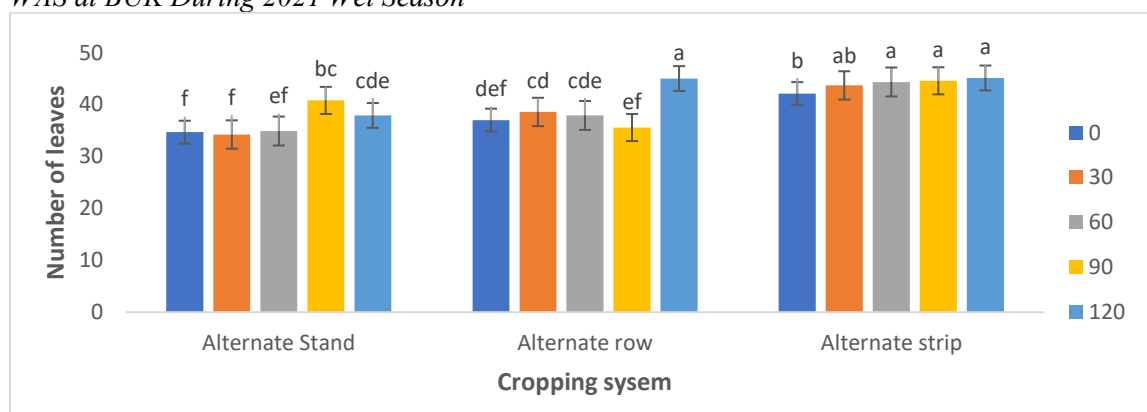
For lablab, the interaction between nitrogen and cropping system significantly ( $p < 0.05$ ) affected the number of leaves per plant at 10 WAS, as presented in Figure 6. The highest leaf number (45.11) was observed under the alternate strip system at 60-120 kg N ha<sup>-1</sup> and in the alternate row system at 120 kg N ha<sup>-1</sup>, while the other treatment combinations resulted in lower leaf counts. Across nitrogen levels, the alternate strip system consistently produced more leaves than the alternate row and alternate stand systems.



**Figure 4:** Interaction of Nitrogen and Cropping System on the Number of Leaves of Popcorn at 10 WAS at BUK During 2020 Wet Season



**Figure 5:** Interaction of Nitrogen and Cropping System on the Number of Leaves of Popcorn at 10 WAS at BUK During 2021 Wet Season



**Figure 6:** Interaction of Nitrogen and Cropping System on the Number of Leaves of Lablab at 10 WAS at BUK During 2020 Wet Season.

### Stem girth of Popcorn and Lablab

Table 4 presents the influence of nitrogen, phosphorus, and cropping system on the stem girth of popcorn and lablab during the 2020, 2021, and 2022 wet seasons at BUK. Results revealed that nitrogen application significantly ( $p < 0.05$ ) influenced stem girth of both popcorn and lablab in 2020 and 2021, but not in 2022. For popcorn, the thickest stems (1.72 cm and 1.94 cm) were obtained at 120 kg N ha<sup>-1</sup>, while the lowest (1.31–1.41 cm) occurred at 0–30 kg N ha<sup>-1</sup>. In lablab, the highest stem girth values (0.75 cm in 2020 and 0.71 cm in 2021) were also recorded at 120 kg N ha<sup>-1</sup>, with lower nitrogen rates producing thinner stems.

Phosphorus application significantly ( $p < 0.05$ ) affected stem girth of both crops across the three seasons. The application of 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> consistently produced the thickest stems for popcorn (2.12 cm in 2020 and 2.38 cm in 2021) and lablab (0.80 cm and 0.79 cm), while the control (0 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>) recorded the thinnest stems.

Cropping system also had a significant effect ( $p < 0.05$ ) on stem girth in 2020 and 2021 for both crops. The alternate strip system resulted in the thickest stems for popcorn (1.89 cm and 2.05 cm) and lablab (0.77 cm and 0.73 cm), followed by the alternate row system, whereas the alternate stand system recorded the lowest values.

**Table 4: Stem Girth of Popcorn and Lablab as influenced by Nitrogen, Phosphorus and Cropping System at BUK during the 2020, 2021 and 2022 Wet Seasons**

| Treatments                                                        | Pop corn           |                   |                   | Lablab            |                    |                   |
|-------------------------------------------------------------------|--------------------|-------------------|-------------------|-------------------|--------------------|-------------------|
|                                                                   | 2020               | 2021              | 2022              | 2020              | 2021               | 2022              |
| <b>Nitrogen (kg N ha<sup>-1</sup>)</b>                            |                    |                   |                   |                   |                    |                   |
| 0                                                                 | 1.41 <sup>c</sup>  | 1.69 <sup>b</sup> | 0.53              | 0.67 <sup>b</sup> | 0.63 <sup>d</sup>  | 0.55              |
| 30                                                                | 1.31 <sup>d</sup>  | 1.44 <sup>c</sup> | 0.54              | 0.67 <sup>b</sup> | 0.65 <sup>bc</sup> | 0.57              |
| 60                                                                | 1.34 <sup>cd</sup> | 1.45 <sup>c</sup> | 0.55              | 0.68 <sup>b</sup> | 0.64 <sup>cd</sup> | 0.54              |
| 90                                                                | 1.51 <sup>b</sup>  | 1.62 <sup>c</sup> | 0.55              | 0.70 <sup>b</sup> | 0.66 <sup>b</sup>  | 0.55              |
| 120                                                               | 1.72 <sup>a</sup>  | 1.94 <sup>a</sup> | 0.54              | 0.75 <sup>a</sup> | 0.71 <sup>a</sup>  | 0.56              |
| P of F                                                            | 0.000              | 0.005             | 0.686             | 0.002             | 0.000              | 0.154             |
| SE±                                                               | 0.037              | 0.097             | 0.015             | 0.014             | 7.227              | 9.607             |
| <b>Phosphorus (kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>)</b> |                    |                   |                   |                   |                    |                   |
| 0                                                                 | 0.57 <sup>c</sup>  | 0.53 <sup>c</sup> | 0.52 <sup>b</sup> | 0.48 <sup>b</sup> | 0.43 <sup>c</sup>  | 0.54 <sup>b</sup> |
| 30                                                                | 1.68 <sup>b</sup>  | 1.98 <sup>b</sup> | 0.55 <sup>a</sup> | 0.80 <sup>a</sup> | 0.75 <sup>b</sup>  | 0.57 <sup>a</sup> |
| 60                                                                | 2.12 <sup>a</sup>  | 2.38 <sup>a</sup> | 0.56 <sup>a</sup> | 0.80 <sup>a</sup> | 0.79 <sup>a</sup>  | 0.56 <sup>a</sup> |
| P of F                                                            | 0.000              | 0.000             | 0.008             | 0.000             | 0.000              | 0.019             |
| SE±                                                               | 0.030              | 0.073             | 0.013             | 0.013             | 0.014              | 0.011             |
| <b>Cropping System (C)</b>                                        |                    |                   |                   |                   |                    |                   |
| Alternate stand                                                   | 1.12 <sup>c</sup>  | 1.31 <sup>c</sup> | 0.54              | 0.65 <sup>b</sup> | 0.62 <sup>b</sup>  | 0.55              |
| Alternate row                                                     | 1.36 <sup>b</sup>  | 1.53 <sup>b</sup> | 0.55              | 0.66 <sup>b</sup> | 0.63 <sup>b</sup>  | 0.56              |
| Alternate strip                                                   | 1.89 <sup>a</sup>  | 2.05 <sup>a</sup> | 0.54              | 0.77 <sup>a</sup> | 0.73 <sup>a</sup>  | 0.55              |
| P of F                                                            | 0.000              | 0.000             | 0.580             | 0.000             | 0.000              | 0.347             |
| SE±                                                               | 0.030              | 0.094             | 0.012             | 0.014             | 0.012              | 0.1566            |
| <b>Interaction</b>                                                |                    |                   |                   |                   |                    |                   |
| N x C                                                             | 0.000              | 0.001             | 0.622             | 0.003             | 0.005              | 0.068             |
| N x P                                                             | 0.000              | 0.000             | 0.742             | 0.007             | 0.034              | 0.039             |
| C x P                                                             | 0.000              | 0.000             | 0.010             | 0.000             | 0.000              | 0.117             |
| N x C x P                                                         | 0.000              | 0.000             | 0.049             | 0.000             | 0.000              | 0.918             |

Means within the same treatment column followed by different letters differ significantly using Student-Newman Keuls Test (SNK).

### Fresh and Dry weight of Popcorn and Lablab

The influence of nitrogen, phosphorus, and cropping system on the fresh and dry weights of popcorn and lablab during the 2020, 2021, and 2022 wet seasons at BUK is shown in Table 5.



Nitrogen application significantly ( $p < 0.05$ ) influenced both the fresh and dry weights of popcorn and lablab in 2020 and 2021, but not in 2022. The highest fresh (200.10–201.48 g) and dry weights (69.42–70.73 g) of popcorn were recorded at 120 kg N ha<sup>-1</sup>, followed closely by 0 kg N ha<sup>-1</sup>, while lower nitrogen rates (30–60 kg N ha<sup>-1</sup>) produced reduced biomass. Similarly, lablab recorded its highest fresh and dry weights (≈199.20 g and 69.64 g) under 120 kg N ha<sup>-1</sup>, indicating that higher nitrogen levels enhanced vegetative growth and biomass accumulation.

Phosphorus also had a significant ( $p < 0.05$ ) effect on both crops. The greatest fresh and dry weights were observed at 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, followed by 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, while the lowest values occurred at 0 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. This suggests that adequate phosphorus supply improved photosynthetic efficiency and nutrient assimilation, thereby increasing biomass production.

Cropping system significantly affected the fresh and dry weights of popcorn and lablab in 2020 and 2021. The alternate strip system produced relatively higher biomass in popcorn (fresh: 180.17 g; dry: 62.13 g) and lablab (fresh: 180.11 g; dry: 62.48 g) compared to the alternate row and alternate stand systems, which recorded lower weights. This indicates that alternate strip cropping provided better spatial arrangement for light interception and nutrient use efficiency. The interaction between experimental factors were significant at certain instances and are shown in Figure 7-11.



Table 5: Fresh and Dry Weight of popcorn and Lablab as influenced by Nitrogen, Phosphorus and Cropping System at BUK During the 2020, 2021 and 2022 Wet Seasons

| Treatments                                                         | Popcorn             |                    |                  |                     |                     |                     | Lablab              |                    |                  |                     |                      |                     |
|--------------------------------------------------------------------|---------------------|--------------------|------------------|---------------------|---------------------|---------------------|---------------------|--------------------|------------------|---------------------|----------------------|---------------------|
|                                                                    | 2020                |                    | 2021             |                     | 2022                |                     | 2020                |                    | 2021             |                     | 2022                 |                     |
|                                                                    | Fresh weight (g)    | Dry weight (g)     | Fresh weight (g) | Dry weight (g)      | Fresh weight (g)    | Dry weight (g)      | Fresh weight (g)    | Dry weight (g)     | Fresh weight (g) | Dry weight (g)      | Fresh weight (g)     | Dry weight (g)      |
| <b>Nitrogen (kg N ha<sup>-1</sup>)</b>                             |                     |                    |                  |                     |                     |                     |                     |                    |                  |                     |                      |                     |
| 0                                                                  | 201.48 <sup>a</sup> | 70.73 <sup>a</sup> | 201.75           | 68.73 <sup>a</sup>  | 197.09 <sup>a</sup> | 29.10               | 201.58 <sup>a</sup> | 70.03 <sup>a</sup> | 201.75           | 68.73 <sup>a</sup>  | 196.34 <sup>a</sup>  | 70.49 <sup>a</sup>  |
| 30                                                                 | 117.31 <sup>b</sup> | 59.80 <sup>b</sup> | 174.61           | 59.92 <sup>ab</sup> | 173.73 <sup>b</sup> | 29.23               | 171.53 <sup>b</sup> | 59.40 <sup>b</sup> | 174.61           | 59.92 <sup>ab</sup> | 174.64 <sup>ab</sup> | 61.62 <sup>ab</sup> |
| 60                                                                 | 148.16 <sup>c</sup> | 50.93 <sup>c</sup> | 198.16           | 42.77 <sup>c</sup>  | 132.67 <sup>c</sup> | 28.42               | 148.94 <sup>b</sup> | 50.69 <sup>c</sup> | 198.16           | 42.77 <sup>c</sup>  | 129.34 <sup>c</sup>  | 45.81 <sup>c</sup>  |
| 90                                                                 | 169.93 <sup>b</sup> | 58.41 <sup>b</sup> | 164.20           | 56.47 <sup>b</sup>  | 105.89 <sup>b</sup> | 33.89               | 170.22 <sup>b</sup> | 58.25 <sup>b</sup> | 164.20           | 56.47 <sup>b</sup>  | 166.73 <sup>b</sup>  | 59.09 <sup>b</sup>  |
| 120                                                                | 200.10 <sup>a</sup> | 69.42 <sup>a</sup> | 197.90           | 68.14 <sup>ab</sup> | 189.54 <sup>a</sup> | 30.56               | 199.20 <sup>a</sup> | 69.64 <sup>a</sup> | 197.90           | 68.14 <sup>ab</sup> | 190.62 <sup>ab</sup> | 67.41 <sup>ab</sup> |
| PV                                                                 | 0.000               | 0.000              | 0.889            | 0.000               | 0.000               | 0.125               | 0.000               | 0.000              | 0.889            | 0.000               | 0.000                | 0.000               |
| SE±                                                                | 5.803               | 1.720              | 45.679           | 3.103               | 6.784               | 1.949               | 6.028               | 1.824              | 45.769           | 3.103               | 6.352                | 2.453               |
| <b>Phosphorous (Kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>)</b> |                     |                    |                  |                     |                     |                     |                     |                    |                  |                     |                      |                     |
| 0                                                                  | 179.48              | 62.29              | 221.17           | 61.97 <sup>a</sup>  | 180.67 <sup>a</sup> | 29.50               | 178.55              | 61.86              | 221.17           | 61.97 <sup>a</sup>  | 181.45 <sup>a</sup>  | 64.03 <sup>a</sup>  |
| 30                                                                 | 179.36              | 60.94              | 159.24           | 53.46 <sup>b</sup>  | 153.74 <sup>b</sup> | 29.22               | 176.14              | 60.78              | 159.24           | 53.46 <sup>b</sup>  | 153.34 <sup>b</sup>  | 63.70 <sup>a</sup>  |
| 60                                                                 | 179.32              | 62.35              | 181.57           | 62.19 <sup>a</sup>  | 180.93 <sup>a</sup> | 32.00               | 180.19              | 62.16              | 181.57           | 62.19 <sup>a</sup>  | 179.82 <sup>a</sup>  | 54.92 <sup>b</sup>  |
| P of F                                                             | 0.999               | 0.532              | 0.207            | 0.000               | 0.000               | 0.135               | 0.628               | 0.577              | 0.207            | 0.000               | 0.000                | 0.000               |
| SE±                                                                | 4.967               | 1.414              | 34.648           | 1.883               | 6.669               | 1.503               | 4.209               | 1.371              | 34.876           | 1.883               | 6.288                | 2.272               |
| <b>Cropping System (C)</b>                                         |                     |                    |                  |                     |                     |                     |                     |                    |                  |                     |                      |                     |
| Alternate Stand                                                    | 179.14              | 62.56              | 180.00           | 61.46 <sup>a</sup>  | 176.42 <sup>a</sup> | 27.86 <sup>b</sup>  | 179.75              | 61.90              | 180.00           | 61.46 <sup>a</sup>  | 177.89 <sup>a</sup>  | 63.45 <sup>a</sup>  |
| Alternate Row                                                      | 178.85              | 60.88              | 218.78           | 61.36 <sup>a</sup>  | 180.72 <sup>a</sup> | 31.55 <sup>a</sup>  | 175.02              | 60.42              | 218.78           | 61.36 <sup>a</sup>  | 178.47 <sup>a</sup>  | 63.45 <sup>a</sup>  |
| Alternate Strip                                                    | 180.17              | 62.13              | 163.19           | 54.79 <sup>b</sup>  | 158.20 <sup>b</sup> | 31.31 <sup>ab</sup> | 180.11              | 62.48              | 163.19           | 54.79 <sup>b</sup>  | 158.25 <sup>b</sup>  | 55.75 <sup>b</sup>  |
| P of F                                                             | 0.965               | 0.561              | 0.281            | 0.000               | 0.001               | 0.067               | 0.390               | 0.381              | 0.281            | 0.012               | 0.000                | 0.000               |
| SE±                                                                | 5.206               | 1.594              | 34.648           | 2.287               | 5.251               | 1.661               | 4.046               | 1.493              | 34.648           | 2.287               | 4.534                | 1.577               |
| <b>Interaction</b>                                                 |                     |                    |                  |                     |                     |                     |                     |                    |                  |                     |                      |                     |
| N x C                                                              | 0.000               | 0.000              | 0.125            | 0.000               | 0.007               | 0.461               | 0.000               | 0.000              | 0.000            | 0.000               | 0.000                | 0.000               |
| N x P                                                              | 0.000               | 0.000              | 0.134            | 0.000               | 0.030               | 0.147               | 0.000               | 0.000              | 0.000            | 0.000               | 0.000                | 0.000               |
| C x P                                                              | 0.000               | 0.000              | 0.003            | 0.000               | 0.000               | 0.191               | 0.000               | 0.000              | 0.000            | 0.000               | 0.000                | 0.000               |
| N x C x P                                                          | 0.000               | 0.000              | 0.132            | 0.000               | 0.000               | 0.093               | 0.000               | 0.000              | 0.000            | 0.000               | 0.000                | 0.000               |

Means within the same treatment column followed by different letters differ significantly using Student-Newman Keuls Test (SNK)

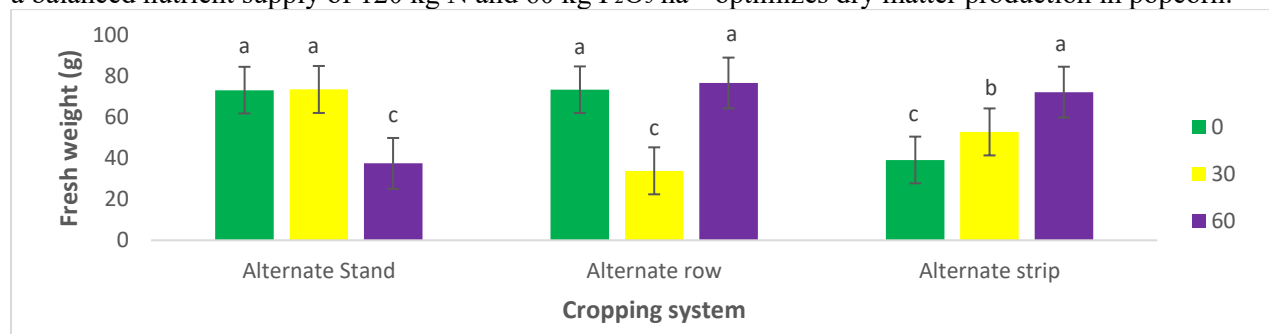
The interaction of phosphorus and cropping system significantly ( $p < 0.001$ ) influenced the fresh weight of popcorn at 10 WAS (Figure 7). The combination of 30 kg  $P_2O_5$  ha $^{-1}$  with the alternate strip system produced the highest fresh weight (219.26 g), which was statistically similar to alternate row  $\times$  60 kg  $P_2O_5$  ha $^{-1}$  (214.29 g) and alternate stand  $\times$  30 kg  $P_2O_5$  ha $^{-1}$  (212.59 g). The lowest value (106.25 g) was recorded under the alternate row  $\times$  30 kg  $P_2O_5$  ha $^{-1}$  combination, indicating that optimal phosphorus levels under alternate strip arrangement favored higher biomass production.

Figure 8 display a significant Nitrogen and cropping system interaction on dry weight, where the highest dry weights (76.01 and 76.53 g) were obtained from the combinations of 120 kg N ha $^{-1}$   $\times$  alternate stand and 30 kg N ha $^{-1}$   $\times$  alternate strip, respectively. Conversely, the lowest dry weight (49.17 g) was recorded under 90 kg N ha $^{-1}$   $\times$  alternate strip. This suggests that high nitrogen availability in alternate stand and moderate nitrogen under alternate strip systems enhanced dry matter accumulation.

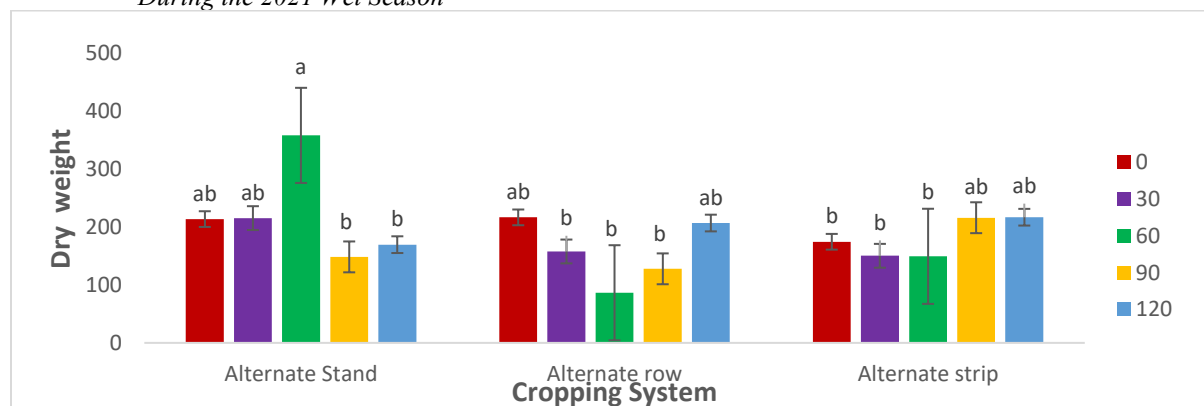
On the other hand, the interaction of phosphorus and cropping system significantly influenced dry weight as presented in Figure 9, where the combination of 60 kg  $P_2O_5$  ha $^{-1}$   $\times$  alternate row produced the highest dry weight (76.74 g), closely followed by alternate strip  $\times$  60 kg  $P_2O_5$  ha $^{-1}$  (72.30 g). The lowest dry weights (33.89–39.19 g) were observed under alternate row and alternate strip  $\times$  30 kg  $P_2O_5$  ha $^{-1}$ . Hence, higher phosphorus application under alternate row arrangement promoted greater dry matter accumulation.

The nitrogen  $\times$  cropping system interaction significantly affected dry weight (Figure 10). The highest dry weights (77.91 and 79.28 g) were obtained from 120 kg N ha $^{-1}$   $\times$  alternate stand and 120 kg N ha $^{-1}$   $\times$  alternate row, respectively. In contrast, the lowest value (32.63 g) occurred under 60 kg N ha $^{-1}$   $\times$  alternate strip. This implies that higher nitrogen supply under alternate stand or row arrangements enhanced biomass accumulation compared to the strip system.

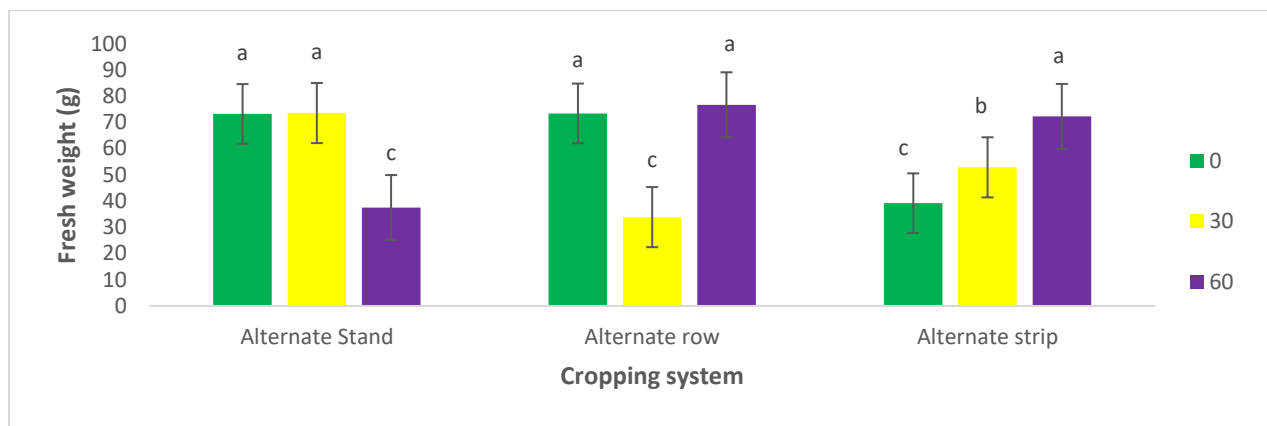
Nitrogen  $\times$  phosphorus interaction was significant for dry weight (Figure 11). The combination of 120 kg N ha $^{-1}$   $\times$  60 kg  $P_2O_5$  ha $^{-1}$  produced the highest dry weight (77.04 g), followed by 0 kg N ha $^{-1}$   $\times$  0 kg  $P_2O_5$  ha $^{-1}$  (76.73 g). The lowest (33.14 g) was obtained at 60 kg N ha $^{-1}$   $\times$  30 kg  $P_2O_5$  ha $^{-1}$ . These results suggest that a balanced nutrient supply of 120 kg N and 60 kg  $P_2O_5$  ha $^{-1}$  optimizes dry matter production in popcorn.



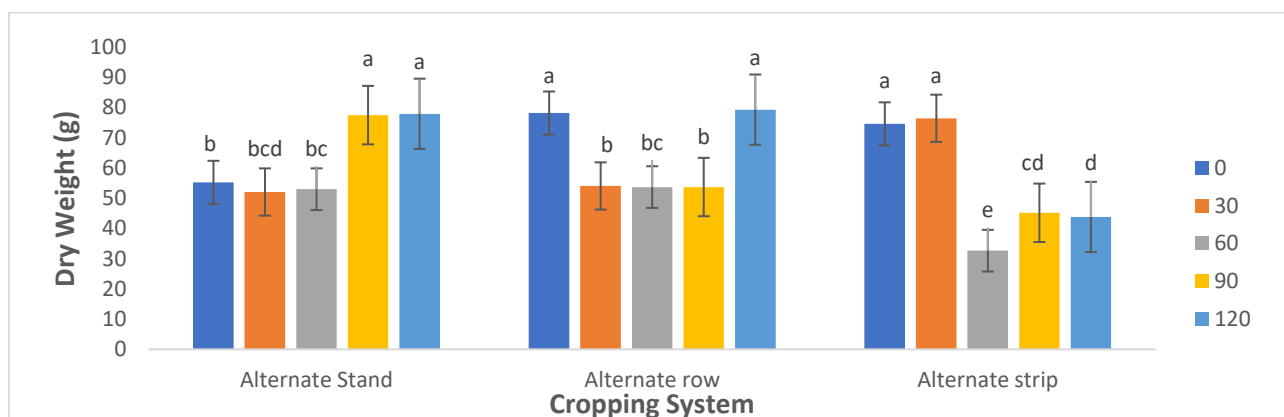
**Figure 7:** Interaction Between Nitrogen and Phosphorus on the Fresh Weight of Popcorn at 10 WAS at BUK During the 2021 Wet Season



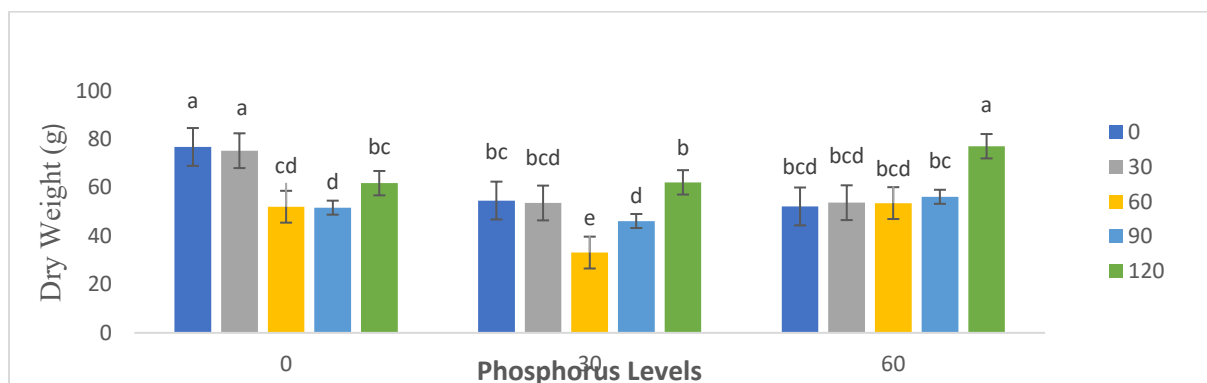
**Figure 8:** Interaction of Nitrogen and Phosphorus on the Dry Weight (g) of Popcorn at 10 WAS at BUK During the 2021 Wet Season



**Figure 9:** *Interaction Between Nitrogen and Phosphorus on the Fresh Weight of Popcorn at 10 WAS at BUK During the 2021 Wet Season*



**Figure 10:** *Interaction Between Nitrogen and Cropping System on the Dry Weight (g) of Popcorn at 10 WAS at BUK During the 2022 Wet Season*



**Figure 11:** *Interaction Between Phosphorus and Cropping System on the Dry Weight (g) of Popcorn at 10 WAS at BUK During the 2021 Wet Season*

## DISCUSSION

The predominance of sandy particles in the experimental soils indicates good drainage but poor nutrient retention and water-holding capacity, typical of Sudan Savanna soils (Sanchez, 2019). The

slightly acidic to near-neutral pH observed falls within the optimal range for nutrient uptake and root proliferation (Hazelton & Murphy, 2016). However, the low levels of organic carbon, total nitrogen, and available phosphorus suggest inherent nutrient deficiencies, explaining the strong crop response to fertilizer application. The low cation exchange capacity further indicates limited nutrient-holding potential, predisposing the soils to nutrient leaching under rainfall (Bationo *et al.*, 2012). Although iron levels were adequate, the low zinc content may have constrained enzymatic activity and overall metabolic efficiency (Alloway, 2009).

The marked increase in popcorn height and lablab vine length with increasing nitrogen rates up to 120 kg N ha<sup>-1</sup> underscores nitrogen's role as a primary growth-limiting nutrient. Nitrogen enhances chlorophyll synthesis and protein formation, thereby stimulating photosynthetic efficiency and vegetative expansion (Mthimunye *et al.*, 2023). The observed seasonal variation, particularly the reduced response in 2022, could be attributed to differences in rainfall or residual nitrogen effects from previous years. Phosphorus application up to 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> also significantly improved plant height and vine length, reflecting its role in root development, energy transfer, and enzymatic activation (Khan *et al.*, 2023). However, beyond this rate, responses diminished likely due to nutrient saturation or fixation in the slightly acidic sandy loam soils, consistent with earlier observations in similar agro-ecologies (Qaswar *et al.*, 2020).

Spatial arrangement also played a key role in crop performance. The alternate strip system consistently produced taller plants and longer vines than other configurations, suggesting more efficient light interception, nutrient uptake, and root-zone complementarity. This system appeared to balance competition and cooperation between popcorn and lablab, enhancing overall resource use efficiency. Comparable trends were reported by Jin *et al.* (2024) and Lu *et al.* (2023), who found that intercropping systems with optimized spatial geometry improved growth and yield through enhanced canopy structure and below-ground interactions.

The number of leaves per plant increased with rising nitrogen and phosphorus levels, confirming their combined influence on vegetative growth and canopy expansion (Gu *et al.*, 2023). Adequate nitrogen promoted leaf area development by enhancing chlorophyll concentration and photosynthetic rate, while phosphorus supported root proliferation and energy metabolism essential for leaf initiation (Zhao *et al.*, 2022). The alternate strip arrangement again favored greater leaf production, likely due to improved microclimatic conditions, reduced shading, and enhanced nutrient cycling through biological nitrogen fixation by lablab (Jaiswal & Dakora, 2022). This spatial advantage aligns with findings by Salinas-Roco *et al.* (2024), who noted that optimized intercropping patterns enhance canopy development and light distribution in cereal-legume systems.

The strong positive effects of nitrogen and phosphorus on fresh and dry weights of both crops reaffirm their importance in promoting carbon assimilation and tissue development (Qin *et al.*, 2025). The superior performance of popcorn and lablab under 120 kg N ha<sup>-1</sup> and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, particularly in the alternate strip system, highlights the benefits of integrating nutrient management with spatial optimization. Comparable findings by Jiang *et al.* (2025) showed that strip intercropping enhanced plant growth and yield through complementary light capture and resource sharing.

The significant interactions among nitrogen, phosphorus, and cropping system indicate that the response of popcorn and lablab to fertilization was not independent but synergistic. The best combinations particularly alternate strip cropping with 120 kg N ha<sup>-1</sup> and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> produced the tallest plants, greatest leaf numbers, and highest fresh and dry biomass. These outcomes demonstrate that nutrient use efficiency and growth performance were maximized when appropriate fertilizer rates were integrated with spatially complementary planting patterns. Similar interactive effects were reported by Meng *et al.* (2022) and Gheith *et al.* (2022), who observed that balanced N and P application in optimized intercropping systems improved biomass accumulation and nutrient uptake efficiency.



Overall, the results indicate that crop productivity in the Sudan Savanna can be substantially improved through integrated nutrient and spatial management. The combination of 120 kg N ha<sup>-1</sup>, 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, and alternate strip cropping proved most effective, enhancing vegetative growth, biomass accumulation, and overall system efficiency. This integrated approach offers a sustainable pathway for maximizing cereal–legume productivity under the fragile soil conditions typical of the region.

## CONCLUSION AND RECOMMENDATIONS

The study demonstrates that nutrient deficiencies, particularly in nitrogen and phosphorus, are major constraints to the growth and productivity of popcorn–lablab intercrops in the Sudan Savanna. Application of these nutrients substantially enhanced plant height, leaf number, stem girth, and biomass accumulation, confirming their pivotal roles in supporting photosynthetic efficiency and vegetative vigor under low-fertility conditions. Nitrogen at 120 kg N ha<sup>-1</sup> and phosphorus at 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> consistently resulted in optimal growth responses across seasons, indicating that these rates meet crop nutrient demand without causing diminishing returns or nutrient imbalances.

The alternate strip cropping system outperformed other spatial arrangements by improving light interception, root-zone complementarity, and nutrient use efficiency, leading to superior vegetative performance in both crops. The observed interactions among nitrogen, phosphorus, and cropping system highlight the importance of integrated nutrient and spatial management for maximizing productivity in cereal–legume intercropping systems.

Practically, adopting 120 kg N ha<sup>-1</sup> and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> under an alternate strip intercropping configuration offers a sustainable intensification strategy for the Sudan Savanna. This integrated management approach enhances resource-use efficiency, supports ecological balance, and contributes to long-term soil fertility improvement and food system resilience in smallholder production environments.

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