



RESEARCH ARTICLE

Phosphorus-induced modulation of physiological and yield responses of cowpea under drought stress

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ABSTRACT

Cowpea (*Vigna unguiculata* L.) is a vital legume for smallholder farmers in sub-Saharan Africa, providing protein, livestock feed, and soil fertility through nitrogen fixation. However, productivity is constrained by drought and phosphorus (P) deficiency. This study evaluated moisture regimes (80%, 50%, and 30% field capacity) and P rates (0, 0.5, 2.0, and 4.0 g P₂O₅ plant⁻¹) on growth and yield of cowpea (cv. CBC1) in a 3×4 factorial RCBD experiment. Drought accelerated maturity by up to 16.8 days, reduced height (35-48%), leaves (35-53%), pods (23-44%), and yield (12.5-29.8%), while increasing 100-seed weight (14.2-33.6%). Phosphorus increased height (19%), leaves (22%), pods (34%), root length (22.5%), and yield (13.5%), but decreased seed weight (16%). Most traits showed additive effects, confirming P cannot substitute for water but partially mitigates drought. Optimal P rates were 2.0-4.0 g plant⁻¹ under well-watered and 2.0 g plant⁻¹ under drought, with CBC1 achieving 7.4 t ha⁻¹. Apply 120-240 kg P₂O₅ ha⁻¹ when rainfall exceeds 400 mm; 120 kg P₂O₅ ha⁻¹ under moderate drought (300-400 mm); prioritize moisture conservation when below 300 mm. Field validation and economic analysis are needed.

Keywords: phenological responses, phosphorus fertilization, root system, semi-arid agriculture, vegetative growth, yield and yield components.

INTRODUCTION

Cowpea (*Vigna unguiculata* L. Walp.) is a multipurpose leguminous plant that is highly valued for its multiple uses within small-scale agricultural farming systems of sub-Saharan Africa as it supplies human food, animal

feed, and biological nitrogen fixation to low input farming systems (Omomowo & Babalola, 2021; Nkomo et al., 2021). Cowpea gains significance in times of climatic variability as a drought-resistant and nitrogen-fixing plant which can lower production risks in rainfed farming and improve nutrient cycling (Namatsheve et al., 2021; Mutetwa et al., 2026; Omomowo & Babalola, 2021).

In Zimbabwe and in similar semi-arid smallholder environments, low soil fertility and variable rainfall conditions continue to be significant barriers for crop production (Namatsheve et al., 2021; Kubiku et al., 2022). Over 70% of smallholder farmers in Zimbabwe practice rain-fed farming mostly in semi-arid areas, where drought leads to substantial reduction in production and food insecurity (Mutetwa et al., 2026a). The aforementioned structural constraints are one of the reasons why yields of crops resilient to climate conditions often stay well below their possible levels in small-scale farming (Kubiku et al., 2022; Omomowo & Babalola, 2021).

Despite being somewhat drought-resistant, cowpea productivity is highly constrained by the lack of water, particularly in southern Africa (Nkomo et al., 2021). Such constraints become more severe due to the short and unpredictable growing seasons that hinder proper crop growth and development as well as affect the realized productivity potential (Guda et al., 2020). In semi-arid farming communities, farmers are known to shift their planting times according to rainfall events to mitigate water stress because untimely crop establishment could result in extremely low yields or even total crop failure.

Lack of phosphorus (P) is another limiting factor, similar to the above one. The soils in southern Africa are typically characterized by low nutrient content and poor soil fertility is known to be one of the major factors constraining productivity in these areas (Dimande et al., 2024; Masvaya et al., 2017; Kubiku et al., 2022). As cowpea productivity relies not only on water but also on nutrient availability, phosphorus scarcity is able to limit crop productivity and the benefits that can be received due to biological N₂ fixation (Omomowo & Babalola, 2021; Masvaya et al., 2017; Dimande et al., 2024).

However, these stresses are interrelated. Water content in the soil influences phosphorus movement and phosphorus absorption by plants, and lack of nutrients affects root performance and the ability to use moisture content in the soil (Guda et al., 2020; Masvaya et al., 2017). The relationship is particularly relevant in the case of low-input agricultural practices when smallholders usually do not provide any additional fertilizers to their leguminous plants (Masvaya et al., 2017; Dimande et al., 2024). Even if there are additional inputs available, recommendations which do not consider rainfall variability and soil constraints often prove to be inefficient in semi-arid Zimbabwe.

The above information thus provides an argument in favor of an integrated approach. In semi-arid Zimbabwe, a combination of water-management and fertility-management practices increased cereal yields, and the cowpea literature suggests the same strategy to be used in addressing the issues at hand (Kugedera et al., 2022; Omomowo & Babalola, 2021). Moreover, intercropping and other ecological intensification practices may increase overall productivity but will not solve the problems associated with nutrient-poor soils and rainfall variability (Namatsheve et al., 2021; Madembo et al., 2020),

In light of this background, one of the critical gaps in knowledge is the insufficient information regarding the interactive effects of drought and phosphorus application on cowpea in the Zimbabwean environment. Previous studies have shown that cowpea production is limited by drought, low soil fertility, and lack of inputs, and requires site-specific input management and genotypes (Nkomo, 2021; Omomowo & Babalola, 2021). Still, there is no sufficient information about moisture-related responses of cowpea to phosphorus fertilization that would be relevant to smallholder farmers operating in drought-stricken areas.

This study assessed the effects of two moisture levels (80% and 50% field capacity) and four phosphorus levels (0, 0.5, 2.0, and 4.0 g P₂O₅ plant⁻¹) on the growth, yield, and yield components of cowpea CBC1 genotype. The research assumption is that phosphorus fertilization will positively influence cowpea production under both moisture regimes, though its agronomic optimum will decline under drought due to the limiting effect of water stress on nutrient uptake efficiency.

MATERIALS AND METHODS

Study Site

This research was carried out at Midlands State University, Gweru, Zimbabwe, which has geographical coordinates 19°50'S, 29°84'E and an elevation of 1457 meters above sea level (Figure 1). This place is characterized by an annual precipitation of 400-600 millimeters and an annual average temperature of 25°C (Zimbabwe Worldplaces, 2022). The soil type of the place is characterized by sandy loam soil that is made up of the fersiallitic family, where the predominant soil is clay minerals. Soil tests taken from the experimental area give the soil properties to be pH(5.9), Total Soluble Salts (74.00ppm), Nitrate nitrogen (6.23 ppm), organic carbon (1.54%), and N: C (0.25).

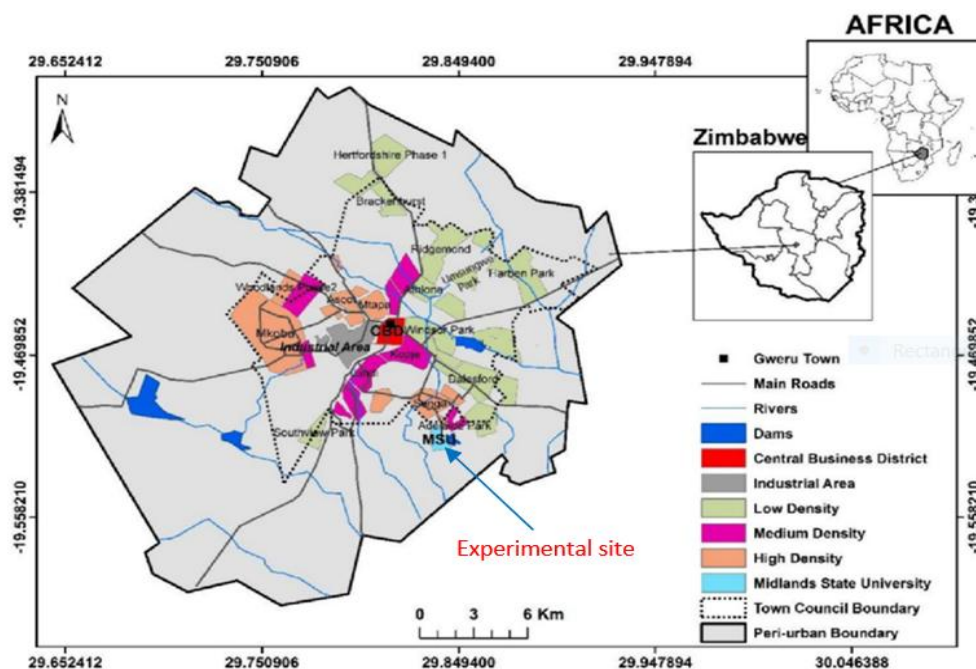


Figure 1. Experimental site, Midlands State University farm

Experimental Design

The experiment employed a 3×4 factorial arrangements laid out in a Randomized Complete Block Design (RCBD) with three replications. Two factors were evaluated: soil moisture regime (three levels) (Table 1) and phosphorus (P) supply (four levels) (Table 2). Each experimental unit consisted of a single polyethylene pot containing two plants.

Table 1. Moisture Regimes (Main Plots)

Code	Description	Soil Moisture (% Field Capacity)
WW	Well-watered control	75-85% FC
MD	Moderate drought	45-55% FC
SD	Severe drought	25-35% FC

Drought conditions were imposed three weeks after sowing, when all plants were fully established, and maintained until physiological maturity. Prior to drought imposition, all pots were maintained at 80% FC to ensure uniform establishment.

Table 2. Phosphorus Treatments (Subplots)

Code	P ₂ O ₅ Rate (g plant ⁻¹)	P ₂ O ₅ Rate (kg ha ⁻¹)*	Description
P0	0	0	Control (no phosphorus)
P1	0.5	30	Low rate
P2	2.0	120	Recommended rate
P3	4.0	240	High rate

*Calculated based on a plant population of 60,000 plants ha⁻¹ (typical cowpea spacing: 75 cm × 22 cm).

Phosphorus was applied as triple superphosphate (TSP, 46% P₂O₅). To avoid nutrient imbalances, all plots received a uniform basal application of compound fertilizer (NPK 7:14:7) at 5 g per plant at the time of sowing.

Potting Medium, Pot Preparation, and Soil Characterization

Homogenized sandy-loam soil topsoil (0-20 cm layer) was taken, air dried and sieved with a 4 mm mesh screen to remove stones and debris. Plastic pots (internal diameter 18 cm, height 20 cm) were filled with 5 kg oven dry equivalent of the soil. All pots were uniformly supplied with non-limiting amounts of nitrogen and potassium (20 mg N kg⁻¹ as urea; 20 mg K kg⁻¹ as KCl) to avoid nutrient deficiency besides phosphorus. All the P treatments were added to the soil at the time of filling up of the pots.

Soil texture was assessed by hydrometer analysis, pH (1:2.5 soil:water) measured by glass electrode pH meter, electrical conductivity by conductivity meter, organic carbon by Walkley-Black procedure, total nitrogen by Kjeldahl procedure, and available phosphorus by Olsen or Mehlich-3 procedure. Soil bulk density and soil water retention data were used to estimate field capacity (FC) of potting mix using standard saturation-drainage procedure.

Field Capacity Determination and Irrigation Management

Field capacity of the potting medium was determined by saturating representative soil samples in pots, allowing free drainage, and then measuring gravimetric water content. Field capacity (%) was calculated as:

$$FC (\%) = [(W_{\text{wet soil}} - W_{\text{dry soil}}) / W_{\text{dry soil}}] \times 100 \quad (i)$$

where wet soil mass is the mass of soil after free drainage, and dry soil mass is the mass after drying at 105°C until constant weight.

Soil relative water content (SRWC) for each treatment was calculated daily using the gravimetric weight method (Xu et al., 2009). Target pot weights corresponding to 80% FC (well-watered), 50% FC (moderate drought), and 30% FC (severe drought) were pre-determined. SRWC was expressed as:

$$SRWC = (W_{\text{soil}} + W_{\text{pot}} - DW_{\text{soil}}) / (W_{\text{FC}} - W_{\text{pot}}) \quad (ii)$$

where: W_{soil} = current soil weight (g), W_{pot} = weight of empty pot (g), DW_{soil} = dry soil weight (g), W_{FC} = soil weight at field capacity (g).

Pots were weighed daily using a digital balance (±1 g precision) and re-watered to their assigned target weight to maintain the prescribed FC. Gravimetric watering was supplemented with periodic volumetric checks using a soil moisture probe (TDR or capacitive sensor) for calibration. Rainfall was excluded as the greenhouse roof prevented external precipitation.

Plant Material, Sowing, and Establishment

An extensively grown cowpea variety (cv. CBC1) that is agriculturally significant and adaptable to conditions in Zimbabwe was selected for use in this research. The seeds were first surface sterilized using 1% sodium hypochlorite solution for 2 minutes before being washed thoroughly in distilled water.

Five seeds were planted per pot at a depth of 3 cm. Thinning of seedlings was done 2 weeks after emergence to ensure that there were only 2 equal seedlings per pot. Pots were watered well until 3 weeks after planting, when drought stress was initiated. Weeds were removed manually by hand-pulling at weekly intervals throughout the growing period to minimize competition for nutrients and water. Pest control was implemented using Karate 2.5 EC pesticide (lambda-cyhalothrin), applied at a rate of 5 mL L⁻¹ of water. Applications commenced at first flowering and continued through pod maturity to control flower and pod-boring insects.

Data Collection

Data were collected on growth, physiological, and yield parameters following standard procedures. Measurements were taken from the two maintained plants per pot.

Table 3. Collected data variables during the investigation

Parameter	Measurement Method	Timing/Stage
Days to physiological maturity (DPM)	Number of days from sowing until 90% of pods have turned brown/dry (characteristic mature colour). Recorded per plant.	Daily observation from start of pod filling until maturity
Height (H)	Plant height was measured using a graduated ruler, from the base of the plant to the tip of the main stem.	At physiological maturity
Leaf number (L)	Manual count of fully expanded green leaves per plant	At 50% flowering
Number of internodes (NIN)	Manual count of visible internodes on main stem	At physiological maturity
Internode length (INL)	Measured using graduated ruler (average of 5 internodes per plant)	At physiological maturity
Total root length (TRL)	Roots washed free of soil; length measured from crown to root tip using graduated ruler	At harvest
Root:shoot ratio (R:S)	Dry weight of roots divided by dry weight of shoots (oven-dried at 70°C to constant weight)	At harvest
Number of Pods per plant (NPP)	Manual count of fully developed mature pods per plant	At harvest
Number of Seeds per pod (NSP)	Random sample of 10 pods per plant; seeds counted and averaged	After threshing
100-seed weight (100-SW)	Random sample of 100 seeds counted, oven-dried, and weighed (triplicate)	After threshing
Total grain yield	Calculated from yield per plant $\times$ plant population (60,000 plants ha ⁻¹)	Calculated

Statistical Analysis

All data were analyzed by ANOVA in a 3 $\times$ 4 factorial experiment in RCBD via GenStat 18th Edition (VSN International, UK). The statistical model consisted of soil moisture, phosphorus level, and their interaction as fixed factors and replication as a random factor. In case where there was significant difference ($p < 0.05$) among treatment means, LSD test was used for mean separation. Normality of residual distribution and homogeneity of variance were tested before carrying out ANOVA using the Shapiro-Wilk test. All graphs and tables were made with help of Microsoft Excel.

RESULTS

Effect of Phosphorus and Moisture on Days to Physiological Maturity

The number of days to physiological maturity was significantly influenced by both the moisture and the phosphorus regimes without any significant interaction between them. Moisture significantly influenced ($F_{1,14} = 169.73$, $p < 0.001$) the maturity. Plants grown under moderate drought conditions reached physiological maturity significantly faster (86.4 days) than those grown under well-watered conditions (96.2 days), showing a difference of 9.8 days due to water stress ($LSD_{0.05} = 1.62$). There was significant influence ($F_{3,14} = 11.77$, $p < 0.001$) of phosphorus on the number of days to maturity, which increased progressively from 87.8 days for P0 to 93.7 days for P3. The P0 regime was significantly lower than all other phosphorus regimes, but P3 regime was significantly higher only than P0 and P1 and was equal to P2 ($LSD_{0.05} = 2.29$). The moisture $\times$ phosphorus interaction was not significant ($F_{3,14} = 0.84$, $p = 0.496$), suggesting a consistent effect of phosphorus regardless of moisture regimes (Table 4).

Table 4. Means for effect of phosphorus and moisture on cowpeas.

Treatment	DPM	H	L	NIN	INL	TRL	R:S	NPP	NSP	100-SW
<i>Moisture</i>										
Well-watered (WW)	96.21 ^z	82.92 ^z	50.96 ^z	13.38 ^z	6.20 ^z	74.08 ^z	0.893 ^x	36.21 ^z	12.83 ^z	17.52 ^x
Moderate drought (MD)	86.38 ^y	53.54 ^y	32.92 ^y	11.75 ^y	4.57 ^y	53.72 ^y	1.003 ^y	27.83 ^y	10.71 ^y	23.41 ^z
Severe drought (SD)	79.38 ^x	43.17 ^x	23.92 ^x	11.92 ^y	3.66 ^x	47.67 ^x	1.106 ^z	20.25 ^x	8.25 ^x	20.00 ^y
LSD _{0.05}	1.31	1.68	2.00	0.93	0.28	3.237	0.0649	1.445	1.001	1.647
P value	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Phosphorus</i>										
P0	84.17 ^a	54.83 ^a	32.28 ^a	11.22 ^a	4.85	0.972	23.67 ^a	10.00	22.56 ^b	0.972
P1	87.00 ^b	59.67 ^b	35.83 ^b	12.22 ^{ab}	4.85	0.980	27.33 ^b	10.22	20.74 ^{ab}	0.980
P2	88.78 ^c	61.44 ^b	36.83 ^{bc}	12.72 ^b	4.79	1.016	30.00 ^c	11.17	19.02 ^a	1.016
P3	89.33 ^c	63.56 ^c	38.78 ^c	13.22 ^b	4.77	1.034	31.39 ^c	11.00	18.92 ^a	1.034
LSD _{0.05}	1.51	1.94	2.31	1.08	0.326	0.0749	1.668	1.156	1.902	0.0749
P value	<0.001	<0.001	<0.001	0.006	ns	ns	<0.001	ns	0.002	ns
Grand Mean	87.3	59.9	35.9	12.3	4.85	1.001	28.10	10.60	20.31	1.001
<i>Interaction</i>										
P value	ns	0.002	ns	ns	ns	ns	0.041	ns	ns	ns
CV%	1.8	3.3	6.6	8.9	7.0	7.7	6.1	11.2	9.6	7.7

Means in a column followed by the same letter are not significantly different at $p < 0.05$ (Fisher's LSD). Abbreviations: see Table 3.

Effect of Phosphorus and Moisture on Plant Height

Plant height showed highly significant response to both moisture and phosphorus treatments. While moisture treatment showed very high effect ($F_{1,14} = 1493.85$, $p < 0.001$) with well-watered plants significantly taller (82.9 cm) than moderately drought treatment (53.5 cm), with an average difference of 29.4 cm ($LSD_{0.05} = 1.63$), phosphorus also showed highly significant increase in height ($F_{3,14} = 42.95$, $p < 0.001$) with average plant height increasing from 61.8 cm at P0 to 73.7 cm at P3 level. Phosphorus levels at P0, P1, P2, and P3 all showed significant effect except for P1 and P2 ($LSD_{0.05} = 2.31$). The interaction of moisture and phosphorus showed highly insignificant but nearing significance value ($F_{3,14} = 3.02$, $p = 0.065$) indicating that phosphorus effects on stem elongation are much more pronounced under well-watered condition. The tallest plants were observed under well-watered with high phosphorus rate (89.2 cm), while the shortest were under drought without phosphorus (48.7 cm) (Table 4).

Effect of Phosphorus and Moisture on Leaf Number

There was a significant increase in leaf number per plant due to moisture and phosphorus but no interaction was observed. There was a highly significant effect of moisture ($F_{1,14} = 360.46$, $p < 0.001$) with well-watered plants having a significantly higher number of leaves (51.0) as compared to moderately drought-treated plants (32.9), a difference of 18.1 leaves ($LSD_{0.05} = 2.04$). Similarly, phosphorus showed a significant effect on leaf number ($F_{3,14} = 13.55$, $p < 0.001$) with an average leaf number of 37.4 at P0 and 45.8 at P3. All phosphorus treatments were significantly different except P2 and P3 ($LSD_{0.05} = 2.88$) (Table 4).

Effect of Phosphorus and Moisture on Number of Internodes

There was a significant difference in internodes per plant due to moisture and phosphorus treatments, with no significant interaction. Moisture significantly influenced internodes ($F_{2,22} = 7.92$, $p = 0.003$), whereby there was an increased number of internodes in well-watered treatments (13.38) compared to moderate (11.75) and severe (11.92) droughts. There was no statistical difference between the two ($LSD_{0.05} = 0.93$). Similarly, phosphorus significantly influenced internodes ($F_{3,22} = 5.42$, $p = 0.006$), whereby there were increasing internodes from 11.22 in P0 to 13.22 in P3. The P0 treatment was different from P2 and P3 and was not different from P1 ($LSD_{0.05} = 1.08$). There was no significant interaction ($F_{6,22} = 0.10$, $p = 0.996$), indicating additive effects of moisture and phosphorus on internode production (Table 4).

Effect of Phosphorus and Moisture on Internode Length

The effect of moisture on internode length was highly significant, whereas that of phosphorus was insignificant, without any significant interaction. The effect of moisture was highly significant ($F_{2,22} = 176.31$, $p < 0.001$), with maximum internodes recorded in well-watered conditions (6.20 cm), then moderate drought (4.57 cm) and severe drought (3.66 cm), respectively. All moisture levels were significantly different ($LSD_{0.05} = 0.284$). Internode length was not affected by phosphorus application ($F_{3,22} = 0.15$, $p = 0.929$), with values ranging between 4.77 cm for P₃ level and 4.85 cm for P₀ and P₁. Interaction between moisture and phosphorus was also not significant ($F_{6,22} = 0.62$, $p = 0.709$) (Table 4).

Effect of Phosphorus and Moisture on Total Root Length

Both moisture and phosphorus significantly increased total root length, while interaction between the two factors was insignificant. The effect of moisture was highly significant ($F_{2,22} = 157.21$, $p < 0.001$); the largest value of total root length belonged to the control group (74.08 cm), followed by moderate drought (53.72 cm) and severe drought (47.67 cm). All moisture levels were significantly different ($LSD_{0.05} = 3.237$). The effect of phosphorus was also highly significant ($F_{3,22} = 15.71$, $p < 0.001$); its mean values increased from 52.08 cm at P0 to 63.79 cm at P3, which was 22.5% increase. All phosphorus levels except P1 and P2 were significantly different ($LSD_{0.05} = 3.737$). Interaction between the factors was insignificant ($F_{6,22} = 0.97$, $p = 0.469$), indicating additive effects on root development (Table 4).

Effect of Phosphorus and Moisture on Root:Shoot Ratio

The effect of moisture on the root to shoot ratio was statistically significant while that of phosphorus had no effect with no significant interaction. The moisture level had a statistical significance effect on the R:S ratio ($F_{1,14} = 19.25$, $p < 0.001$). The moderate drought treatment had a high R:S ratio (1.003) as compared to the well-watered treatment (0.893). This indicates that relatively more root biomass was allocated during the period of stress. The phosphorus had no statistical significance effect on the R:S ratio ($F_{3,14} = 0.49$, $p = 0.692$) while the interaction between the moisture and phosphorus had no statistical significance ($F_{3,14} = 0.52$, $p = 0.674$) (Table 4).

Effect of Phosphorus and Moisture on Pods per Plant

The number of pods per plant was significantly increased with moisture and phosphorus, and the interaction was near significance. There was a significant effect of moisture ($F_{1,14} = 161.88$, $p < 0.001$), where well-watered plants had significantly more pods (36.21) compared to the plants experiencing moderate drought (27.83), which had 8.38 fewer pods ($LSD_{0.05} = 1.41$). There was also a significant effect of phosphorus ($F_{3,14} = 37.74$, $p < 0.001$), as the number of pods increased from 26.83 at P0 to 36.08 at P3, an increase of 34% ($LSD_{0.05} = 1.99$). There was no significant interaction between moisture and phosphorus ($F_{3,14} = 3.06$, $p = 0.063$), although the trend indicated that phosphorus had greater benefits when the plants were well-watered. There were the most pods with well-watering with high phosphorus (41.83 pods), while the lowest was under drought without phosphorus (17.33 pods) (Table 4).

Effect of Phosphorus and Moisture on Seeds per Pod

The number of seeds per pod was influenced by moisture content but not phosphorus, and there was no significant interaction effect. Moisture content had a highly significant influence on the number of seeds per pod ($F_{2,22} = 45.19$, $p < 0.001$) such that the highest number of seeds per pod was found in plants grown under well-watered conditions (12.83) compared to moderate (10.71) and severe drought (8.25). All moisture

treatments were different ($LSD_{0.05} = 1.001$). There was no significant difference due to phosphorus in number of seeds per pod ($F_{3,22} = 2.11$, $p = 0.128$), with mean number varying from 10.00 at P0 to 11.17 at P2. There was no significant interaction effect ($F_{6,22} = 0.63$, $p = 0.704$), confirming that seeds per pod is primarily water-limited rather than phosphorus-responsive (Table 4).

Effect of Phosphorus and Moisture on 100-Seed Weight

The hundred-seed weight was affected significantly by moisture and phosphorus, with no significant interaction between them. Significant effect on seed weight was observed due to the effect of moisture ($F_{1,14} = 51.49$, $p < 0.001$), with drought stress significantly affecting an increase in seed weight (23.41 g) in comparison to well-watered treatment (17.52 g), representing a 33.6% increase ($LSD_{0.05} = 1.65$). Significant effect of phosphorus rate on seed weight was also observed ($F_{3,14} = 8.26$, $p = 0.002$), with an increase in phosphorus rate causing a continuous decrease in seed weight from 22.56 g for P0 to 18.92 g for P3, representing a 16% decrease ($LSD_{0.05} = 1.90$). No significant interaction between moisture and phosphorus on seed weight was observed ($F_{3,14} = 1.13$, $p = 0.371$). The maximum seed weight was recorded under drought and no phosphorus (25.98 g) while minimum seed weight were under well-watered conditions with high phosphorus (14.35 g) (Figures 4).

Effect of Phosphorus and Moisture on Grain Yield per Hectare

There was a very high significance of moisture and phosphorus on the grain yield per hectare without any interaction between the factors. Moisture was highly significant ($F_{1,14} = 190.45$, $p < 0.001$), with more water resulting in significantly higher grain yield ($7106.70 \text{ kg ha}^{-1}$) than moderate drought ($6218.03 \text{ kg ha}^{-1}$), which was 12.5% less under drought ($LSD_{0.05} = 139.8$). Similarly, phosphorus had a very high significance on the grain yield ($F_{3,14} = 35.46$, $p < 0.001$), with grain yield ranging from $6177.60 \text{ kg ha}^{-1}$ at P0 to $7013.55 \text{ kg ha}^{-1}$ at P3, which is 13.5% higher ($LSD_{0.05} = 197.6$). Except for P2 and P3, all other phosphorus levels differed significantly. There was no significance in the interaction ($F_{3,14} = 0.17$, $p = 0.914$), thereby proving additive effects on final grain yield (Figures 2 and 3). The maximum yield occurred at the combination of well-watered conditions and highest phosphorus level ($7445.40 \text{ kg ha}^{-1}$), while the lowest was under drought without phosphorus ($5737.80 \text{ kg ha}^{-1}$), representing a 29.8% difference between the best and worst treatments.

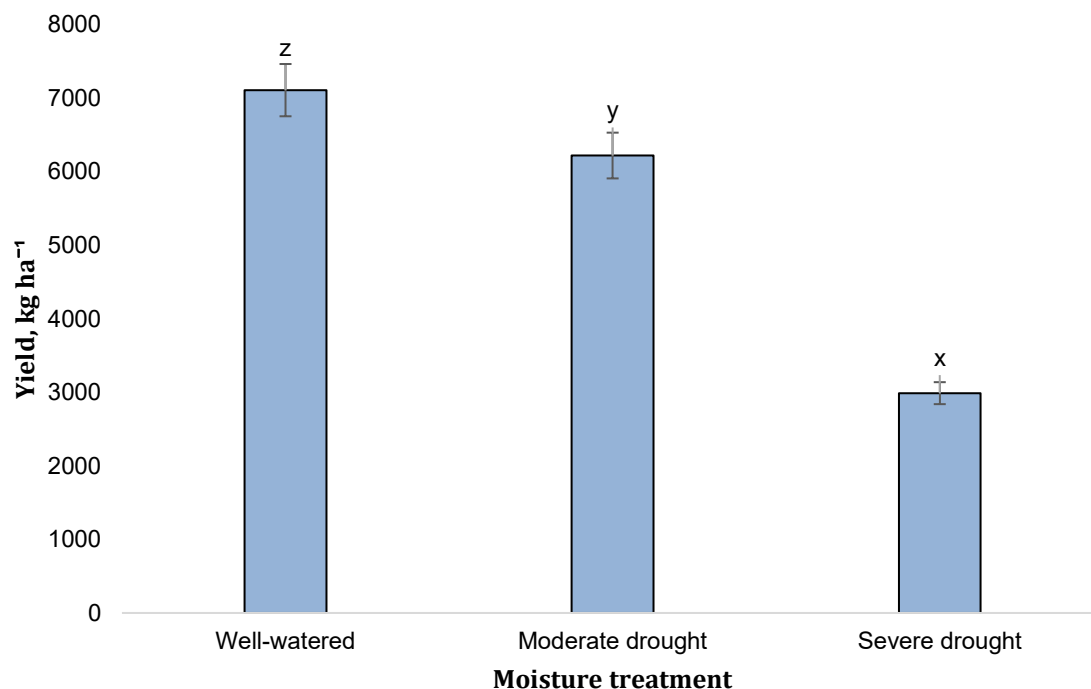


Figure 2. Means of yield of cowpeas as influenced by moisture treatment.

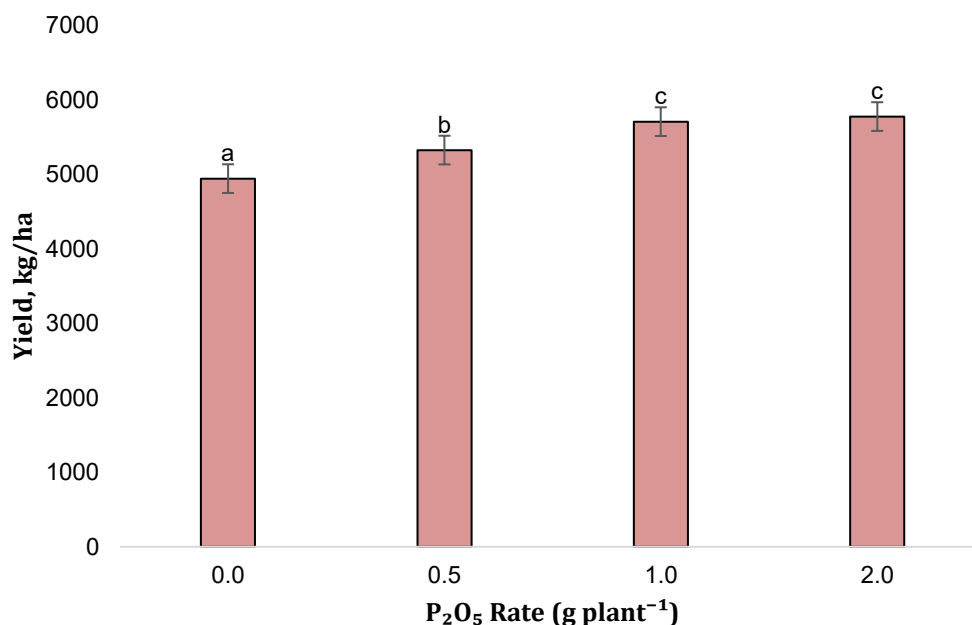


Figure 3. Means of yield of cowpeas as influenced by phosphorus levels.

DISCUSSION

The occurrence of drought significantly impacted cowpea growth, development, and yield formation, while phosphorus mostly improved vegetative growth and reproductive performance (Olorunwa et al., 2021; Melo et al., 2024; Verma et al., 2026). In most research findings, the presence of water scarcity decreased plant height, leaf area, number of leaves, biomass, stomatal conductance, and photosynthesis, which indicates that drought limits cowpea productivity both structurally and physiologically (Melo et al., 2024; De Melo et al., 2025). On the contrary, phosphorus treatment improved plant height, plant branching, nodulation, chlorophyll content, number of pods, and yield, which shows that P increases the source size and reproductive performance rather than the size of seeds (Nikhitha et al., 2023; Kumar et al., 2024).

The fact that maturity is reached at an earlier stage in drought treatment is linked to the stress-escape hypothesis of development, where plants reduce the duration of their growth period in the presence of drought stress (Loftus, 2025; Horn & Shimelis, 2020). While the focus of most cowpea drought experiments is on yield reduction rather than on maturity date, all of them indicate that reproductive-stage drought is particularly harmful for cowpea since flowering and post-anthesis drought led to a strong reduction in pod formation, grain filling, and yield (Mekonnen et al., 2022; Horn & Shimelis, 2020). It may be concluded that the acceleration of maturity caused by drought is an example of adaptation of cowpea to avoid drought exposure during particularly sensitive reproductive stages (Loftus, 2025). On the other hand, P stress delayed flowering or maturity a little while promoting growth and yield. The biology behind it is logical since P allows continuous leaf development and nodulation.

The reduction in the height of plants and the number of leaves under drought conditions matches well with the general knowledge on stress effects in cowpeas (Arnaout et al., 2019; Sanusi et al., 2025). Water stress hindered the development of shoots from the seedling stage until maturity, limited total dry weight accumulation, the expansion of leaves, and growth of shoots through stomatal closure, limiting CO₂ absorption, reduced cellular pressure, and poor pigment content (Olorunwa et al., 2021; Melo et al., 2024; Sanusi et al., 2025). Severe drought also interfered with the nodulation and biological nitrogen fixation process, limiting shoot sugars supplied to roots and causing inadequate dry weight of roots and shoots, which means yield loss was both a problem of water and nutrients and carbon allocation (De Melo et al., 2025). Such processes provide an explanation of why drought-tolerant cowpea genotypes still experience large yield loss under stress conditions from the early stage up to flowering and seed filling stages (Boukar et al., 2019; Mekonnen et al., 2022; Horn & Shimelis, 2020).

In contrast, phosphorus has been shown to enhance vegetative development and yield formation parameters in field conditions (Verma et al., 2026; Nikhitha et al., 2023; Kumar et al., 2024). An adequate P supply boosted branches, trifoliolate leaves, nodules, dry biomass of the crop, and number of pods, which translated into improved seed and stover yields (Kumar et al., 2024; Nikhitha et al., 2023; Somvanshi et al., 2024). Still, the response was not limitless. Several recently published works showed that 40-50 kg P₂O₅ ha⁻¹ was enough for achieving most of the agronomic effect, whereas 60 kg ha⁻¹ generally performed equally well and 50 kg ha⁻¹ showed diminishing returns unless combined with biofertilizers or micronutrients (Verma et al., 2026; Kumar et al., 2024; Singh et al., 2025). Similarly, in low-input systems, response functions were also nonlinear, with a mean increase in grain yield of 47% recorded up to 22.5 kg ha⁻¹ P in the Sahelian and Sudan Savanna regions (Sermé et al., 2018). Thus, these data confirm that phosphorus positively affected yield formation predominantly through an increased number of sinks via pod development and improvement of vegetative source potential, but not via the uniform increase of all yield parameters (Kumar et al., 2024; Singh et al., 2025).

The root results merit careful interpretation because drought effects on roots involve both absolute growth and relative allocation. While drought decreased both root biomass and root surface area along with shoot biomass, shoot development was generally more limited than root growth, increasing root/shoot ratios even as root growth was decreased (De Melo et al., 2025). Some genotypes, however, retained deep or fine roots, longer root lengths or increased root/shoot ratios under stress, and these genotypes had higher water contents, higher water productivity and improved yield stability. This is an important point because other root phenotypes related to P acquisition, such as longer primary roots and denser lateral root hairs, have been associated with increased grain yield under low P availability (Mohammed et al., 2021). Thus, the drought and P interaction may include below-ground influences on root growth and development.

The reproductive attributes were the most sensitive reactions to drought in the current experiment, which is consistent with the results obtained in other experiments on cowpeas (Mekonnen et al., 2022; Arnaout et al., 2019). The pod number, seeds per pod, and seed yield were affected by drought more often than seed size, and the stress during the reproduction stage may significantly decrease the cowpea yield (Horn & Shimelis, 2020; Arnaout, 2019). Such an observation is understandable since stomatal limitation, lower carbon fixation, nodulation disruption, pollen/pod development impairment, and assimilation transport reduction occur in flowers and grains during the same period (Melo et al., 2024; De Melo et al., 2025; Mekonnen et al., 2022). At the same time, phosphorus promoted pod number and seed yield in various studies but had a different effect on seeds per pod and test weight (Nikhitha et al., 2023; Kumar et al., 2024). Such an inconsistency indicates the assumption that the effect of phosphorus on cowpeas happens mainly due to reproductive structure establishment and better crop growth, not due to higher seed filling (Nikhitha et al., 2023; Singh et al., 2025).

The lack of an apparent interaction between moisture and phosphorus implies additivity for most variables included in the study. This interpretation is reasonable based on current literature, although it must be made carefully since interaction intensity varies as a function of stress magnitude, stage of development, genotype, and presence of microbial symbionts (Mekonnen et al., 2022; Olorunwa et al., 2021; Singh et al., 2025). Some reports have documented how phosphorus or biological inputs containing phosphorus could offset the adverse effects of stress through the maintenance of nodulation, photosynthetic efficiency, water status, and yield components (Singh et al., 2025). Other reports demonstrate how drought can severely constrain stomatal conductance, carbon fixation, and nitrogen fixation below 60% soil water content, leaving little room for rescue through biological inputs (De Melo et al., 2025). Rather than suggesting substitution between P and water, it seems appropriate to conclude that proper amounts of P facilitate maintaining physiological functions under stress according to physiological thresholds imposed by water availability (Loftus et al., 2025; Mohammed et al., 2021).

Implications for Cowpea Production in Zimbabwe

However, for small-scale farmers in semi-arid Zimbabwe (Natural Regions III-V), when good rainfall conditions (above 400 mm) are expected, it is advisable to use 120-240 kg P₂O₅ ha⁻¹ (2.0- 4.0 g plant⁻¹). When moderate drought (rainfall between 300-400 mm) conditions prevail, 120 kg P₂O₅ ha⁻¹ (2.0g plant⁻¹) is the best choice as more phosphorus would be unnecessary. If soils are phosphorus deficient but the expected rainfall is below 300 mm, it is better to focus on soil moisture conservation through mulching, tying of ridges, and early planting rather than application of phosphorus (Kugedera et al., 2022). Extension workers should design decision rules

which match the amount of phosphorus used to expected rainfall. The fact that drought leads to heavier 100-seed weight means that moderate drought improves seed quality.

Limitations and Future Research

The limitations include the pot culture system not representing field conditions, the experiment being carried out using one cultivar (CBC1), soil sterilization reducing mycorrhizal fungi, and yield measurement assuming equal plant stand. Further investigations are suggested for validation of results in field conditions, study involving several cultivars, terminal drought stress, economic evaluation, role of mycorrhizae and physiology measurements.

CONCLUSION

The results of this experiment show that the moisture content and phosphorus fertilization have considerable influence on the growth, yield and yield components of the cowpea, and that their effects are mostly additive rather than synergistic. Moisture deficiency promoted the process of maturity, impaired vegetative growth, decreased reproductive success and grain yield, and resulted in increased seed weight as compensation. Phosphorus application stimulated growth, increased pod number and grain yield, and decreased seed weight. The most effective phosphorus dose depends on the moisture level and equals 2.0- 4.0 g plant⁻¹ in favorable conditions and 2.0g plant⁻¹ in drought conditions; the upper rate only marginally increases yield under drought conditions. The CBC1 variety was successful both in well-watered and drought conditions, reaching the maximum grain yield equal to 7.4 t ha⁻¹. The results of this experiment can be used to make recommendations regarding phosphorus management in drought-stressed.

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AUTHORS' CONTRIBUTIONS

Moses Mutetwa: Conceptualization (lead), Writing original draft (lead), visualization. Clapperton Mapwanyire: Conceptualization (support), data analysis, writing original draft, project administration, supervision. Tanaka Grace Munasireyi: Conceptualization (support), writing original draft, project administration. Rachel Magaya: Writing-review, visualization, validation and editing. Marilyn Wimbiso Kutamahufa: Writing-review, validation and editing. Allen Gwangwadza: Writing-review, validation and editing. Nation Chikumba: Writing-review and editing, visualization, supervision. Wonder Ngezimana: Conceptualization (support), Writing original draft (support), validation, project administration, supervision.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable.

CONSENT FOR PUBLICATION

Not Applicable

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AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

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