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INTEGRATED APPLICATION OF BIO-STIMULANTS AND PHOSPHORUS ENHANCES PHENOLOGY, GROWTH, AND YIELD OF MAIZE

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Article Info

Abstract

Maize productivity is often constrained by suboptimal nutrient availability and poor early crop establishment, which can limit growth, reproductive development, and yield. This study investigated the effects of varying levels of bio-stimulants (0, 8, 10, and 12 L ha^{-1}) and phosphorus (0, 60, 90, and 120 kg ha^{-1}) on maize phenology, growth, and yield attributes at Charbagh Nursery Farm, Swabi, during Kharif 2024 using a randomized complete block (RCB) design with four replications. The results showed that both factors significantly influenced maize development, with notable interactions for several traits. Bio-stimulant application accelerated seed emergence, increased single leaf area, and enhanced plant height, while higher phosphorus levels improved leaf area and growth vigor. Tasseling and silking were delayed by bio-stimulants, allowing prolonged vegetative growth, with the combined application of 12 L ha^{-1} bio-stimulant and 120 kg ha^{-1} phosphorus producing the greatest delay. Grain yield components, including grains per ear and thousand-grain weight, as well as biological and grain yields, were significantly enhanced under higher levels of both factors, with the highest values recorded under combined application (408 grains ear^{-1}, 252.7 g thousand-grain weight, 12,958 kg ha^{-1} biological yield, and 4,326 kg ha^{-1} grain yield). Harvest index was also improved, reaching 41.6% under 10 L ha^{-1} bio-stimulant × 90 kg ha^{-1} phosphorus. In conclusion, integrating bio-stimulants with phosphorus at optimal levels enhances early crop establishment, promotes reproductive development, and maximizes maize yield, offering a practical strategy for sustainable intensification of maize production.

Keywords: *Crop intensification, Grain production, Reproductive development, Sustainable agriculture, Vegetative growth.*

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, contributing significantly to global food security, livestock feed, and agro-industrial processing. Globally, maize covers more than 205 million hectares, producing over 1.2 billion tons annually (FAO, 2023). In Pakistan, maize ranks as the second major cereal after wheat and is cultivated on nearly 1.4 million hectares, producing about 9.5 million tons during 2024–25 (USDA, 2024). The crop supports the national economy through its contribution to agriculture, which accounts for approximately 23–24% of Pakistan's GDP and employs nearly 40% of the labour force (Gop, 2023). Despite this importance, maize productivity remains below global potential due to constraints such as soil degradation, nutrient deficiency, and climatic variability.

Declining soil fertility due to low organic matter and nutrient imbalances is a major limiting factor in maize production across Pakistan (PARC, 2022). Over-reliance on synthetic fertilizers such as urea has led to reduced nutrient-use efficiency, poor soil structure, and depleted biological activity (Khan et al., 2020). These limitations are often compounded by abiotic stresses, including temperature fluctuations, irregular rainfall, and water scarcity, which further decrease nutrient availability and crop performance. In this context, bio-stimulants have emerged as promising tools to enhance crop resilience. Derived from natural sources such as seaweed extracts, microbial metabolites, humic substances, or plant derivatives, bio-stimulants enhance physiological and metabolic processes including root development, nutrient uptake, enzyme activity, and stress tolerance (Kumar et al., 2018; Zhang et al., 2020). Organic bio-stimulants, in particular, offer an environmentally friendly alternative that can reduce dependence on synthetic fertilizers while improving soil health and crop productivity.

Despite their increasing global use, the adoption of organic bio-stimulants in Pakistan remains limited, and scientific evidence supporting their effectiveness under local conditions is insufficient. In particular, there is limited understanding of the optimal dose of bio-stimulants for maize and how these inputs interact with mineral nutrients such as phosphorus. Phosphorus deficiency is widespread in Pakistani soils due to high pH, calcium fixation, and limited fertilizer efficiency, restricting root growth, photosynthesis, and grain development (Chen et al., 2019a). Integrating bio-stimulants with phosphorus fertilizers has the potential to enhance nutrient-use efficiency, stimulate microbial activity, improve root architecture, and enhance overall crop productivity (Liu et al., 2020; Chen et al., 2019b; Niu et al., 2020c). However, systematic evaluation of these combined effects under field conditions remains a key knowledge gap.

Therefore, this study was conducted to address these gaps by examining bio-stimulant and phosphorus integration under local agro-ecological conditions. The objectives of this study were to quantify the proper dose of bio-stimulant for maize production; to investigate the interactive effect of bio-stimulant and phosphorus on maize productivity and to evaluate the individual effect of phosphorus application levels on maize growth, yield components, and grain yield.

Methodology

Experimental site and design

A field trial titled was conducted at the Charbagh Nursery Farm, Swabi, during Kharif 2024 using a randomized complete block (RCB) design with four replications. The study evaluated bio-stimulant levels as the main-plot factor and phosphorus levels as the subplot factor. The bio-stimulant (a liquid formulation containing seaweed extract, liquid protein, amino acids, and beneficial microorganisms) was applied through fertigation at emergence and tasseling using clean tube-well water, with approximately 300–400 L ha^{-1} per application. Phosphorus was applied at four levels (0, 60, 90, and 120 kg ha^{-1}), while bio-stimulant treatments included B1 (control), B2 (8 L ha^{-1}), B3 (10 L ha^{-1}), and B4 (12 L ha^{-1}).

Agronomic practices

Maize hybrid Pioneer 3025 was planted on ridges in plots measuring 4.5 × 5 m (six rows spaced 75 cm apart). A basal dose of nitrogen (120 kg ha^{-1}) and potassium (60 kg ha^{-1}) was applied uniformly at sowing, and all other agronomic practices, including irrigation and thinning, were maintained consistently across all treatment combinations.

Parameters recorded

Days to emergence were recorded as the number of days from sowing until 50% of the seedlings had emerged, based on daily observations. Days to tasseling were measured as the period from sowing until visible tassels appeared on 50% of the plants. Days to silking were noted when silk emergence occurred on 50% of plants, while physiological maturity was recorded when 50% of the plants exhibited a black layer at the kernel base. Single leaf area was determined at tasseling by collecting the flag leaf from five randomly selected plants per plot and calculating area using Leaf Area = Length × Width × 0.75. Plant height was measured at maturity on five randomly chosen plants from the base to the tassel tip, and ears per plant were obtained by counting ears from eight selected plants per plot. Grains per ear were determined by counting grains on ten randomly selected ears from each plot. Biological yield was measured by harvesting and weighing all above-ground plant material from the net plot area and converting it to kg ha^{-1}, while thousand-grain weight was recorded by weighing 1000 cleaned, sun-dried grains using a digital balance. Grain yield was determined by threshing grains from the net plot area, drying them to 12–14% moisture, weighing, and converting to kg ha^{-1}. Harvest index (%) was calculated as (grain yield / biological yield) × 100.

Statistical analysis

For statistical analysis, all recorded data were analyzed through analysis of variance (ANOVA) based on a randomized complete block (RCB) design. Mean comparisons were carried out using the Least Significant Difference (LSD) test and planned mean comparisons following the procedure outlined by Khan *et al.* (2019). Graphs were created using Microsoft excel 2010.

Results

Crop phenological development

The phenological response of maize was significantly influenced by both bio-stimulant and phosphorus levels, with varying interaction effects across traits (Table 1). Days to emergence were affected by both factors, although their interaction was non-significant. Plots without bio-stimulant required the most time to emerge (9 days), while all other bio-stimulant levels (8, 10, and 12 L ha^{-1}) resulted in similar and earlier emergence (8 days). Likewise, phosphorus levels of 90 and 120 kg ha^{-1} produced the longest emergence period (9 days), significantly greater than the control and 60 kg ha^{-1} treatments (8 days). Days to tasseling were significantly influenced by bio-stimulants but not by phosphorus alone. The 12 L ha^{-1} bio-stimulant delayed tasseling the most (56 days), followed by 10 L ha^{-1} (55 days), whereas 0 and 8 L ha^{-1} recorded the earliest tasseling (54 days). Days to silking were significantly affected by both factors, with a highly significant B × P interaction. The control bio-stimulant treatment recorded the earliest silking (60 days), while 12 L ha⁻¹ resulted in the latest (62 days), and 8 and 10 L ha⁻¹ produced intermediate values (61 days). Across phosphorus levels, the control treatment reached silking stage earlier (60 days) compared with all other doses (61 days), and the combination of 12 L ha⁻¹ with 120 kg ha⁻¹ phosphorus caused the greatest delay (63 days). Days to physiological maturity were significantly influenced by both factors, with a significant interaction between them. Maturity was longest under 12 L ha⁻¹ (112 days) and shortest under the control (110 days), while phosphorus also increased maturity duration at 120 kg ha⁻¹ (112 days).

Table 1. Phenological Traits of Maize Under Bio-stimulant and Phosphorus Levels.

Factor & Levels	Days to emergence	Days to tasseling	Days to silking	Days to physiological maturity
Bio-stimulant (B)				
0 L ha^{-1}	9 ± 0.08 a	54 ± 0.20 c	60 ± 0.25 c	110 ± 0.10 c
8 L ha^{-1}	8 ± 0.07 b	54 ± 0.18 c	61 ± 0.22 b	111 ± 0.12 b
10 L ha^{-1}	8 ± 0.07 b	55 ± 0.19 b	61 ± 0.21 b	111 ± 0.11 b
12 L ha^{-1})	8 ± 0.08 b	56 ± 0.21 a	62 ± 0.23 a	112 ± 0.10 a
LSD (B)	0.14	0.40	0.50	0.20
Phosphorus (P)				
0 kg ha^{-1}	8 ± 0.07 b	55 ± 0.18	60 ± 0.20 b	110 ± 0.11 c
60 kg ha^{-1}	8 ± 0.07 b	55 ± 0.18	61 ± 0.21 a	111 ± 0.10 b
90 kg ha^{-1}	9 ± 0.08 a	55 ± 0.19	61 ± 0.21 a	111 ± 0.12 b
120 kg ha^{-1}	9 ± 0.08 a	55 ± 0.19	61 ± 0.22 a	112 ± 0.11 a
LSD (P)	0.26	ns	0.30	0.40

Distinct letters in the columns and rows indicate statistically significant differences, whereas "ns" represents a non-significant effect.

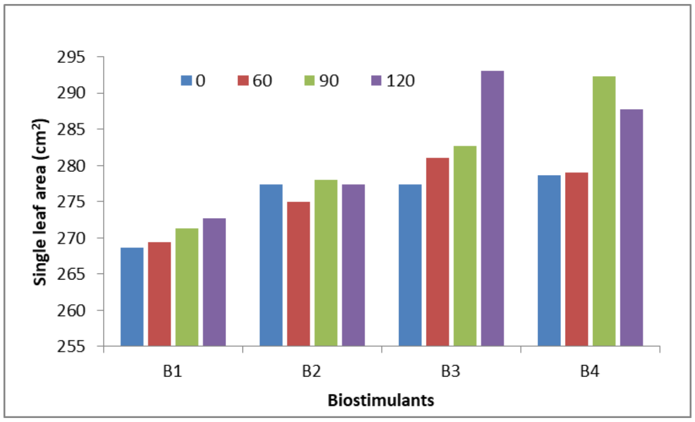
Growth and yield attributes

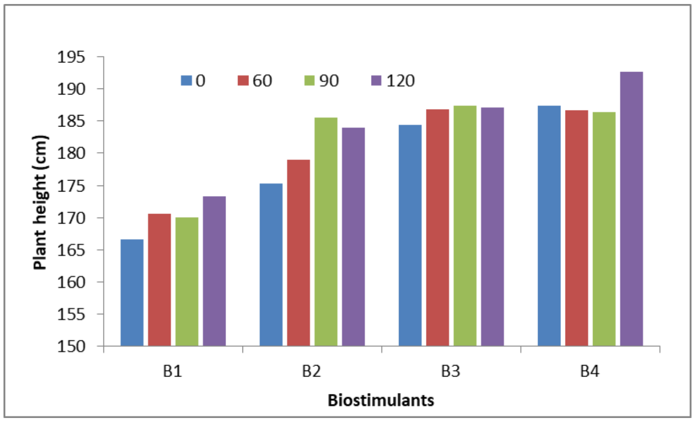
The growth and yield attributes of maize were greatly influenced by both bio-stimulant and phosphorus levels (Table 2). Single leaf area increased steadily with rising bio-stimulant doses, from the lowest value under control to the highest at 10 L ha⁻¹ and 12 L ha⁻¹ (283.5 and 284.4 cm^2), which were statistically similar. Interaction showed that leaf area was highest under the combine application of 8 L ha^{-1} of bio stimulant and 120 kg ha^{-1} of phosphorus (Figure 1). Phosphorus also enhanced leaf area, increasing from 0 kg ha^{-1} (270.5 cm^2) to 120 kg ha^{-1} (282.7 cm^2). Plant height showed a similar pattern, with the greatest height recorded at 12 L ha^{-1} of bio-stimulant (188.3 cm) and 120 kg ha^{-1} of phosphorus (184.3 cm), while their combination (12 L ha^{-1} × 120 kg ha^{-1}) produced the tallest plants (192.7 cm) and the minimum height (166 cm) occurred under control (Figure 1). Grains ear^{-1} increased with the highest values at 12 L ha^{-1} (390) and 120 kg ha^{-1} (361), and the maximum combined effect under 12 L ha^{-1} × 120 kg ha^{-1} (408), whereas the lowest grain count (293) occurred under control (Figure 1). Thousand grain weight was also affected, increasing from 203.8 g at 0 L ha^{-1} to 248.2 g at 12 L ha^{-1}, while only 120 kg ha^{-1} produced a notable increase among phosphorus levels (234.9 g). The highest interaction effect for thousand grain weight occurred at 12 L ha^{-1} × 60 kg ha^{-1} (252.7 g), whereas the lowest was recorded under 0 L ha^{-1} × 120 kg ha^{-1} (196.7 g) as stated in Figure 1.

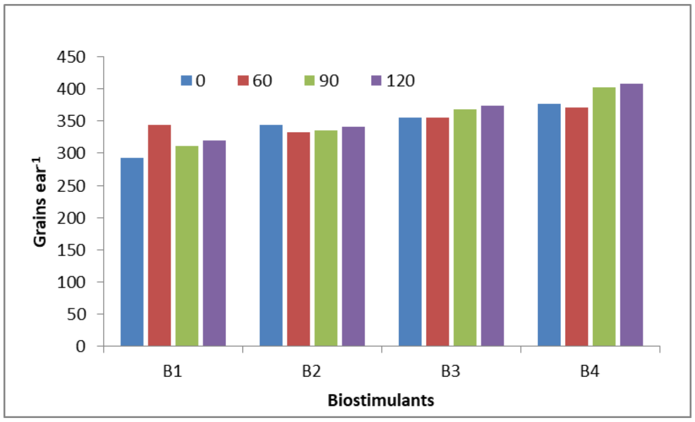
Table 2. Maize Growth and Yield Traits under Bio-stimulants and Phosphorus Levels.

Factor & Levels	Single Leaf Area (cm^2)	Plant Height (cm)	Grains per Ear	Thousand-Grain Weight (g)
Bio-stimulant (B)				
0 L ha^{-1}	270.5 ± 1.8 c	170.2 ± 1.0 d	318 ± 3.5 d	203.8 ± 2.7 d
8 L ha^{-1}	276.9 ± 1.9 b	181.0 ± 1.1 c	339 ± 3.6 c	217.1 ± 2.8 c
10 L ha^{-1}	283.5 ± 2.0 a	186.4 ± 1.2 b	363 ± 3.8 b	234.4 ± 2.9 b
12 L ha^{-1})	284.4 ± 2.0 a	188.3 ± 1.2 a	390 ± 4.0 a	248.2 ± 3.0 a
LSD (B)	3.6	0.4	7	5.4
Phosphorus (P)				
0 kg ha^{-1}	270.5 ± 1.8 c	170.2 ± 1.0 d	318 ± 3.5 d	203.8 ± 2.7 d
60 kg ha^{-1}	276.1 ± 1.9 b	180.8 ± 1.1 c	351 ± 3.6 b	223.6 ± 2.8 b
90 kg ha^{-1}	281.1 ± 2.0 a	182.3 ± 1.2 b	354 ± 3.8 b	222.8 ± 2.9 b
120 kg ha^{-1}	282.7 ± 2.0 a	184.3 ± 1.2 a	361 ± 4.0 a	234.9 ± 3.0 a
LSD (P)	2.6	0.3	8	3.8

Distinct letters in the columns and rows indicate statistically significant differences, whereas "ns" represents a non-significant effect.


0
60
90
120
Single leaf area (cm²)
295
290
285
280
275
270
265
260
255
B1
B2
B3
B4
Biostimulants


0
60
90
120
Plant height (cm)
195
190
185
180
175
170
165
160
155
150
B1
B2
B3
B4
Biostimulants


0
60
90
120
Grains ear⁻¹
450
400
350
300
250
200
150
100
50
0
B1
B2
B3
B4
Biostimulants

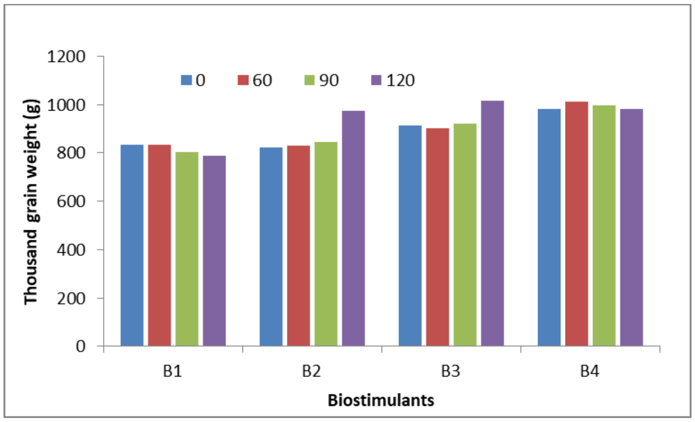

0
60
90
120
Thousand grain weight (g)
1200
1000
800
600
400
200
0
B1
B2
B3
B4
Biostimulants

Figure 1. Interactive effect of phosphorus levels and bio stimulants on growth and yield attributes of maize. B1 = 0 L ha^{-1} bio-stimulant, B2 = 8 L ha^{-1} bio-stimulant, B3 = 10 L ha^{-1} bio-stimulant, B4 = 12 L ha^{-1} bio-stimulant.

Biological yield (kg ha^{-1}) grain yield (kg ha^{-1}) and harvest index (%)

The biological and grain yield of maize were influenced by both bio-stimulant and phosphorus levels (Table 3). Biological yield increased with higher bio-stimulant doses, rising from 9,380 kg ha^{-1} under 0 L ha^{-1} to 9,603, 10,235, and 11,196 kg ha^{-1} at 8, 10, and 12 L ha^{-1}, respectively. Phosphorus also enhanced biological yield, increasing from 9,153 kg ha^{-1} at 0 kg ha^{-1} to 10,106 and 10,284 kg ha^{-1} at 60 and 90 kg ha^{-1}, with the maximum (10,871 kg ha^{-1}) at 120 kg ha^{-1}. The interaction effect occurred at 12 L ha^{-1} × 120 kg ha^{-1}, producing the highest biological yield (12,958 kg ha^{-1}), whereas the lowest (7,921 kg ha^{-1}) occurred under control (Figure 2). Similarly, increasing bio-stimulant levels raised grain yield from 2573 kg ha^{-1} in untreated plots to 3038, 3328, and 3934 kg ha^{-1} at 8, 10, and 12 L ha^{-1}, respectively. Phosphorus also improved grain yield, with 120 and 90 kg ha^{-1} (3717 and 3656 kg ha^{-1}). The maximum interactive yield (4326 kg ha^{-1}) was noticed under 12 L ha^{-1} × 120 kg ha^{-1}, while the minimum (2067 kg ha^{-1}) occurred under control (Figure 2). Harvest index was also significantly affected, increasing from 28.6% under 0 L ha^{-1} to 31.8%, 32.7%, and 35.3% under 8, 10, and 12 L ha^{-1}, respectively, while phosphorus produced the highest index at 90 kg ha^{-1} (35.8%) over control (28.2%).

Table 3. Maize Yield and Harvest Index under Bio-stimulants and Phosphorus Levels

Factor & Levels	Biological Yield (kg ha^{-1})	Grain Yield (kg ha^{-1})	Harvest Index (%)
Bio-stimulant (B)			
0 L ha^{-1}	9380 ± 160 c	2689 ± 50 d	28.6 ± 0.6 c
8 L ha^{-1}	9603 ± 165 c	3038 ± 55 c	31.8 ± 0.7 b
10 L ha^{-1}	10235 ± 170 b	3328 ± 60 b	32.7 ± 0.7 b
12 L ha^{-1})	11196 ± 172 a	3934 ± 65 a	35.3 ± 0.8 a
LSD (B)	320	101	1.3
Phosphorus (P)			
0 kg ha^{-1}	9380 ± 160 c	2689 ± 50 d	28.6 ± 0.6 c
60 kg ha^{-1}	10106 ± 163b	3043 ± 54 b	30.1 ± 0.7 b

90 kg ha⁻¹	10284 ± 171 b	3656 ± 60 a	35.8 ± 0.7 a
120 kg ha⁻¹	10871 ± 175 a	3717 ± 65 a	34.3 ± 0.8 b
LSD (P)	194	92	1.0

Distinct letters in the columns and rows indicate statistically significant differences, whereas "ns" represents a non-significant effect.

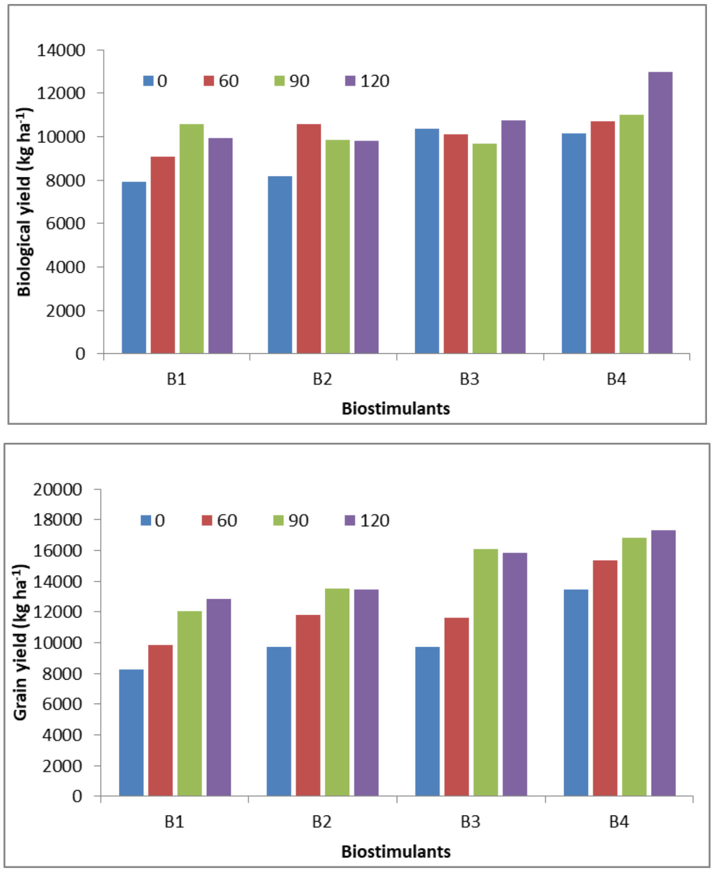


Figure 2. Interactive effect of phosphorus levels and bio stimulants on biological and grain yield of maize. B1 = 0 L ha⁻¹ bio-stimulant, B2 = 8 L ha⁻¹ bio-stimulant, B3 = 10 L ha⁻¹ bio-stimulant, B4 = 12 L ha⁻¹ bio-stimulant.

Discussion

Bio-stimulants and phosphorus play distinct yet complementary roles in early maize development and establishment. Bio-stimulants enhance seed metabolic activity, likely through the activation of hormonal pathways, particularly gibberellins and other growth regulators, which accelerate germination and reduce days to emergence (Nephali et al., 2020). In this study, seed emergence in control plots without bio-stimulants averaged 9 days, whereas treatments with bio-stimulants at 8, 10, and 12 L ha^{-1} reduced emergence to approximately 8 days. This effect is further supported by reports that bio-stimulants activate key enzymes involved in seed mobilization and induce early cell division, promoting quicker emergence (Sharma et al., 2024). Phosphorus, in contrast, contributes to energy transfer via ATP and promotes root system development, essential for establishing healthy seedlings. Changes in maize phenology due to bio-stimulants are likely mediated by hormonal regulation and metabolic pathways, affecting the synthesis and action of phytohormones such as gibberellins, cytokinin's, and abscisic acid, which influence the vegetative-reproductive phase transition (Bhowmick et al., 2024; Kumar, 2023).

Delayed tasseling induced by bio-stimulants allows greater vegetative biomass accumulation, favorable for nutrient assimilation and yield formation, whereas phosphorus modulates cellular energy status and signal transduction without directly altering tasseling time, enhancing the plant's response to bio-stimulants (Bhupen Chandra et al., 2022). Similarly, days to silking are influenced by the interplay of bio-stimulants and phosphorus, with bio-stimulants prolonging the vegetative phase to enable more leaf area expansion and resource accumulation, while phosphorus ensures sufficient energy and metabolic activity for sustained growth. The combined application of 12 L ha^{-1} bio-stimulants with 120 kg ha^{-1} phosphorus delayed silking, allowing improved kernel set and yield potential (Franzoni et al., 2020; Li et al., 2024). The extended period to physiological maturity observed with these treatments may be linked to bio-stimulant-mediated alterations in phytohormone balance, such as increased cytokinin's and modulated gibberellins, delaying senescence and prolonging nutrient assimilation and biomass accumulation, while phosphorus supports energy metabolism and biosynthetic processes necessary for sustained cellular activity (Nephali et al., 2020; Khan et al., 2023).

The observed decrease in weed biomass under higher bio-stimulant regimes can be attributed to competitive suppression, whereby enhanced basal metabolic activity and accelerated root development increase crop vigor, enabling maize to develop a larger shoot and root system. This improved establishment enhances access to light and water while creating a competitive microhabitat that limits resources available to weeds (Dixon, 2024). Early growth promotion by bio-stimulants also ensures quicker and more uniform stand establishment, reducing the window for weed germination and growth (Rajesaheb et al., 2025). Bio-stimulants act both directly, by optimizing plant developmental physiology, and indirectly, by shifting the competitive equilibrium in favor of the crop (Matysiak et al., 2018). When combined with phosphorus, plant height at maturity is further increased due to enhanced cell division, root elongation, and biomass accumulation. The bio-stimulant used, comprising seaweed extract, proteins, amino acids, and beneficial microorganisms, provides growth regulators such as auxins, cytokinin's, and gibberellins that stimulate cell expansion and internode elongation, while proteins and amino acids serve as building blocks and signaling molecules that enhance biosynthetic and metabolic activity (Ali et al., 2021).

Beneficial microorganisms improve nutrient uptake and soil health, and phosphorus supports adenosine triphosphate and other energy molecule formation, further promoting structural growth and photosynthetic potential (Malhotra et al., 2018). The increase in grains per ear with higher bio-stimulant application is linked to hormonal regulation, as active compounds from seaweed extract, amino acids, and microorganisms elevate levels of cytokinin's and gibberellins, promoting ovary development, kernel set, and cell division in developing ears (Pollicap, 2018). Phosphorus complements these effects by supporting energy transfer through ATP synthesis and nucleic acid production, essential for energy-intensive reproductive processes (Vance et al., 2003). The strong interaction between bio-stimulants and phosphorus indicates that optimal phosphorus availability not only supplies energy but also enhances bio-stimulant-induced hormonal effects, resulting in synergistic increases in grains per ear, highlighting the importance of integrating hormonal regulation with nutrient management to maximize reproductive performance in maize (Das et al., 2015).

The enhancement in thousand grain weight with increasing bio-stimulant application can be attributed to improved grain filling dynamics, as bio-stimulants upregulate key genes involved in carbohydrate metabolism and starch biosynthesis (Baltazar et al., 2021). Bio-stimulants containing seaweed extracts, proteins, amino acids, and beneficial microorganisms stimulate genes linked to sucrose synthase and invertase activities, promoting efficient assimilate partitioning during grain filling, while hormonal effects, including elevated cytokinin's and gibberellins, further enhance the duration and efficiency of this phase (Ali et al., 2021). Phosphorus complements these processes by increasing adenosine triphosphate production, supporting energy-intensive biosynthetic pathways necessary for grain filling (Maity et al., 2024). The synergistic effect of combining bio-stimulants with phosphorus not only improves assimilate partitioning but also ensures sufficient energy availability and optimal metabolic and genetic activity, leading to higher thousand grain weight.

Biological yield, reflecting the total biomass production of the plant, is also enhanced under higher bio-stimulant doses due to improved photosynthetic efficiency, expanded leaf area, and better root and shoot development, while phosphorus supports cellular metabolism and energy generation through ATP synthesis (Rajesaheb et al., 2025; Malhotra et al., 2018). This synergy produces a stronger crop capable of converting more assimilates into biomass.

Similarly, grain yield benefits from the integrated action of bio-stimulants and phosphorus, as higher ear formation, increased grains per ear, and greater thousand grain weight result from improved photosynthetic efficiency, nutrient utilization, and hormonal balance (Johnson et al., 2024; Schröder et al., 2010). The highest bio-stimulant × phosphorus interaction, particularly at 12 L ha^{-1} bio-stimulant and 120 kg ha^{-1} phosphorus, underscores the importance of synchronizing hormonal regulation with nutrient supply to maximize yield, consistent with outcomes of Ocwa et al. (2024), Masood et al. (2011), and Fosu-Mensah et al. (2016). Harvest index, representing the proportion of economic yield to total biomass, also increased with higher bio-stimulant application due to enhanced photosynthetic efficiency and optimized carbohydrate partitioning, with bio-stimulants modulating phytohormonal balances to favor reproductive allocation (Rajesaheb et al., 2025). Adequate phosphorus availability further supports ATP synthesis, efficient grain filling, and kernel development, and the combined application of bio-stimulants and phosphorus at optimal levels maximizes source-sink efficiency, resulting in the highest partitioning of biomass to grain yield (Grant et al., 2001).

Conclusion

Bio-stimulants and phosphorus had a significant effect on maize growth and yield. The combined application of 12 L ha^{-1} bio-stimulant and 120 kg ha^{-1} phosphorus improved plant height (188.3 cm), and single leaf area (maximum 284.4 cm^2). Delayed tasseling and silking positively influenced reproductive development, resulting in enhanced yield components such as grains per ear (390) and thousand grain weight (248.2 g) as well as biological (10,826 kg ha^{-1}) and grain yields (3,934 kg ha^{-1}) and increased harvest index. Based on these findings, it is recommended to implement the combined use of 12 L ha^{-1} bio-stimulant and 90 kg ha^{-1} phosphorus to maximize growth and yield benefits, apply bio-stimulants at critical stages such as emergence and tasseling to improve early establishment and extend reproductive development, and integrate bio-stimulants into nutrient management strategies to enhance crop performance.

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