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# Effects of Foliar-applied Biostimulants and Micronutrients on Growth, Yield and Economics of Winter Maize (*Zea mays* L.)

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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**Abstract**

A two-year field investigation was conducted during the *rabi* (winter) seasons of 2024-25 and 2025-26 at the Instructional Farm of the Department of Agronomy, ITM University, Gwalior, Madhya Pradesh, India, to evaluate the effect of foliar-applied biostimulants (chitosan, seaweed extract and protein hydrolysate) and micronutrients (Fe, Zn and I), alone and in combination, on the growth, yield and economics of winter maize (*Zea mays* L.). The experiment comprised sixteen treatments, namely an absolute control ($T_1$), three individual biostimulants ($T_2$-$T_4$), three individual micronutrients ($T_5$-$T_7$), four dual and triple biostimulant combinations ($T_8$-$T_{11}$), three dual and triple micronutrient combinations ($T_{12}$- $T_{15}$) and a six-component consortium ($T_{16}$) combining all biostimulants and micronutrients, laid out in a randomised block design with three replications. Foliar application of the consortium treatment ($T_{16}$) consistently and significantly outperformed all other treatments, recording the tallest plants (224.8 cm), highest dry matter accumulation (273.5 g plant$^{-1}$), highest SPAD-based chlorophyll content (57.4), heaviest cob with husk (243.8 g plant$^{-1}$), maximum number of grains cob$^{-1}$ (685.3), maximum cobs plant$^{-1}$ (1.88) and the highest grain yield (6.5 t ha$^{-1}$), representing increases of 21.2, 15.5, 45.0, 46.0, 78.0 and 49.2 per cent, respectively, over the control, pooled across both years. Grain yield showed a strong positive correlation with dry matter accumulation (r = 0.991), stover yield (r =

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0.986), cob weight with husk (r = 0.961) and fresh weight (r = 0.969). Grain yield showed a strong linear association with dry matter accumulation ($R^2$ = 0.983) among the pooled treatment means, while a multiple regression model incorporating dry matter accumulation, chlorophyll content and cob weight explained 98.8 per cent of the variability in grain yield. Although the consortium treatment produced the highest gross and net returns (₹1,68,496-1,84,664 and ₹1,21,455-1,36,936 $ha^{-1}$, respectively), the combined micronutrient treatment Fe + Zn + I ($T_{15}$) recorded the highest benefit-cost ratio (2.83-3.14), indicating greater input-use efficiency. Overall, integrated foliar application of biostimulants and micronutrients improved growth, yield and economic returns of winter maize under the conditions of the two-year field experiment.

*Keywords: Biostimulants; economics; foliar nutrition; micronutrients; winter maize.*

## 1. Introduction

Maize (*Zea mays* L.), often referred to as the "queen of cereals" owing to its highest genetic yield potential among cereals, occupies a pivotal position in global food, feed, fodder and industrial raw material security. In India, maize ranks third among food grain crops after rice and wheat, and its cultivation during the *rabi* (winter) season has emerged as a remunerative alternative to the traditional wheat-rice system because of higher yield potential, favourable agro-climatic conditions, reduced biotic stress and better price realisation. However, the sustained intensification of cereal-based cropping systems, coupled with imbalanced fertilisation, has led to widespread depletion of soil micronutrient reserves, particularly iron (Fe), zinc (Zn) and iodine (I), which are important for maintaining optimum crop growth and productivity.

Under climate-change-driven variability in temperature, rainfall and radiation regimes, conventional soil-based nutrient management is increasingly being complemented by foliar nutrition strategies that offer rapid, targeted and resource-efficient correction of nutrient deficiencies while minimising losses associated with soil fixation, leaching and volatilisation. Plant biostimulants - a diverse group of substances and microorganisms that, when applied to plants, enhance nutrition efficiency, abiotic stress tolerance and quality traits regardless of their nutrient content - have gained substantial global attention as environmentally benign tools for sustainable crop production (Rouphael & Colla, 2020; du Jardin, 2015). Among these, chitosan, a deacetylated derivative of chitin, is known to elicit defence responses, improve membrane integrity and enhance nutrient and water uptake (Malerba & Cerana, 2016); seaweed extracts supply natural cytokinins, auxins and betaines that stimulate cell division and source-sink activity (Battacharyya *et al*., 2015); and protein hydrolysates provide bioactive peptides and free amino acids that regulate nitrogen metabolism and hormonal balance (Colla *et al*., 2015).

Field evidence on zinc biofortification in maize indicates that combining biofertilizers with foliar Zn can improve growth, yield and grain Zn-related attributes under field conditions (Singh *et al*., 2024). A controlled maize study using foliar Moringa oleifera leaf extract also reported improvements in several growth traits, supporting the broader relevance of plant-derived biostimulant formulations (Zia *et al*., 2021). Two-year field trials with red and brown seaweed extracts reported improvements in maize growth and yield across the tested extracts, indicating the crop-specific potential of seaweed-based biostimulants under field conditions (Gandhi *et al*., 2024). More recently, combined seed coating and foliar application of seaweed nanopowders improved maize growth and physiological attributes, further supporting the relevance of seaweed-derived inputs for maize (Abdul Rahman *et al*., 2025).

Simultaneously, foliar application of micronutrients such as Fe, Zn and I can complement soil-based nutrient management by supplying nutrients during critical crop growth stages. Their application may support chlorophyll formation, enzyme activity and reproductive development, thereby contributing to crop growth and yield (Bender *et al*., 2013; Ariraman *et al*., 2022; Stewart *et al*., 2021). Although the individual roles of biostimulants and micronutrients have been reasonably well documented, information on their integrated foliar applications, particularly a six-component consortium combining three biostimulants and three micronutrients, on the growth, chlorophyll status, yield formation and economics of winter maize remains scarce, especially under the sub-tropical agro-climate of Gwalior, Madhya Pradesh. Furthermore, correlation and regression analyses examining the associations between growth traits and grain yield have rarely been reported for winter maize under the sub-tropical agro-climate of Gwalior, Madhya Pradesh.

Against this backdrop, the present investigation was undertaken with the following objectives: (i) to evaluate the individual and combined effects of foliar-applied chitosan, seaweed extract, protein hydrolysate, Fe, Zn and I on plant height, fresh weight, dry matter accumulation and chlorophyll content of winter maize; (ii) to assess their influence on cob weight, grain number, cob number, grain yield, stover yield, biological yield and harvest index; (iii) to work out the economics and benefit-cost ratio of the different foliar treatments; and (iv) to examine the associations between growth and yield attributes and grain yield using correlation and regression analyses.

## 2. Materials and Methods

### 2.1 Experimental Site and Climate

The field experiment was conducted during two consecutive *rabi* (winter) seasons of 2024-25 and 2025-26 at the Instructional Research Farm, Department of Agronomy, ITM University, Gwalior (26.23° N latitude, 78.18° E longitude, 197 m above mean sea level), Madhya Pradesh, India. The region falls under a sub-tropical, semi-arid climate characterised by hot, dry summers and cold winters, with the *rabi* season offering moderate temperatures, higher solar radiation, lower relative humidity and negligible rainfall, conditions considered most conducive for realising the genetic yield potential of winter maize. The experimental soil was sandy clay loam in texture, slightly alkaline in reaction, medium in available nitrogen, phosphorus and potassium, and comparatively low in available Fe, Zn and I, indicating scope for micronutrient-based intervention.

### 2.2 Experimental Design and Treatments

The experiment was laid out in a Randomised Block Design (RBD) with sixteen treatments replicated thrice. The treatments comprised: **$T_1$** - Control; **$T_2$** - Chitosan @ 0.25%; **$T_3$** - Seaweed extract @ 0.5%; **$T_4$** - Protein hydrolysate @ 0.25%; **$T_5$** - Iron (Fe) @ 0.3%; **$T_6$** - Zinc (Zn) @ 0.4%; **$T_7$** - Iodine (I) @ 0.05%; **$T_8$** - Chitosan @ 0.25% + Protein hydrolysate @ 0.25%; **$T_9$** - Chitosan @ 0.25% + Seaweed extract @ 0.5%; **$T_{10}$** - Seaweed extract @ 0.5% + Protein hydrolysate @ 0.25%; **$T_{11}$** - Chitosan @ 0.25% + Seaweed extract @ 0.5% + Protein hydrolysate @ 0.25%; **$T_{12}$** - Fe @ 0.3% + Zn @ 0.4%; **$T_{13}$** - Zn @ 0.4% + I @ 0.05%; **$T_{14}$** - Fe @ 0.3% + I @ 0.05%; **$T_{15}$** - Fe @ 0.3% + Zn @ 0.4% + I @ 0.05%; and **$T_{16}$** - Consortium (Chitosan @ 0.25% + Seaweed extract @ 0.5% + Protein hydrolysate @ 0.25% + Fe @ 0.3% + Zn @ 0.4% + I @ 0.05%). The recommended nutrient dose of 100:60:40 kg NPK $ha^{-1}$ was applied uniformly to all treatments. All foliar sprays, except the control, were applied twice - at the knee-high and silking growth stages - using a knapsack sprayer, with all other agronomic operations (land preparation, sowing, fertilisation, irrigation and plant protection) kept uniform across treatments in accordance with the recommended package of practices for winter maize.

### 2.3 Observations Recorded

Five randomly selected and tagged plants from each net plot were used to record plant height (cm) at harvest, fresh weight (g $plant^{-1}$) at harvest, dry matter accumulation (g $plant^{-1}$) at harvest and SPAD-based chlorophyll content at 90 days after sowing (DAS) using a CCM-200 Plus chlorophyll content meter. At harvest, cob weight with husk (g $plant^{-1}$), number of grains $cob^{-1}$, number of cobs $plant^{-1}$, grain yield, stover yield and biological yield (t $ha^{-1}$) were recorded and harvest index (%) was computed as the ratio of grain yield to biological yield. Treatment-wise cost of cultivation, gross returns, net returns and benefit-cost (B:C) ratio were worked out based on the prevailing market prices of inputs and produce during each cropping season.

### 2.4 Statistical Analysis

The data recorded for each character were statistically analysed using the analysis of variance (ANOVA) technique appropriate for a 186andomized block design (Gomez & Gomez, 1984). Treatment means were compared using the standard error of mean [SE(m)±] and least significant difference (LSD) at 5% probability level. In addition, to elucidate the inter-relationships among growth and yield-contributing characters, Pearson's correlation coefficients were computed among treatment means (pooled over both years, n = 16) for eleven key growth, yield and economic parameters. Simple linear regression models were fitted to examine the associations between grain yield and individual growth and yield-attributing characters. A multiple linear regression model incorporating dry matter accumulation, chlorophyll content and cob weight with husk was fitted to examine their combined association with grain yield. All statistical computations were performed using OPSTAT and R-Studio.

## 3. Results and Discussion

The data pertaining to growth, physiological, yield and economic parameters of winter maize as influenced by foliar application of biostimulants and micronutrients, pooled over two consecutive seasons (2024-25 and 2025-26), are presented in Tables 1-4 and depicted graphically in Figs. 1-7. In general, the six-component consortium treatment ($T_{16}$), combining chitosan, seaweed extract, protein hydrolysate, Fe, Zn and I, consistently and significantly outperformed all other treatments for every parameter studied, indicating that the combined treatment produced a greater response than the individual treatments.

### 3.1 Plant Height, Fresh Weight and Dry Matter Accumulation

Plant height increased progressively with crop age under all treatments, and significant treatment differences were recorded at harvest during both years (Table 1). The consortium treatment ($T_{16}$) produced the tallest plants (220.75 and 228.76 cm during 2024-25 and 2025-26, respectively), registering an increase of 20.9 and 21.6 per cent, respectively, over the control ($T_1$), which recorded the shortest plants (182.60 and 188.19 cm). Pooled across years, $T_{16}$ exceeded the control by 21.2%.

The enhancement in plant height under integrated foliar nutrition may be attributed to complementary physiological mechanisms operating simultaneously at the cellular and whole-plant level. Seaweed extract supplies naturally occurring cytokinins, auxins and gibberellins that stimulate cell division and elongation (Hernandez-Herrera *et al*., 2014); chitosan improves membrane permeability, water relations and nutrient absorption (Mondal *et al*., 2012); protein hydrolysate furnishes free amino acids and signalling peptides that promote protein synthesis (Colla *et al*., 2015); while Fe, Zn and I collectively support chlorophyll biosynthesis, auxin metabolism and enzyme activation (Kobayashi *et al*., 2019). The greater performance of the combined treatment compared with individual inputs indicates a greater response under integrated foliar application, consistent with the observations of Rouphael and Colla (2020) and Bulgari *et al*. (2019) in other field crops.

Fresh weight and dry matter accumulation at harvest followed a similar upward trend with the level of input integration (Table 1).

The consortium treatment recorded the highest fresh weight (555.56 and 573.56 g $plant^{-1}$) and dry matter accumulation (267.58 and 279.34 g $plant^{-1}$) during 2024-25 and 2025-26, representing pooled increases of 45.9 and 15.5 per cent, respectively, over the control. Dry matter accumulation showed a comparatively tighter and more consistent response across treatments than fresh weight, reflecting genuine biomass build-up rather than transient turgidity effects.

The higher biomass accumulation under integrated foliar nutrition may be associated with improved chlorophyll status and nutrient availability, which were accompanied by greater biomass production under the combined treatment over a longer duration. Similar responses in vegetative biomass following biostimulant application have been reported by Ali *et al*. (2021) and Ertani *et al*. (2019).

**Table 1. Effect of foliar-applied biostimulants and micronutrients on plant height (cm), fresh weight (g plant$^{-1}$) and dry matter accumulation (g plant$^{-1}$) of winter maize at harvest (2024-25 and 2025-26)**

| Treatment | Plant height (cm) | | Fresh weight (g plant$^{-1}$) | | Dry matter accumulation (g plant$^{-1}$) | |
|---|---|---|---|---|---|---|
| | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 |
| $T_1$ | 182.60 | 188.19 | 378.04 | 396.04 | 231.68 | 241.77 |
| $T_2$ | 193.60 | 199.53 | 387.45 | 405.45 | 232.25 | 242.40 |
| $T_3$ | 198.10 | 204.17 | 393.65 | 411.65 | 236.18 | 246.48 |
| $T_4$ | 190.40 | 196.23 | 384.68 | 402.68 | 232.00 | 242.12 |
| $T_5$ | 199.04 | 207.54 | 411.77 | 429.77 | 238.73 | 249.16 |
| $T_6$ | 199.29 | 208.64 | 422.25 | 440.25 | 240.80 | 251.36 |
| $T_7$ | 197.47 | 207.07 | 406.15 | 424.15 | 238.33 | 248.77 |
| $T_8$ | 200.09 | 209.53 | 436.93 | 454.93 | 240.35 | 250.87 |
| $T_9$ | 200.12 | 209.58 | 442.30 | 460.30 | 240.38 | 250.88 |
| $T_{10}$ | 199.63 | 209.32 | 427.70 | 445.70 | 240.00 | 250.48 |
| $T_{11}$ | 201.59 | 212.00 | 481.81 | 499.81 | 246.70 | 257.48 |
| $T_{12}$ | 201.54 | 211.95 | 479.04 | 497.04 | 244.55 | 255.23 |
| $T_{13}$ | 201.52 | 210.07 | 470.76 | 488.76 | 243.65 | 254.30 |
| $T_{14}$ | 201.07 | 209.94 | 465.11 | 483.11 | 243.53 | 254.18 |
| $T_{15}$ | 208.63 | 218.69 | 519.33 | 537.33 | 255.48 | 266.67 |
| $T_{16}$ | 220.75 | 228.76 | 555.56 | 573.56 | 267.58 | 279.34 |
| SE(m)± | 3.14 | 3.19 | 18.36 | 18.36 | 2.00 | 2.12 |
| LSD (P=0.05) | 8.97 | 9.13 | 53.27 | 53.27 | 5.72 | 6.06 |

### 3.2 Chlorophyll Content, Cob Weight with Husk and Number of Grains Cob$^{-1}$ and Number of Cobs Plant$^{-1}$

Chlorophyll content (SPAD value) recorded at 90 DAS was significantly influenced by the treatments in both years (Table 2, Fig. 1). The consortium treatment ($T_{16}$) recorded the highest SPAD value (56.63 and 58.17 during 2024-25 and 2025-26, respectively), an increase of 45.0 per cent over the control, pooled across years, while the control recorded the lowest values (38.28 and 40.92).

Among the individual micronutrients, zinc produced the greatest improvement in chlorophyll content, consistent with its established role in chlorophyll biosynthesis and enzyme activation, while among biostimulants, the triple combination ($T_{11}$) was most effective.

Iron is a structural and functional component of the photosynthetic electron-transport chain and is directly involved in chlorophyll biosynthesis; zinc activates carbonic anhydrase and several dehydrogenases essential for photosynthetic metabolism; and iodine has been reported to influence antioxidant responses and stress tolerance (Kobayashi *et al*., 2019; Ariraman *et al*., 2022; Medrano-Macías *et al*., 2016). The higher chlorophyll content recorded under micronutrient-inclusive treatments, further amplified by biostimulants, was associated with greater biomass accumulation and yield.

Yield-attributing characters, namely cob weight with husk, number of grains cob$^{-1}$ and number of cobs plant$^{-1}$, were significantly and positively influenced by the integrated foliar treatments (Table 2, Fig. 2). The consortium treatment recorded the heaviest cob with husk (239.94 and 247.67 g plant$^{-1}$), the highest number of grains cob$^{-1}$ (668.94 and 701.61) and the maximum number of cobs plant$^{-1}$ (1.86 and 1.90) during 2024-25 and 2025-26, respectively - pooled increases of 46.0, 78.0 and 22.2 per cent, respectively, over the control.

The disproportionately larger gain in grain number (78.0%) relative to cob weight (46.0%) suggests that the integrated treatment was associated with greater development of grain-number-related yield components. This is consistent with the findings of Rouphael and Colla (2020), who attributed such improvements in reproductive efficiency of biostimulant-treated crops to enhanced nutrient-use efficiency and prolonged photosynthetic activity during the reproductive phase. Among individual treatments, the triple biostimulant combination ($T_{11}$) and the triple micronutrient combination ($T_{15}$) performed comparably for cob number, underscoring that biostimulants and balanced micronutrition can independently, and in combination, enhance reproductive development (Ali *et al*., 2021; Ariraman *et al*., 2022).

### 3.3 Grain Yield, Stover Yield and Harvest Index

The cumulative improvement in growth and yield attributes translated into significantly higher grain yield, stover yield and biological yield under the consortium treatment (Table 3, Fig. 3). Pooled over both years, $T_{16}$ recorded 6.50 t ha$^{-1}$ grain yield, 13.25 t ha$^{-1}$ stover yield and 19.75 t ha$^{-1}$ biological yield, representing increases of approximately 49.2, 17.1 and 15.5 per cent, respectively, over the control. Harvest index, however, remained statistically at par across treatments (32.5-33.2%; Table 3), indicating that the observed yield gains resulted primarily from an overall enhancement in total biomass production, with proportionate improvement in both source capacity and sink strength, rather than from an altered assimilate-partitioning efficiency, a pattern consistent with the source-sink equilibrium concept described by Reynolds *et al*. (2022).

The greater grain yield under integrated foliar nutrition was associated with greater plant height, dry matter accumulation, chlorophyll content and yield attributes. Comparable yield responses under biostimulant and micronutrient management have been reported by Halpern *et al*. (2015), Dimkpa and Bindraban (2016), Bulgari *et al*. (2019) and Rouphael and Colla (2018).

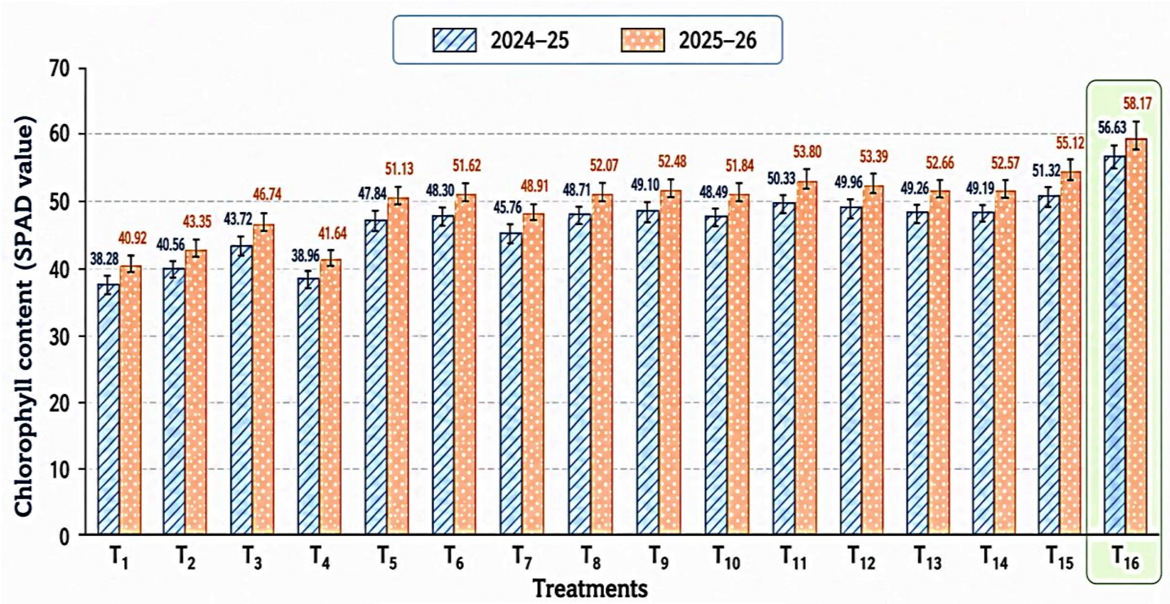


**Fig. 1. Effect of treatments on chlorophyll content (SPAD value) of winter maize at 90 DAS**

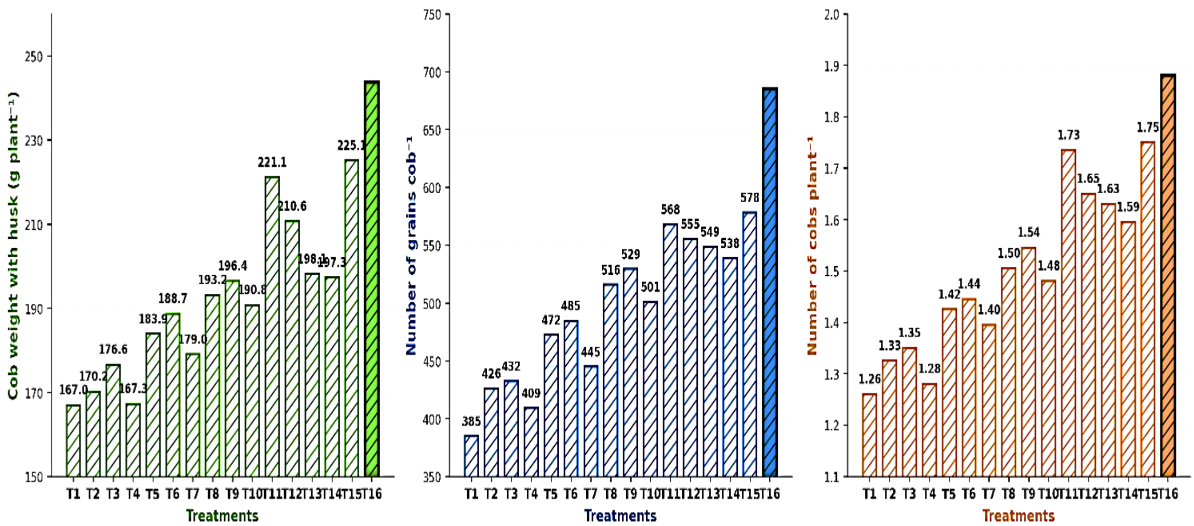


**Fig. 2. Effect of treatments on cob weight with husk, number of grains cob$^{-1}$ and number of cobs plant$^{-1}$ of winter maize (pooled mean 2024-25 and 2025-26)**

**Table 2. Effect of treatments on chlorophyll content (SPAD, 90 DAS), cob weight with husk (g plant$^{-1}$), number of grains cob$^{-1}$ and number of cobs plant$^{-1}$ of winter maize (2024-25 and 2025-26)**

| Treatment | Chlorophyll content (SPAD Values, 90 DAS) | | Cob weight with husk (g plant$^{-1}$) | | No. of grains cob$^{-1}$ | | No. of cobs plant$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 |
| $T_1$ | 38.28 | 40.92 | 164.50 | 169.54 | 366.87 | 402.99 | 1.22 | 1.30 |
| $T_2$ | 40.56 | 43.35 | 168.25 | 172.05 | 416.06 | 436.05 | 1.31 | 1.34 |
| $T_3$ | 43.72 | 46.74 | 174.75 | 178.43 | 422.64 | 442.22 | 1.33 | 1.37 |
| $T_4$ | 38.96 | 41.64 | 165.00 | 169.55 | 400.99 | 417.15 | 1.26 | 1.30 |
| $T_5$ | 47.84 | 51.13 | 181.13 | 186.62 | 446.56 | 498.44 | 1.41 | 1.44 |
| $T_6$ | 48.30 | 51.62 | 185.13 | 192.20 | 459.36 | 510.18 | 1.43 | 1.46 |

| Treatment | Chlorophyll content (SPAD Values, 90 DAS) | | Cob weight with husk (g plant$^{-1}$) | | No. of grains cob$^{-1}$ | | No. of cobs plant$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 |
| **$T_7$** | 45.76 | 48.91 | 176.13 | 181.90 | 434.37 | 455.42 | 1.36 | 1.43 |
| **$T_8$** | 48.71 | 52.07 | 190.63 | 195.75 | 503.37 | 528.22 | 1.48 | 1.53 |
| **$T_9$** | 49.10 | 52.48 | 191.75 | 201.09 | 514.50 | 544.29 | 1.51 | 1.58 |
| **$T_{10}$** | 48.49 | 51.84 | 187.75 | 193.88 | 482.71 | 519.38 | 1.46 | 1.50 |
| **$T_{11}$** | 50.33 | 53.80 | 215.40 | 226.70 | 542.58 | 593.09 | 1.68 | 1.79 |
| **$T_{12}$** | 49.96 | 53.39 | 205.80 | 215.45 | 535.32 | 575.43 | 1.61 | 1.69 |
| **$T_{13}$** | 49.26 | 52.66 | 191.88 | 204.28 | 528.78 | 568.54 | 1.58 | 1.68 |
| **$T_{14}$** | 49.19 | 52.57 | 191.04 | 203.47 | 522.28 | 554.71 | 1.55 | 1.64 |
| **$T_{15}$** | 51.32 | 55.12 | 221.51 | 228.71 | 558.41 | 597.91 | 1.72 | 1.78 |
| **$T_{16}$** | 56.63 | 58.17 | 239.94 | 247.67 | 668.94 | 701.61 | 1.86 | 1.90 |
| **SE(m)±** | 1.08 | 1.07 | 17.08 | 15.77 | 56.25 | 52.12 | 0.07 | 0.03 |
| **LSD (P=0.05)** | 3.08 | 3.06 | 5.98 | 5.52 | 19.68 | 18.24 | 0.19 | 0.09 |

**Table 3. Effect of treatments on grain yield (t ha$^{-1}$), stover yield (t ha$^{-1}$) and harvest index (%) of winter maize (2024-25 and 2025-26)**

| Treatment | Grain yield (t ha$^{-1}$) | | Stover yield (t ha$^{-1}$) | | Harvest index (%) | |
|---|---|---|---|---|---|---|
| | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 |
| **$T_1$** | 5.50 | 5.60 | 11.40 | 11.70 | 32.50 | 32.50 |
| **$T_2$** | 5.50 | 5.70 | 11.40 | 11.70 | 32.60 | 32.70 |
| **$T_3$** | 5.70 | 5.80 | 11.60 | 11.90 | 32.80 | 32.90 |
| **$T_4$** | 5.50 | 5.70 | 11.40 | 11.70 | 32.50 | 32.60 |
| **$T_5$** | 5.70 | 5.90 | 11.70 | 12.00 | 32.80 | 32.90 |
| **$T_6$** | 5.80 | 5.90 | 11.80 | 12.00 | 32.80 | 32.90 |
| **$T_7$** | 5.70 | 5.80 | 11.70 | 11.90 | 32.80 | 32.90 |
| **$T_8$** | 5.80 | 5.90 | 11.80 | 12.00 | 32.90 | 33.00 |
| **$T_9$** | 5.80 | 5.90 | 11.80 | 12.00 | 32.90 | 33.00 |
| **$T_{10}$** | 5.80 | 5.90 | 11.80 | 12.00 | 32.80 | 32.90 |
| **$T_{11}$** | 5.90 | 6.10 | 12.10 | 12.40 | 32.80 | 32.90 |
| **$T_{12}$** | 5.90 | 6.00 | 12.00 | 12.30 | 32.90 | 33.00 |
| **$T_{13}$** | 5.90 | 6.00 | 11.90 | 12.20 | 32.90 | 33.00 |
| **$T_{14}$** | 5.90 | 6.00 | 11.90 | 12.20 | 32.90 | 33.00 |
| **$T_{15}$** | 6.20 | 6.40 | 12.50 | 12.80 | 33.10 | 33.20 |
| **$T_{16}$** | 6.40 | 6.60 | 13.10 | 13.40 | 32.90 | 32.90 |
| **SE(m)±** | 0.05 | 0.06 | 0.18 | 0.19 | 0.41 | 0.42 |
| **LSD (P=0.05)** | 0.16 | 0.17 | 0.53 | 0.53 | NS | NS |

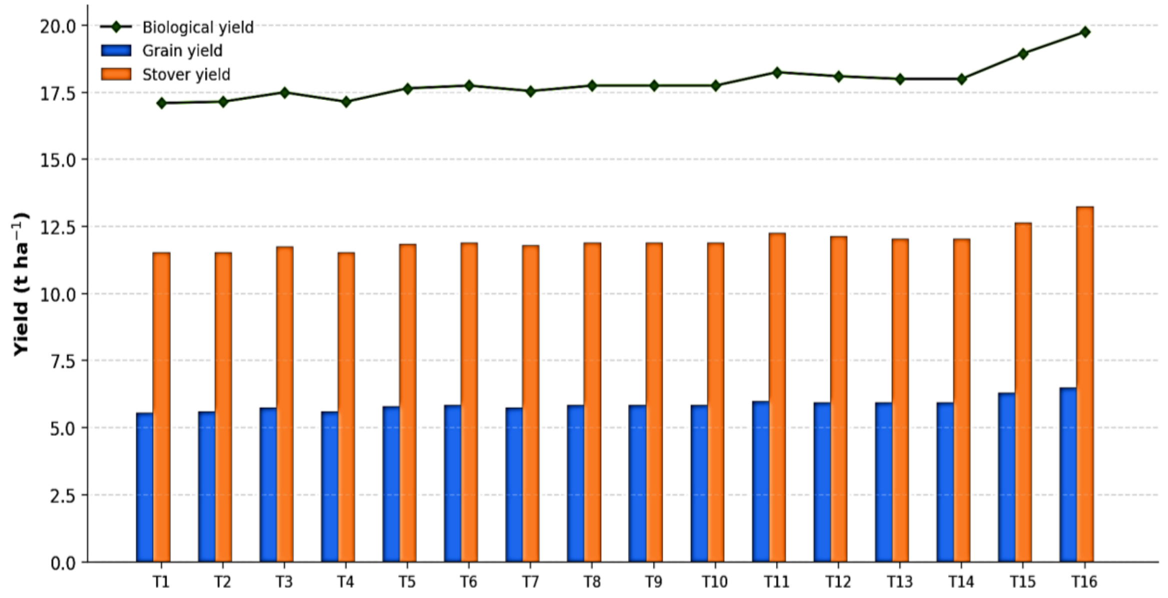


**Fig. 3. Effect of treatments on grain, stover and biological yield of winter maize (pooled mean 2024-25 and 2025-26)**

### 3.4 Economics and Benefit-Cost Ratio

The economics of winter maize cultivation, as influenced by the different treatments, is presented in Table 4 and Fig. 4. The cost of cultivation increased progressively with the number of foliar inputs applied, being highest under the six-component consortium (₹47,041-47,727 ha$^{-1}$) and lowest under the control (₹38,290-38,888 ha$^{-1}$). Despite the higher input cost, the consortium treatment recorded the highest gross returns (₹1,68,496-1,84,664 ha$^{-1}$) and net returns (₹1,21,455-1,36,936 ha$^{-1}$) during both years, confirming that the additional expenditure was more than compensated by the substantial yield gain.

Interestingly, the benefit-cost ratio followed a different trend: the combined micronutrient treatment Fe + Zn + I ($T_{15}$) recorded the highest B:C ratio (2.83-3.14), closely followed by zinc alone (2.82-3.12) and the triple biostimulant combination (2.81-3.10), whereas the consortium treatment, despite its highest absolute returns, recorded a comparatively lower B:C ratio (2.58-2.87) owing to the cumulative cost of six simultaneous foliar inputs. This indicates that when the objective is to maximise absolute productivity and total returns, the consortium treatment ($T_{16}$) is most appropriate, whereas when input-use efficiency and return per rupee invested are the priority, the balanced micronutrient treatment Fe + Zn + I ($T_{15}$) offers the most favourable economic proposition - a pattern consistent with earlier reports on the cost-effectiveness of balanced micronutrient nutrition in cereals (Cakmak, 2008; Cakmak & Kutman, 2018; Alloway, 2008).

**Table 4. Effect of treatments on cost of cultivation, gross returns, net returns and benefit-cost ratio of winter maize (2024-25 and 2025-26)**

| Treatment | Cost of cultivation (₹ ha$^{-1}$) | | Gross returns (₹ ha$^{-1}$) | | Net returns (₹ ha$^{-1}$) | | B:C ratio | |
|---|---|---|---|---|---|---|---|---|
| | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 | 2024-25 | 2025-26 |
| $T_1$ | 38290 | 38888 | 145082 | 157912 | 1,06,792 | 1,19,024 | 2.79 | 3.06 |
| $T_2$ | 39840 | 40463 | 146014 | 159852 | 1,06,174 | 1,19,389 | 2.66 | 2.95 |
| $T_3$ | 40015 | 40638 | 149010 | 163154 | 1,08,995 | 1,22,515 | 2.72 | 3.01 |
| $T_4$ | 39621 | 40232 | 145463 | 159248 | 1,05,842 | 1,19,016 | 2.67 | 2.96 |
| $T_5$ | 39585 | 40198 | 150551 | 164839 | 1,10,966 | 1,24,641 | 2.80 | 3.10 |
| $T_6$ | 39590 | 40196 | 151360 | 165750 | 1,11,770 | 1,25,553 | 2.82 | 3.12 |
| $T_7$ | 39840 | 40440 | 149814 | 164032 | 1,09,973 | 1,23,591 | 2.76 | 3.06 |
| $T_8$ | 41171 | 41807 | 152098 | 166573 | 1,10,926 | 1,24,765 | 2.69 | 2.98 |
| $T_9$ | 41565 | 42213 | 152137 | 166579 | 1,10,572 | 1,24,366 | 2.66 | 2.95 |
| $T_{10}$ | 41346 | 41982 | 151559 | 165962 | 1,10,213 | 1,23,980 | 2.67 | 2.95 |
| $T_{11}$ | 40885 | 41506 | 155572 | 170340 | 1,14,686 | 1,28,834 | 2.81 | 3.10 |
| $T_{12}$ | 41140 | 41748 | 154579 | 169290 | 1,13,439 | 1,27,541 | 2.76 | 3.06 |
| $T_{13}$ | 41135 | 41750 | 154147 | 168807 | 1,13,012 | 1,27,057 | 2.75 | 3.04 |
| $T_{14}$ | 42896 | 43557 | 154005 | 168578 | 1,11,109 | 1,25,021 | 2.59 | 2.87 |
| $T_{15}$ | 42435 | 43058 | 162623 | 178089 | 1,20,188 | 1,35,031 | 2.83 | 3.14 |
| $T_{16}$ | 47041 | 47727 | 168496 | 184664 | 1,21,455 | 1,36,936 | 2.58 | 2.87 |

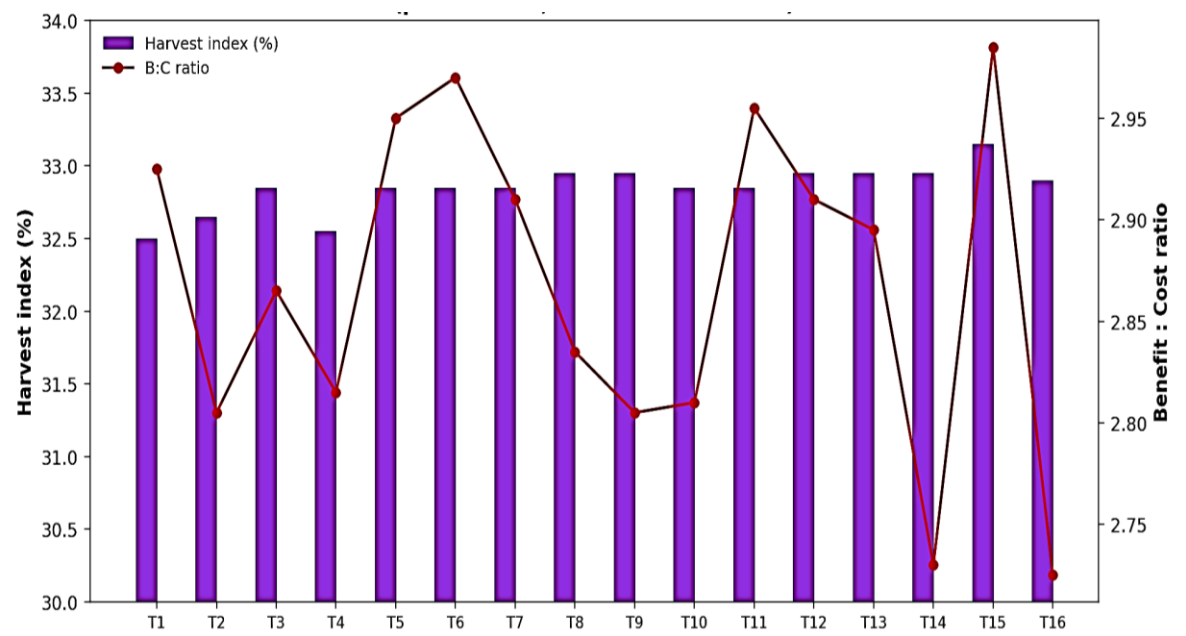


**Fig. 4. Effect of treatments on harvest index (%) and benefit-cost ratio of winter maize (pooled mean, 2024-25 and 2025-26)**

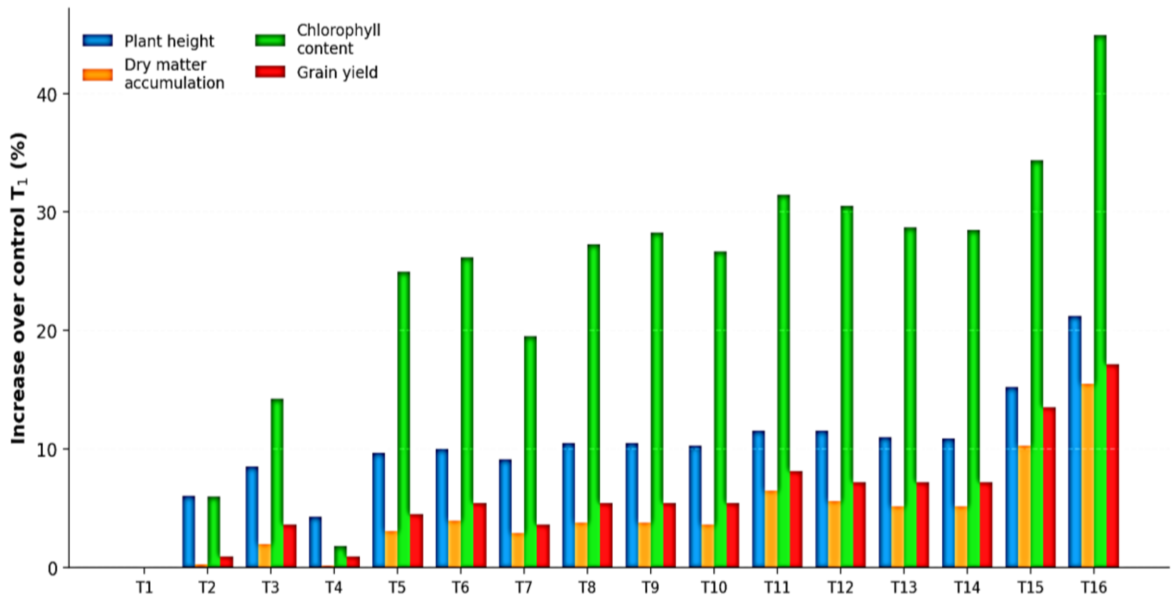


**Fig. 5. Percentage increase in plant height, dry matter accumulation, chlorophyll content and grain yield of winter maize over control ($T_1$)**

### 3.5 Correlation Studies

Pearson's correlation analysis among the treatment means (pooled over two years, n = 16) revealed strong, highly significant ($p < 0.001$) positive associations among nearly all growth and yield parameters (Table 5, Fig. 6). Grain yield exhibited the strongest correlation with dry matter accumulation (r = 0.991) and stover yield (r = 0.986), followed by cob weight with husk (r = 0.961), fresh weight (r = 0.969), number of grains cob$^{-1}$ (r = 0.948), number of cobs plant$^{-1}$ (r = 0.943), plant height (r = 0.949) and chlorophyll content (r = 0.892). Harvest index showed a comparatively weaker, though still significant, positive correlation with grain yield (r = 0.717), reaffirming that yield gains were driven predominantly by biomass accumulation rather than a shift in partitioning efficiency. Notably, the benefit-cost ratio showed a weak, statistically non-significant negative correlation with grain yield (r = −0.101) and most growth parameters, indicating the economic trade-off discussed above - the highest-yielding treatment did not necessarily give the highest return per unit investment. The near-unity correlation between dry matter accumulation and grain yield highlights dry matter accumulation as a closely associated physiological trait for screening biostimulant/micronutrient combinations in winter maize breeding and agronomic trials.

**Table 5. Pearson correlation matrix among growth, yield and economic parameters of winter maize (treatment means pooled over two years, n = 16)**

| | PH | FW | DMA | CHL | CW | GPC | CPP | GY | SY | HI | BCR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **PH** | 1.00 | 0.90 | 0.94 | 0.94 | 0.91 | 0.93 | 0.90 | 0.95 | 0.92 | 0.77 | -0.18 |
| **FW** | 0.90 | 1.00 | 0.96 | 0.89 | 0.98 | 0.98 | 0.99 | 0.97 | 0.96 | 0.71 | -0.11 |
| **DMA** | 0.94 | 0.96 | 1.00 | 0.86 | 0.96 | 0.94 | 0.93 | 0.99 | 1.00 | 0.64 | -0.13 |
| **CHL** | 0.94 | 0.89 | 0.86 | 1.00 | 0.90 | 0.94 | 0.92 | 0.89 | 0.84 | 0.85 | -0.05 |
| **CW** | 0.91 | 0.98 | 0.96 | 0.90 | 1.00 | 0.97 | 0.98 | 0.96 | 0.96 | 0.69 | -0.05 |
| **GPC** | 0.93 | 0.98 | 0.94 | 0.94 | 0.97 | 1.00 | 0.98 | 0.95 | 0.93 | 0.72 | -0.20 |
| **CPP** | 0.90 | 0.99 | 0.93 | 0.92 | 0.98 | 0.98 | 1.00 | 0.94 | 0.92 | 0.73 | -0.07 |
| **GY** | 0.95 | 0.97 | 0.99 | 0.89 | 0.96 | 0.95 | 0.94 | 1.00 | 0.99 | 0.72 | -0.10 |
| **SY** | 0.92 | 0.96 | 1.00 | 0.84 | 0.96 | 0.93 | 0.92 | 0.99 | 1.00 | 0.61 | -0.13 |
| **HI** | 0.77 | 0.71 | 0.64 | 0.85 | 0.69 | 0.72 | 0.73 | 0.72 | 0.61 | 1.00 | 0.10 |
| **BCR** | -0.18 | -0.11 | -0.13 | -0.05 | -0.05 | -0.20 | -0.07 | -0.10 | -0.13 | 0.10 | 1.00 |

**Note- PH = Plant height; FW = Fresh weight; DMA = Dry matter accumulation; CHL = Chlorophyll content; CW = Cob weight with husk; GPC = Grains cob$^{-1}$; CPP = Cobs plant$^{-1}$; GY = Grain yield; SY = Stover yield; HI = Harvest index; BCR = Benefit-cost ratio*

### 3.6 Regression Studies

Simple linear regression analysis further quantified these relationships (Table 6, Fig. 7). Grain yield showed the strongest linear association with dry matter accumulation ($R^2 = 0.983$), followed by cob weight with husk ($R^2 = 0.923$), plant height ($R^2 = 0.900$), number of grains cob$^{-1}$ ($R^2 = 0.898$), number of cobs plant$^{-1}$ ($R^2 = 0.889$) and chlorophyll content ($R^2 = 0.795$), all of which were highly significant ($p < 0.001$). This indicates that over 98 per cent of the variation in grain yield among treatments could be explained by dry matter accumulation alone.

**Fig. 6. Pearson's correlation matrix among growth, yield and economic parameters of winter maize**

**Table 6. Simple and multiple linear regression relationships between grain yield and growth and yield-attributing characters of winter maize**

| Independent variable (X) | Regression equation | $R^2$ | *p*-value |
|---|---|---|---|
| **Plant height (cm)** | GY = 0.280 + 0.0275 × PH | 0.900 | <0.001 |
| **Dry matter accumulation (g plant$^{-1}$)** | GY = −0.574 + 0.0261 × DMA | 0.983 | <0.001 |
| **Chlorophyll content (SPAD)** | GY = 3.674 + 0.0452 × CHL | 0.795 | <0.001 |
| **Cob weight with husk (g plant$^{-1}$)** | GY = 3.790 + 0.0108 × CW | 0.923 | <0.001 |
| **No. of grains cob$^{-1}$** | GY = 4.355 + 0.0030 × GPC | 0.898 | <0.001 |
| **No. of cobs plant$^{-1}$** | GY = 3.942 + 1.2799 × CPP | 0.889 | <0.001 |
| **Multiple (DMA + CHL + CW)** | GY = −0.020 + 0.0223·DMA + 0.0064·CHL + 0.0004·CW | 0.988 | <0.001 |

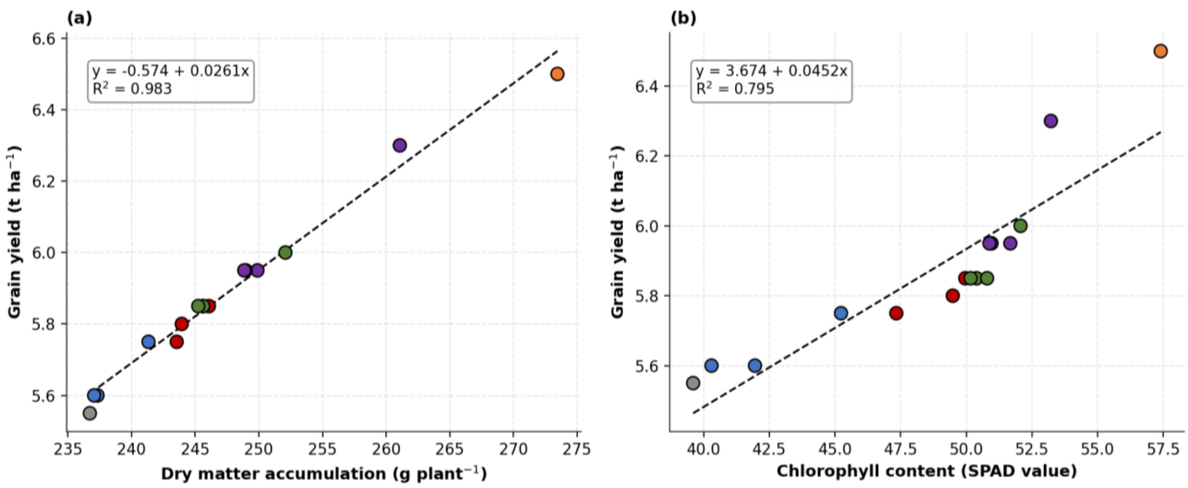

**Fig. 7. Linear regression of grain yield on (a) dry matter accumulation and (b) chlorophyll content of winter maize**

**Table 7. Combined analysis of variance for selected growth and yield parameters of winter maize (pooled basis)**

| Parameter | Source of variation | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
|---|---|---|---|---|---|---|
| Plant height | **Year** | 1 | 2304.102 | 2304.102 | 398.075 | 0.000 |
| | **Treatment** | 15 | 8590.233 | 572.682 | 98.941 | 0.000 |
| | **Replication within year** | 6 | 562.545 | 93.757 | 1.833 | 0.101 |
| | **Location x Treatment** | 15 | 86.822 | 5.788 | 0.113 | 1.000 |
| | **Error** | 90 | 4602.364 | 51.137 | NA | NA |
| Chlorophyll content | **Year** | 1 | 312.313 | 312.313 | 566.845 | 0.00 |
| | **Treatment** | 15 | 2802.049 | 186.803 | 339.047 | 0.00 |
| | **Replication within year** | 6 | 8.597 | 1.433 | 0.310 | 0.93 |
| | **Location x Treatment** | 15 | 8.264 | 0.551 | 0.119 | 1.00 |
| | **Error** | 90 | 416.030 | 4.623 | NA | NA |
| Dry matter accumulation | **Year** | 1 | 3583.552 | 3583.552 | 10325.232 | 0 |
| | **Treatment** | 15 | 10378.781 | 691.919 | 1993.615 | 0 |
| | **Replication within year** | 6 | 9975.677 | 1662.613 | 97.763 | 0 |
| | **Location x Treatment** | 15 | 5.206 | 0.347 | 0.020 | 1 |
| | **Error** | 90 | 1530.594 | 17.007 | NA | NA |
| Grain Yield | **Year** | 1 | 0.783 | 0.783 | 2125.585 | 0.000 |
| | **Treatment** | 15 | 6.868 | 0.458 | 1243.165 | 0.000 |
| | **Replication within year** | 6 | 0.298 | 0.050 | 3.364 | 0.005 |
| | **Location x Treatment** | 15 | 0.006 | 0.000 | 0.025 | 1.000 |
| | **Error** | 90 | 1.330 | 0.015 | NA | NA |

A multiple linear regression model incorporating dry matter accumulation, chlorophyll content and cob weight with husk as independent variables further improved the predictive power ($GY = -0.020 + 0.0223 \times DMA + 0.0064 \times CHL + 0.0004 \times CW$; multiple $R^2 = 0.988$), indicating that these three physiological and yield-component traits together accounted for nearly 99 per cent of the variability in grain yield of winter maize under the present experimental conditions. Because these analyses were based on 16 pooled treatment means, the regression relationships should be interpreted as exploratory associations rather than broadly predictive relationships.

## 4. Conclusion

The present two-year field investigation showed that integrated foliar application of biostimulants and micronutrients improved growth, yield attributes, yield and economic returns of winter maize compared with individual treatments and the untreated control.

The six-component consortium treatment (chitosan @ 0.25% + seaweed extract @ 0.5% + protein hydrolysate @ 0.25% + Fe @ 0.3% + Zn @ 0.4% + I @ 0.05%) consistently recorded the highest plant height, biomass accumulation, chlorophyll content, yield attributes, grain yield and net returns, and is recommended where the objective is to maximise absolute productivity and profitability. However, where the priority is maximising return per unit investment, the combined application of Fe @ 0.3% + Zn @ 0.4% + I @ 0.05% offers the most economically efficient option, recording the highest benefit-cost ratio. Correlation and regression analyses showed strong associations between grain yield and selected growth and yield attributes; however, these relationships were based on pooled treatment means and should be interpreted as exploratory associations rather than causal or broadly predictive relationships. Under the conditions of the present study, the consortium treatment may be considered a potential integrated foliar nutrition option for improving winter maize productivity and economic returns.

## 5. Limitations

The findings are specific to two *rabi* seasons at a single experimental location in Gwalior and should therefore be interpreted within those agro-climatic and soil conditions. The correlation and regression analyses were based on 16 pooled treatment means, limiting broader predictive inference and precluding causal interpretation of the observed associations. Treatment responses may vary across locations, soil fertility conditions and seasons. Consequently, multi-location and longer-term field validation would be needed before generalising the relative agronomic and economic performance of the foliar treatments.

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## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that no competing interests exist.

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