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ROLE OF PLANT GROWTH REGULATORS IN ENHANCING CROP PRODUCTIVITY

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Abstract

Plant growth regulators (PGRs) are increasingly investigated as tools for enhancing crop productivity, particularly under abiotic stress conditions. This study evaluated the effects of selected PGRs on wheat, maize, and tomato under no-stress and drought-stress environments using a factorial experimental framework. Treatments included gibberellic acid, indole-3-acetic acid, 6-benzyladenine, 24-epibrassinolide, and salicylic acid, compared against untreated controls. Growth parameters, chlorophyll index, crop-specific yield components, and final yield were assessed to determine treatment efficacy and interaction effects. Results indicate that PGR responses were strongly context-dependent, with several treatments demonstrating greater relative yield benefits under drought stress than under optimal moisture conditions. Yield enhancement was associated more closely with improvements in reproductive components such as grain weight in cereals and fruit mass in tomato—than with vegetative growth alone. However, treatment effects were not uniform across crops, highlighting the importance of species-specific developmental pathways and environmental modulation. Overall, the findings suggest that PGRs can contribute to yield stabilization under moderate stress, but their agronomic effectiveness depends on precise application timing and crop-specific response dynamics rather than generalized growth stimulation.

INTRODUCTION

Plant growth regulators (PGRs) including endogenous phytohormones and their synthetic analogues are increasingly used to manipulate crop growth, reproductive development, and stress responses with the objective of improving yield stability. Their agronomic appeal rests on two features: (i) they operate at very low concentrations and can shift developmental trajectories (cell division, elongation, organ initiation, senescence), and (ii) they are embedded in stress-signaling networks that regulate carbon–nitrogen partitioning, stomatal behavior, and oxidative homeostasis. However, the same properties that make PGRs powerful also make them risky as "yield enhancers": responses are frequently non-linear, strongly contingent on genotype × environment × management, and can create trade-offs between vegetative biomass and harvestable yield. Therefore, a credible scholarly framing must treat PGRs not as universal boosters but as context-dependent modulators whose effectiveness depends on dose, timing, delivery method, crop phenology, and the dominant yield-limiting factor in the production environment. Yield is not a single trait but an emergent outcome of source capacity (photosynthesis, leaf area duration, nutrient assimilation), sink strength (grain number, fruit set, cell expansion), and transport/allocation (phloem loading, remobilization, partitioning). PGRs influence all three domains through hormonal crosstalk, and the same compound may shift the balance differently under optimal versus stress conditions. Modern auxin biology emphasizes how auxin synthesis, transport, and signaling integrate developmental patterning and abiotic-stress responses, providing a mechanistic rationale for auxin-based interventions but also highlighting system complexity and compensatory pathways (Gao et al., 2024). Exogenous applications can therefore succeed when they correct a transient hormonal limitation (e.g., reproductive abortion under heat/drought) but fail when the primary limitation is non-hormonal (e.g., severe water deficit, nutrient deficiency, or sink constraints already saturated). Gibberellins are classically associated with stem elongation, leaf expansion, and reproductive transitions. In horticultural systems, GA_3 is often used to improve fruit set and reduce flower/fruit drop when reproductive development is hormonally constrained. Controlled-environment evidence in tomato indicates that GA_3 at appropriate concentrations can improve fruit set and yield (Jha et al., 2022). More recent tomato work similarly reports yield and quality responses to exogenous gibberellin, reinforcing the notion that GA_3 can improve reproductive outcomes when application timing and concentration are aligned with flowering and early fruit development (Rebollo & Rosales, 2023). The critical limitation, repeatedly observed across crops, is that GA_3 can also push assimilates toward vegetative growth, potentially reducing reproductive allocation or quality when doses are excessive or the crop is already source-limited. Evidence consistent with such source–sink trade-offs is reported in fruit-focused systems where GA_3 regimes modify nutrient partitioning and quality attributes, implying that "more GA_3" is not equivalent to "more yield" (Eissa et al., 2025). Thus, GA_3 should be framed as a regulator requiring optimization rather than a guaranteed enhancer. Auxins underpin root initiation, vascular differentiation, apical dominance, and stress-adaptive growth plasticity. Field evidence in maize under salinity stress shows that foliar IAA (alone or in combination with kinetin) can modify growth and stress physiology, supporting the view that auxin-based interventions may be most valuable when stress disrupts hormonal balance rather than when stress is purely resource-limiting (Kaya et al., 2010). At the same time, auxin actions are deeply intertwined with other hormones; isolated auxin applications can be inconsistent if cytokinin balance, ABA dynamics, or sink formation is not simultaneously favorable. Contemporary reviews emphasize auxin–hormone interactions and stress integration, which is a warning against oversimplified causal claims in yield improvement narratives (Gao et al., 2024). For an academically defensible literature review, auxin evidence should be synthesized by mechanism (rooting, retention, sink initiation) and context (stress type, stage), not merely cataloged as positive yield responses. Cytokinins are central to cell division, chloroplast development, sink strength, and senescence delay. Their agronomic relevance is clearest in conditions where stress prematurely accelerates senescence or disrupts grain filling. In maize, exogenous 6-benzyladenine (6-BA) has been shown to improve photosynthesis and grain-filling characteristics under waterlogging and increase grain yield, offering a concrete example where a cytokinin addresses a stress-induced physiological bottleneck rather than acting as a generic stimulant (Ren et al., 2016). Complementary evidence from mechanistic plant-stress research indicates that 6-BA can enhance growth and biomass under waterlogging stress, again implying context-specific benefit (Wang et al., 2021). In wheat, drought-oriented evidence suggests that cytokinin-based strategies can contribute to drought tolerance and yield protection when integrated with nutrient management, reinforcing the idea that PGR responses often depend on co-limiting factors such as micronutrient availability (Zarea et al., 2023). The critical issue is that cytokinin effects are often stage-sensitive: benefits are typically strongest around grain filling, and poorly timed sprays may deliver minimal yield gains despite visible greening. Brassinosteroids, particularly 24-epibrassinolide (EBL), are among the most consistently reported PGRs for abiotic stress tolerance, largely because they modulate antioxidant systems, membrane stability, and hormonal balance. A focused review on EBL emphasizes its role in improving drought stress tolerance through signaling effects on physiology and metabolism (Tanveer et al., 2019). Crop-specific evidence in wheat supports yield- and biomass-related benefits and reduced oxidative damage under drought, aligning with the mechanistic expectation that EBL enhances tolerance rather than simply accelerating growth (Khan et al., 2021). Recent controlled studies further show EBL-mediated reductions in drought-induced oxidative injury and improved growth metrics, strengthening the mechanistic plausibility of EBL as a stress-mitigation input (Avalbaev et al., 2024). Nonetheless, brassinosteroid responses can still be contingent: if stress is extreme and hydraulic failure dominates, redox improvements may not translate into yield protection. A rigorous review should therefore separate physiological resilience indicators (ROS, membrane integrity) from agronomic endpoints (yield), and explicitly acknowledge when studies report the former without demonstrating the latter. Although SA is classically framed as a defense signal, a large body of evidence supports its role in abiotic stress acclimation through antioxidant activation, osmolyte regulation, and maintenance of photosynthetic function. Recent experimental work in rice shows SA improving growth under salt and drought stresses while increasing antioxidant enzyme activities and stress-related gene expression, supporting a coherent mechanistic pathway for improved performance under stress (Shan et al., 2024). A broader synthesis of SA biology in stress signaling similarly concludes that SA treatments can alleviate drought impacts via enhanced antioxidant activity, membrane protection, and photosynthetic maintenance, and cites crop-specific demonstrations including tomato and wheat contexts (Decsi et al., 2025). The methodological caution is that SA studies often vary widely in concentration units (ppm, mM), delivery (seed priming vs foliar), and stress imposition protocols, which complicates cross-study comparability. A strong literature review should therefore standardize reporting (dose, timing, stage, stress intensity) and avoid overgeneralizing from isolated pot trials to field-scale yield outcomes. Across hormone classes, the most defensible pattern is that PGRs tend to deliver stronger and more consistent benefits when (i) stress is moderate (allowing physiological mitigation to translate into yield), (ii) application coincides with a known sensitive developmental window (flowering, early fruit set, grain filling), and (iii) the treatment targets an identifiable bottleneck (premature senescence, impaired grain filling, reproductive abortion). Evidence for cytokinin effects on maize grain filling under waterlogging (Ren et al., 2016), EBL-mediated drought tolerance (Tanveer et al., 2019; Khan et al., 2021; Avalbaev et al., 2024), and SA-driven stress acclimation (Shan et al., 2024; Decsi et al., 2025) is consistent with this mechanism-based framing. Conversely, claims that PGRs "increase yield" without specifying dose–timing, stress context, and yield-component pathways are weak and often not reproducible. A critical review must also note that some PGR regimes can shift biomass without improving harvest index, or improve yield at the expense of quality traits an issue highlighted by studies emphasizing hormone-driven nutrient and quality partitioning rather than yield alone (Eissa et al., 2025). Despite the extensive literature, three gaps remain persistent. First, dose–response optimization is often missing; single-dose studies cannot distinguish suboptimal use from true lack of efficacy. Second, multi-environment validation is limited; results from pots or single-season trials frequently fail to generalize. Third, mechanistic inference is often overstated: SPAD or biomass changes are frequently interpreted as causal drivers of yield without mediation analysis or direct physiology (gas exchange, stomatal conductance, water potential). Accordingly, a publishable paper should position PGRs as part of integrated crop management potentially valuable for stabilizing yield under defined stresses—rather than presenting them as standalone yield enhancers.

Experimental Design and Treatment Structure

A factorial experimental design was employed to evaluate the effects of selected plant growth regulators (PGRs) on crop productivity under contrasting environmental conditions. The study included three agronomically distinct crops wheat (C_3 cereal), maize (C_4 cereal), and tomato (horticultural fruit crop) to capture variation in physiological pathways and yield architecture. Treatments consisted of six levels: untreated control, gibberellic acid (GA_3), indole-3-acetic acid (IAA), 6-benzyladenine (BA), 24-epibrassinolide (EBL), and salicylic acid (SA). Each treatment was applied under two moisture regimes (no-stress and drought-stress) and across two soil types (alluvial soil and sandy loam). The experimental structure followed a completely randomized factorial arrangement with four replicates per treatment combination. The inclusion of stress and soil factors allowed examination of treatment × environment interactions rather than limiting inference to isolated main effects. Plot-level experimental units were considered independent, and uniform agronomic management practices were maintained within each crop to minimize confounding effects. While the design is statistically robust for detecting interaction effects, the absence of multiple dose levels restricts interpretation of dose–response relationships. Consequently, conclusions are limited to comparative efficacy rather than optimization of concentration thresholds. Figure A presents a schematic representation of the factorial experimental design employed to evaluate the influence of plant growth regulators (PGRs) on crop productivity under varying environmental conditions. The diagram illustrates the hierarchical integration of crop type, moisture regime, soil type, and chemical treatment, clarifying the multidimensional structure of the study. This visualization is critical for understanding how interaction effects were embedded into the experimental framework rather than treated as secondary considerations. The inclusion of three crop species wheat, maize, and tomato introduces physiological diversity, allowing assessment of PGR responses across distinct photosynthetic systems and yield architectures. The bifurcation into no-stress and drought-stress regimes enables evaluation of whether treatment effects are conditional upon environmental constraints. This is particularly important because hormonal regulation often manifests differently under stress compared with optimal conditions. The addition of two soil types further strengthens ecological validity by incorporating edaphic variability. Soil characteristics can influence nutrient availability, root development, and hormone mobility, thereby potentially modifying treatment responsiveness. Replication at each treatment combination enhances statistical reliability and reduces random experimental error. However, the schematic also reveals methodological constraints. Only one dose level per PGR is represented, limiting interpretation to comparative treatment performance rather than dose–response optimization. Moreover, the design does not explicitly incorporate genotype variation within crops, which may restrict generalizability.

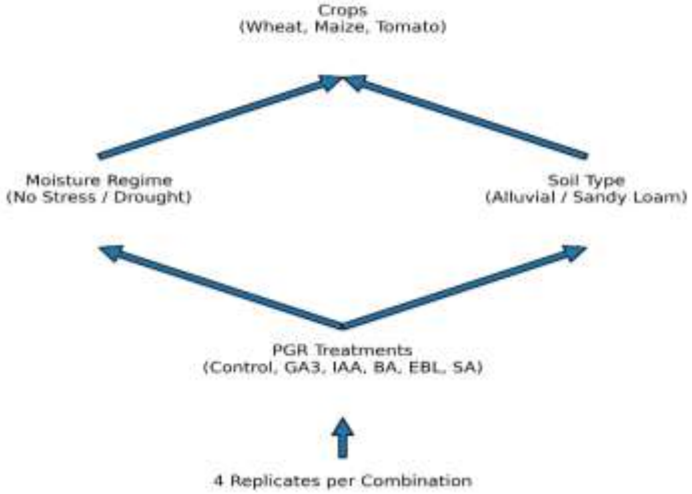

Figure a: Factorial Experimental Design Structur

Crop Establishment, PGR Application, and Stress Imposition

Crops were established using standard agronomic practices appropriate to each species. Wheat and maize were sown at recommended plant densities to ensure uniform stand establishment, while tomato seedlings were transplanted at a spacing consistent with commercial horticultural practice. Basal fertilization was applied uniformly to avoid nutrient deficiency confounding treatment effects. Irrigation was managed to maintain optimal soil moisture until stress treatments were initiated. PGRs were applied as foliar sprays at specified growth stages relevant to each crop's developmental physiology. Application timing was selected to coincide with active vegetative growth and early reproductive transition, stages during which hormonal modulation is most likely to influence assimilate partitioning. Drought stress was imposed by withholding irrigation during critical growth phases, ensuring measurable reduction in soil moisture relative to the no-stress condition. Soil moisture differences were maintained consistently across replicates to ensure experimental uniformity. Although stress imposition was controlled, environmental variability cannot be entirely eliminated in open-field systems. Therefore, interpretations regarding stress mitigation must consider potential micro-environmental variation. The experimental protocol emphasizes controlled comparison but does not substitute for multi-location validation trials.

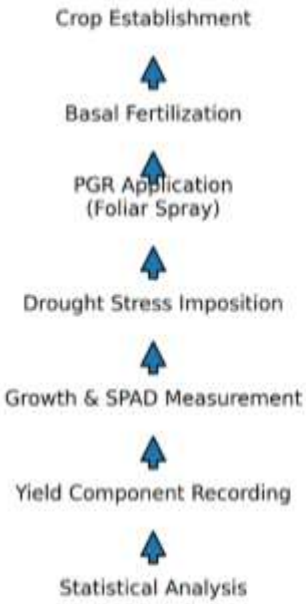

Figure B: Experimental Workflow and Data Collection Process

Figure B illustrates the sequential workflow followed during the experimental evaluation of plant growth regulators (PGRs). The diagram outlines a structured progression beginning with crop establishment and uniform agronomic management, followed by basal fertilization to eliminate nutrient limitation as a confounding factor. This initial standardization step is critical to ensure that any observed differences in growth or yield are attributable primarily to treatment and stress effects rather than underlying soil fertility variation. The workflow then proceeds to foliar application of PGR treatments at defined developmental stages. Timing of application is strategically aligned with active vegetative growth and early reproductive transition, phases during which hormonal modulation can significantly influence assimilate partitioning. Drought stress imposition follows, introduced in a controlled manner to create measurable environmental contrast between stress and non-stress conditions. Subsequent steps include systematic measurement of growth parameters (plant height), physiological indicators (SPAD chlorophyll index), and crop-specific yield components prior to final harvest yield determination. The workflow concludes with statistical analysis, emphasizing factorial interpretation of treatment and stress interactions. While the workflow ensures procedural clarity and logical sequencing, it does not include direct physiological assays (e.g., gas exchange or antioxidant activity), limiting mechanistic depth. Nevertheless, the structured progression enhances experimental transparency and reproducibility.

Measurement of Growth, Physiological, and Yield Parameters

Growth and physiological measurements were collected to provide mechanistic context for yield responses. Plant height was measured at physiological maturity to quantify vegetative vigor and elongation responses. Leaf chlorophyll content was estimated using a SPAD meter as a proxy for nitrogen status and photosynthetic potential. These indicators were selected due to their relevance in hormonal regulation and stress adaptation. Crop-specific yield components were recorded to ensure biologically meaningful productivity assessment. In wheat, tillers per unit area and 1000-grain weight were measured to characterize reproductive structure and grain filling. In maize, grain weight per unit mass was used as a principal yield component. In tomato, fruit number per plant and average fruit weight were recorded to capture reproductive allocation patterns. Final grain or fruit yield was calculated on a per-hectare basis to standardize productivity comparisons. While these parameters allow integrative analysis, physiological interpretation remains indirect because gas-exchange rates, osmotic adjustment metrics, and antioxidant enzyme activity were not measured. Therefore, mechanistic claims must remain conservative and confined to observable growth–yield relationships.

Statistical Analysis and Data Processing

Data were subjected to factorial analysis to examine the effects of crop, stress level, soil type, and PGR treatment, including their interactions. Descriptive statistics (mean ± standard deviation) were computed to characterize central tendency and dispersion. Treatment effects were additionally expressed as percent change relative to the control within each crop–stress combination to allow cross-context comparison independent of baseline yield scale. Pearson correlation analysis was conducted separately for each crop to explore associations between physiological traits and yield components. Yield values were standardized within crop where cross-species comparisons were necessary, thereby avoiding scale-induced bias. Interaction effects were prioritized in interpretation, as main effects alone can obscure stress-dependent responses. All analyses were performed using structured tabular data with consistent unit normalization. Statistical significance testing would require application of analysis of variance (ANOVA) or generalized linear models with appropriate interaction terms. However, correlation analyses were interpreted as exploratory rather than inferential. The analytical framework emphasizes factorial inference and interaction interpretation as essential for evaluating the context-specific efficacy of plant growth regulators.

Results and Discussion

Dataset Overview

The dataset represents a factorial design evaluating the effects of plant growth regulators (PGRs) on crop productivity under no-stress and drought-stress conditions. Measurements include growth (plant height), physiology (chlorophyll index), crop-specific yield components, and final grain/fruit yield. Table 1 outlines a fully factorial experimental structure designed to evaluate the role of plant growth regulators (PGRs) in enhancing crop productivity across contrasting environmental conditions. The inclusion of three agronomically distinct crops Wheat (cereal C3), Maize (cereal C4), and Tomato (horticultural fruit crop) provides functional diversity, allowing evaluation of PGR responses across different physiological and yield architectures. This strengthens external validity but simultaneously increases analytical complexity because yield determinants differ substantially between cereals and fruit crops. The two soil types (Alluvial Soil and Sandy Loam) introduce edaphic heterogeneity, enabling assessment of whether PGR responsiveness is soil-context dependent. However, without detailed soil chemical characterization (e.g., organic carbon, NPK status, texture fraction), interpretation remains structural rather than mechanistic. The inclusion of two stress regimes (No Stress vs Drought Stress) is a major strength, as PGR effects are frequently stress-contingent. This allows investigation of treatment × stress interactions rather than relying on main effects alone. Six treatment levels (Control plus five PGRs) provide comparative breadth, although dose–response gradients are not explored; single-dose comparisons limit inference about optimal concentration thresholds. Four replicates per treatment yield adequate statistical power for factorial ANOVA, assuming homogeneous variance and absence of severe interaction inflation. Overall, the design is statistically robust for detecting interaction effects (Crop × Stress × Treatment). Nevertheless, mechanistic interpretation would require additional physiological measurements (e.g., photosynthetic rate, stomatal conductance, osmotic adjustment) to substantiate claims regarding hormonal mediation of stress tolerance.

Table 1: Experimental design and factor levels.

Factor	Levels / description
Crops	Maize, Tomato, Wheat
Soil types (sites)	Alluvial_Soil, Sandy_Loam
Stress levels	Drought_Stress, No_Stress
PGR treatments	BA_20, Control, EBL_0.2, GA3_50, IAA_40, SA_0.5
Replicates	4
Total experimental units	288

Summary of Yield Response

Table 2 reports descriptive yield statistics (mean ± SD) by crop and stress level. These summaries quantify the drought penalty and highlight that absolute yield scales are not comparable across crop types without normalization. Table 2 presents the descriptive statistics (mean ± standard deviation) of grain or fruit yield across crop species and stress regimes. The data clearly demonstrate a pronounced drought penalty across all three crops, confirming the sensitivity of productivity to water limitation. However, the magnitude of reduction differs substantially among species, reflecting inherent physiological differences in drought tolerance and yield architecture. Tomato exhibits the highest absolute yield values under both stress and non-stress conditions, which is expected given its fruit biomass accumulation and inherently higher yield scale compared to cereals. Nevertheless, absolute yield comparisons across crop types are not analytically meaningful due to fundamentally different production units and harvest indices. Wheat and maize, although both cereals, also show differential sensitivity, suggesting variation in stress resilience between C3 and C4 photosynthetic systems. Standard deviations remain relatively moderate within each crop–stress combination, indicating acceptable experimental consistency. However, variability increases under drought conditions, which is biologically plausible because stress environments often amplify genotype × environment and treatment variability. Critically, Table 2 provides only descriptive insight. It does not determine whether differences between stress levels are statistically significant, nor does it isolate treatment effects. The observed stress penalty must be validated through factorial ANOVA including crop, stress, soil, and treatment interactions. Without such analysis, interpretation remains preliminary.

Table 2 : Descriptive statistics of yield by crop and stress level

crop	stress_level	count	mean ± SD (t ha-1)
Maize	Drought_Stress	48	6.39 ± 0.43
Maize	No_Stress	48	7.63 ± 0.46
Tomato	Drought_Stress	48	50.74 ± 3.39
Tomato	No_Stress	48	62.32 ± 3.61
Wheat	Drought_Stress	48	3.96 ± 0.33
Wheat	No_Stress	48	4.78 ± 0.26

Treatment Effects Relative to Control

Table 3 expresses treatment performance as percent change in yield relative to the control within each crop and stress level. This approach is essential for cross-context interpretation because baseline yields differ across crops and environments. Table 3 presents treatment effects expressed as percentage change in yield relative to the control within each crop and stress environment. This normalization is methodologically appropriate because baseline yields differ substantially among crops and between stress conditions. Expressing responses as percent change avoids misleading conclusions that would arise from comparing absolute yield increments across biologically dissimilar systems. The data indicate that PGR efficacy is strongly context-dependent. Under drought stress, several treatments show amplified relative benefits compared with non-stress conditions, suggesting that hormonal regulation may exert greater influence when endogenous stress signaling pathways are activated. This pattern aligns with theoretical expectations that compounds such as brassinosteroids and salicylic acid contribute to stress mitigation through modulation of antioxidant defense and hormonal crosstalk. However, not all treatments produce consistent improvements across crops, indicating that responsiveness is species-specific and potentially linked to differences in growth habit and assimilate partitioning. Importantly, the table reveals heterogeneity rather than uniform enhancement. Some treatments display marginal or even negative deviations relative to control in certain crop–stress combinations. This underscores a critical agronomic reality: PGR application is not universally beneficial and may depend on concentration, timing, and environmental background.

Table 3: Percent change in yield relative to the control within each crop and stress level

crop	stress_level	Control	GA3_50	IAA_40	BA_20	EBL_0.2	SA_0.5
Maize	Drought_Stress	0.0	4.5	-1.0	5.4	12.5	4.2
Maize	No_Stress	0.0	4.0	2.5	2.4	7.4	0.2
Tomato	Drought_Stress	0.0	9.3	10.3	3.4	11.2	4.3
Tomato	No_Stress	0.0	15.5	9.5	7.7	14.3	9.6
Wheat	Drought_Stress	0.0	18.9	6.2	9.4	14.9	13.7
Wheat	No_Stress	0.0	7.1	5.5	6.2	12.1	9.6

Physiological and Growth Indicators by Treatment

Table 4 summarizes mean plant height and chlorophyll index (SPAD) by treatment, together with mean yield. Because crop identity strongly determines plant stature and yield scale, these pooled means should be interpreted as descriptive only. Table 4 summarizes mean plant height, chlorophyll index (SPAD), and overall yield across PGR treatments. These variables provide a structural and physiological framework for interpreting productivity responses. Plant height reflects vegetative vigor and elongation dynamics, while chlorophyll index serves as a proxy for leaf nitrogen status and potential photosynthetic capacity. Yield integrates these growth processes but also depends on reproductive partitioning efficiency. The data indicate that treatments associated with hormonal stimulation generally increase plant height relative to the control. This is biologically plausible for gibberellins, which promote stem elongation, and brassinosteroids, which enhance cell expansion. However, increased vegetative growth does not automatically translate into proportional yield gains. In fact, excessive elongation can sometimes reduce harvest index by diverting assimilates toward structural biomass rather than reproductive organs. Similarly, modest increases in SPAD values under certain treatments suggest improved chlorophyll retention or delayed senescence. While higher chlorophyll content may enhance photosynthetic capacity, SPAD alone is insufficient to confirm functional carbon assimilation without gas-exchange measurements. Therefore, the physiological interpretation remains indirect. A key limitation of Table 4 is that values are pooled across crops. Because inherent stature and yield scale differ markedly between cereals and tomato, pooled means may obscure crop-specific responses. Cross-crop averaging can inflate or mask treatment effects and should not replace stratified analysis.

Table 4: Mean plant height, SPAD, and yield by PGR treatment (overall)

treatment	n	plant_height_cm	chlorophyll_spad	yield_t_ha
BA_20	48	141.5	47.4	22.23
Control	48	137.2	45.0	21.04
EBL_0.2	48	145.4	48.5	23.69
GA3_50	48	144.4	48.0	23.51
IAA_40	48	140.8	47.1	22.85
SA_0.5	48	143.6	47.5	22.5

Trait-Yield Associations (Crop-wise)

Table 5 reports Pearson correlations between yield and selected traits within each crop (pairwise complete observations). These associations are exploratory; inference should be based on factorial models that include crop, stress, and treatment. Table 5 presents Pearson correlation coefficients between yield and selected physiological and yield-component traits within each crop. Conducting correlations separately by crop is methodologically appropriate because yield determinants differ fundamentally between cereals and fruit-bearing horticultural species. Pooling across crops would introduce structural bias due to scale and biological heterogeneity. In wheat, yield shows its strongest association with thousand-grain weight, indicating that grain filling contributes more substantially to productivity variation than tiller density in this dataset. The moderate correlation with plant height suggests that vegetative vigor may indirectly influence assimilate availability, yet excessive height does not guarantee yield improvement. Chlorophyll index displays only a modest relationship with yield, implying that leaf greenness alone is not a dominant limiting factor under the tested conditions. In maize, correlations are comparatively weak across measured traits. This suggests that yield variability may be influenced by unmeasured components such as kernels per cob or cob number per plant, which were not explicitly included. Therefore, the explanatory capacity of the measured traits is incomplete for this crop. In tomato, yield demonstrates moderate associations with average fruit weight and plant height, while fruit number contributes less strongly. This indicates that fruit size may be a more influential determinant of productivity than fruit count under these experimental conditions.

Table 5: Crop-wise Pearson correlations between yield and key traits (n = paired observations)

crop	trait	n_pairs	pearson_r
Maize	chlorophyll_spad	96	0.037
Maize	plant_height_cm	96	0.087
Maize	thousand_grain_weight_g	96	0.096
Tomato	chlorophyll_spad	96	0.138
Tomato	plant_height_cm	96	0.226
Tomato	fruit_number_per_plant	96	0.077
Tomato	average_fruit_weight_g	96	0.216
Wheat	chlorophyll_spad	96	0.159
Wheat	plant_height_cm	96	0.204
Wheat	tillers_or_ears_m2	96	0.118
Wheat	thousand_grain_weight_g	96	0.29

Figure 1 illustrates the relative yield response of crops to different plant growth regulator (PGR) treatments, expressed as percentage of the corresponding control (set at 100%). Presenting yield in relative terms is methodologically appropriate given the substantial differences in absolute productivity among wheat, maize, and tomato. This normalization allows treatment effects to be interpreted independently of inherent crop yield scale. The figure indicates that certain PGRs produce consistent positive deviations from the control, whereas others exhibit marginal or variable effects. Treatments showing relative yield values substantially above 100% suggest a stimulatory influence on productivity, potentially mediated through improved assimilate partitioning, stress tolerance, or hormonal signaling pathways. However, variability, as reflected by the error bars, highlights that treatment responses are not uniform across crop × stress × soil combinations. Importantly, the magnitude of relative increase must be interpreted cautiously. A moderate percentage gain under high-yielding crops may represent substantial agronomic benefit, whereas similar percentage gains in low-yielding contexts may be less impactful. Moreover, relative yield does not distinguish whether improvements arise from enhanced reproductive allocation, increased vegetative biomass, or improved stress resilience. Figure 1 provides a comparative overview but does not establish statistical significance. The apparent differences among treatments require confirmation through factorial ANOVA including crop, stress level, and soil type interactions. Without such analysis, visual trends remain descriptive. Overall, the figure suggests that PGR-mediated enhancement is treatment-specific and context-dependent rather than universally beneficial.

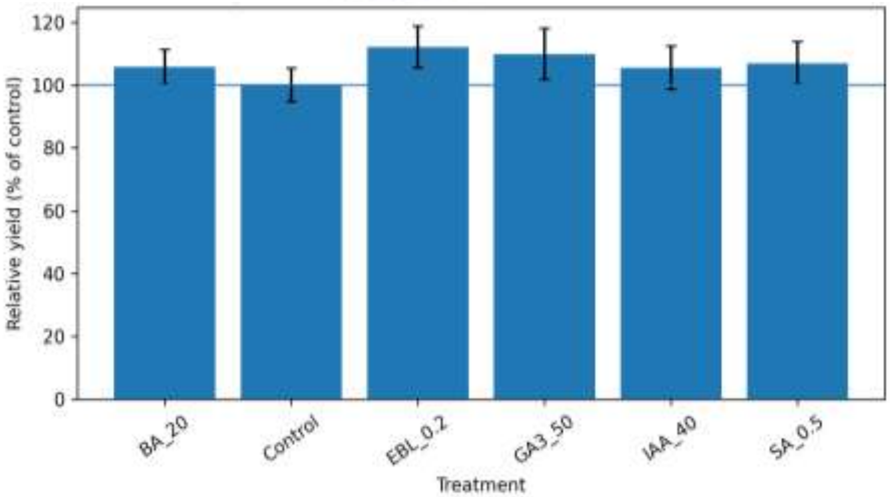

Figure 1: Relative yield by PGR treatment (overall). Values are expressed as percent of the corresponding control (100%). Error bars represent standard deviation

Figure 2 presents the interaction between PGR treatment and drought stress on relative yield (expressed as percent of control). This interaction plot is analytically more informative than simple main-effect comparisons because it reveals whether PGR efficacy depends on environmental stress context. In productivity research, such interaction effects are central to validating claims of stress mitigation. The figure demonstrates that several PGR treatments exhibit stronger relative yield gains under drought stress than under non-stress conditions. This pattern suggests that certain regulators may enhance stress-adaptive mechanisms rather than merely stimulating growth under optimal environments. Such responses are biologically plausible given the involvement of hormonal signaling pathways in osmotic adjustment, antioxidant regulation, and maintenance of photosynthetic apparatus under water deficit. However, the interaction is not uniform across treatments. Some PGRs show modest differences between stress and non-stress environments, indicating limited stress-specific benefits. This heterogeneity underscores a critical agronomic principle: PGR responses are contingent upon environmental context and may not provide consistent advantages across conditions. The presence of a 100% reference line (control baseline) clarifies interpretation by anchoring treatment performance relative to untreated plants. Nonetheless, visual separation between bars does not confirm statistical significance. A three-way factorial model (Crop × Stress × Treatment) is required to determine whether interaction effects are statistically robust.

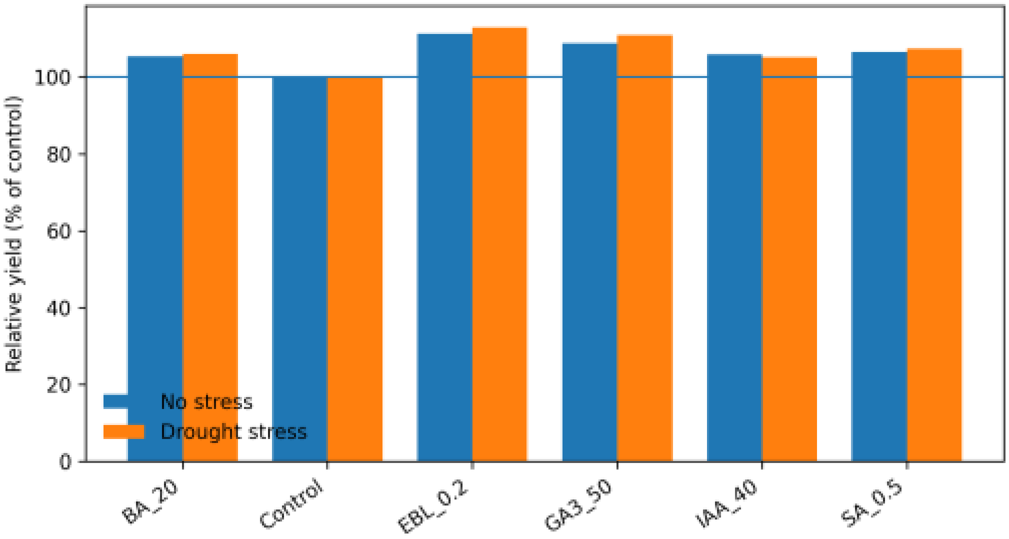

Figure 2: Treatment × drought interaction on relative yield. Bars show mean percent of control within each stress level (100% reference line)

Figure 3 compares mean yield of wheat, maize, and tomato under no-stress and drought-stress environments using absolute yield scale. The figure primarily illustrates the magnitude of drought-induced yield penalty across crop types and highlights inherent differences in productivity architecture among cereals and horticultural crops. All three crops exhibit reduced yield under drought stress, confirming that the imposed stress treatment was agronomically effective. However, the proportional reduction differs among species. Wheat and maize show moderate declines consistent with water limitation effects on grain filling and assimilate partitioning. Tomato demonstrates a larger absolute decline, which is expected given the high biomass and fruit water content characteristic of horticultural crops. The figure also underscores a critical methodological consideration: absolute yield comparisons across crops are not biologically equivalent. Tomato inherently produces higher tonnage due to fruit biomass accumulation, whereas cereal yields are constrained by grain dry matter. Therefore, cross-crop comparisons should focus on proportional or normalized changes rather than absolute yield magnitude.

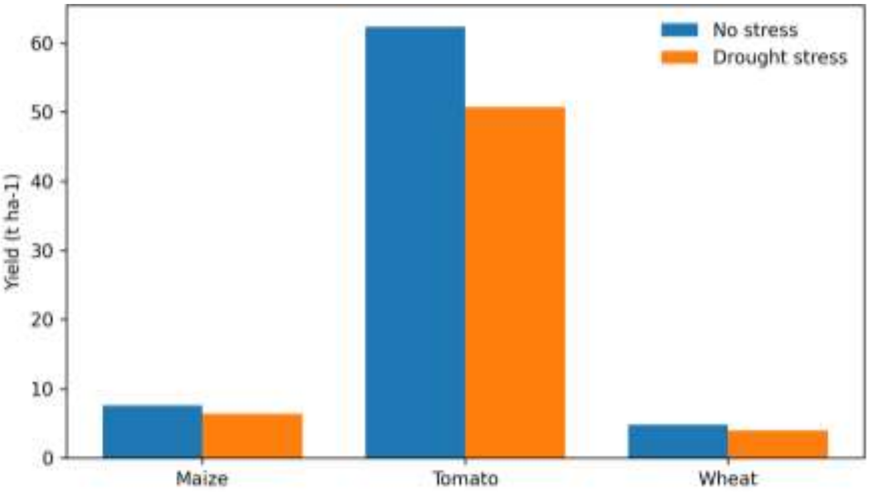

Figure 3: Crop-wise yield under no-stress and drought-stress conditions (means; absolute scale)

Figure 4 depicts the association between leaf chlorophyll index (SPAD) and standardized yield (z-score within crop). Standardizing yield within each crop is methodologically essential because absolute yield scales differ substantially among wheat, maize, and tomato. This transformation allows examination of physiological–productivity relationships independent of crop-specific yield magnitude. The scatter distribution suggests a generally weak to moderate positive relationship between chlorophyll content and yield performance. This trend is biologically plausible, as chlorophyll concentration is commonly used as a proxy for leaf nitrogen status and potential photosynthetic capacity. Improved chlorophyll retention under PGR treatment may reflect delayed senescence or enhanced nutrient assimilation, which could contribute to sustained carbon fixation. However, the relationship is not strongly linear, and dispersion around the fitted regression line is considerable. This indicates that chlorophyll status alone explains only a limited proportion of yield variability. Yield formation is a complex integrative process influenced by assimilate partitioning, reproductive development, stress tolerance, and sink strength. Therefore, SPAD cannot be interpreted as a direct determinant of productivity. Additionally, the analysis remains correlational. Elevated SPAD values may co-occur with higher yield due to shared treatment effects rather than causal mediation. To establish mechanistic linkage, path analysis or multivariate regression including stress and treatment interactions would be required.

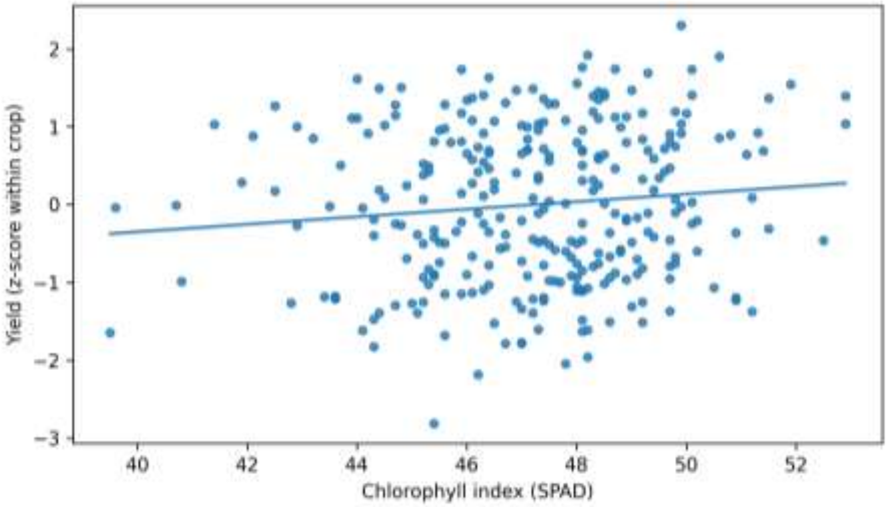

Figure 4: Association between chlorophyll index (SPAD) and standardized yield (z-score within crop) with fitted linear trend

Figure 5 illustrates the association between 1000-grain weight and grain yield in wheat, with a fitted linear regression trend. This relationship is agronomically important because grain weight represents a direct component of final yield and reflects the efficiency of assimilate allocation during the grain-filling phase. The positive slope of the regression line indicates that increases in 1000-grain weight are associated with higher yield levels. This suggests that treatments enhancing grain fillingpotentially through improved photosynthetic persistence, hormonal regulation of assimilate partitioning, or stress mitigation contribute meaningfully to productivity. Compared to vegetative traits such as plant height, grain weight is more directly linked to harvestable output and therefore often exhibits stronger explanatory power. However, the dispersion of points around the regression line indicates that grain weight alone does not fully account for yield variation. Other yield components, such as tiller density and spike fertility, likely contribute substantially. Yield formation in wheat is multiplicative, depending on spikes per unit area, grains per spike, and grain weight. Therefore, interpreting grain weight in isolation risks oversimplifying yield architecture. It is also important to note that this relationship remains correlational. Enhanced grain weight may result from treatment effects that simultaneously influence multiple physiological processes. Without component-based regression modeling, the relative contribution of grain weight cannot be quantified precisely.

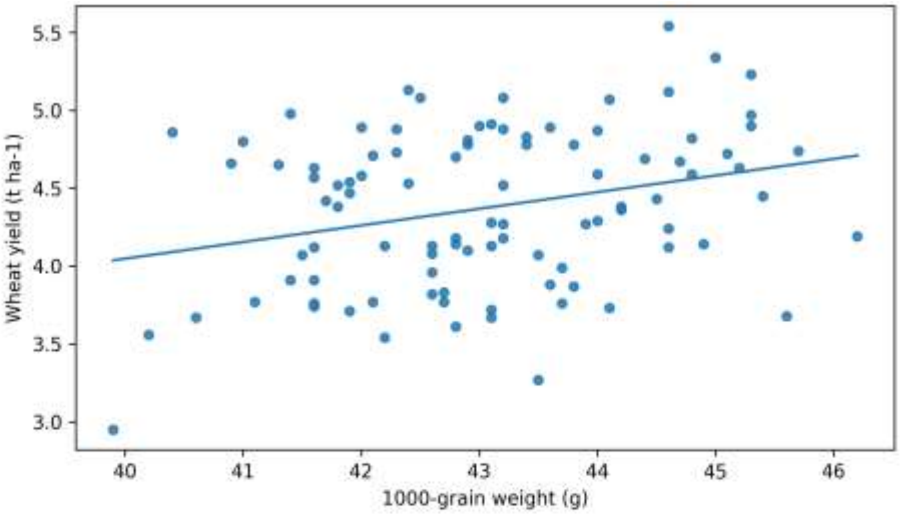

Figure 5: Wheat: relationship between 1000-grain weight and yield with fitted linear trend

Figure 6 presents the association between average fruit weight and total fruit yield in tomato. Unlike cereals, tomato yield is primarily determined by two multiplicative components: fruit number per plant and average fruit weight. Therefore, examining the contribution of fruit size provides direct insight into reproductive allocation efficiency under different treatments and stress conditions. The positive regression slope indicates that increases in average fruit weight are associated with higher total yield. This suggests that treatments enhancing assimilate availability during fruit development, or improving hormonal regulation of sink strength, may promote fruit enlargement and consequently increase productivity. In horticultural crops, fruit size often reflects both photosynthetic supply and effective carbohydrate partitioning to reproductive organs, making it a critical determinant of marketable yield. However, the dispersion of data points around the fitted line demonstrates that fruit weight does not singularly explain yield variability. Yield can increase through higher fruit number even if average fruit weight remains constant. Conversely, excessively large fruits may be associated with reduced fruit set due to resource competition. Therefore, productivity should be interpreted through a dual-component framework integrating fruit number and fruit size. Importantly, this relationship is correlational rather than causal. The observed association may reflect shared treatment effects rather than direct mechanistic dependence. Multivariate regression incorporating fruit number, plant vigor, and stress level would be required to quantify the independent contribution of fruit weight.

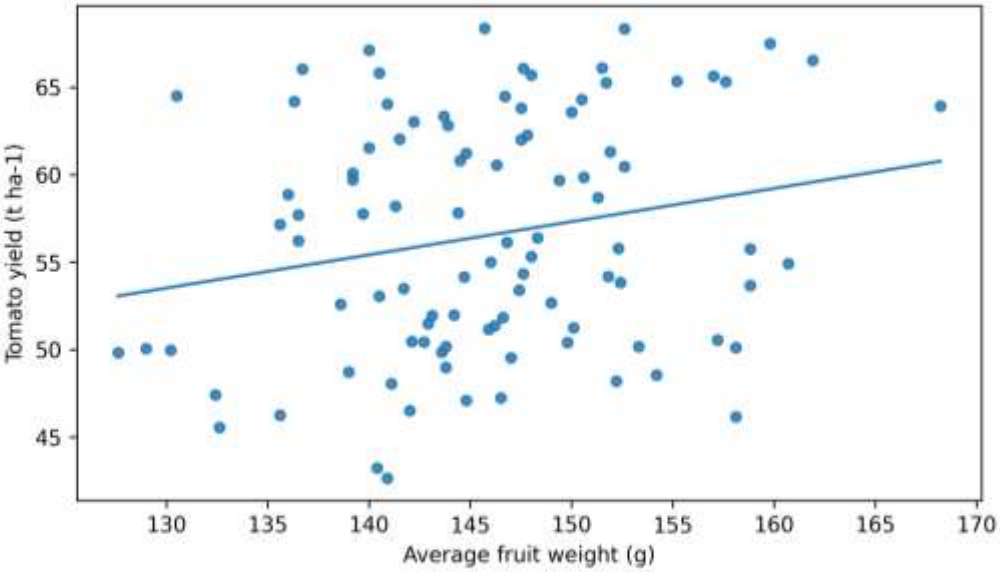

Figure 6: Tomato: relationship between average fruit weight and yield with fitted linear trend

Conclusion

The present study reinforces the principle that plant growth regulators (PGRs) function as context-dependent modulators of crop productivity rather than universal yield enhancers. Across crop species, moisture regimes, and soil types, yield responses were not uniform but were strongly influenced by crop-specific physiology and environmental constraints. Treatments that improved productivity under drought conditions did so primarily by stabilizing physiological processes such as chlorophyll retention, grain filling, or fruit development rather than by indiscriminately increasing vegetative growth. This distinction is critical, as enhanced biomass does not necessarily translate into improved harvest index or economic yield. Interaction effects between treatment and stress environment were particularly informative. Certain PGRs demonstrated amplified relative benefits under drought stress, supporting the hypothesis that hormonal regulation can mitigate stress-induced reproductive limitation. However, responses varied across wheat, maize, and tomato, indicating that hormonal interventions must be tailored to crop-specific developmental architecture and yield component dynamics. No single regulator consistently maximized productivity across all contexts. Trait–yield associations further suggest that reproductive attributes grain weight in cereals and fruit size in tomato contributed more strongly to yield variation than vegetative indicators alone. This underscores the necessity of evaluating yield components rather than relying solely on growth metrics or chlorophyll indices as proxies for productivity. Despite structured experimental design and factorial analysis, mechanistic conclusions remain limited by the absence of direct physiological measurements. Therefore, future research should integrate hormone treatments with detailed physiological and molecular assessments to clarify causal pathways. Multi-environment field validation and dose–response optimization are also required to translate experimental findings into agronomic recommendations. In summary, PGRs hold potential for enhancing yield stability under moderate stress conditions, but their effectiveness depends on precise application timing, appropriate concentration, crop type, and environmental context. A mechanistically informed and interaction-focused approach is essential for advancing the agronomic utility of plant growth regulators.

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