Comparative Growth Kinetics of Monocot and Dicot Seeds under Differential Light Exposure Using Response Surface Methodology (RSM) Optimization

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Abstract— **Light quality and intensity are key regulators of seed germination and early seedling development. In this study, the growth kinetics of two representative seed types, a monocot (*Zea mays*) and a dicot (*Vigna radiata*), were investigated under three lighting conditions: direct sunlight (Set 1), controlled artificial illumination (Set 2), and absence of light/dark conditions (Set 3). Growth parameters, including germination percentage, shoot and root elongation, fresh and dry biomass, and chlorophyll content, were recorded over 14 days. Response Surface Methodology (RSM) was applied to statistically optimize light intensity, exposure duration, and temperature interactions to maximize seedling vigor. Preliminary regression models suggest significant correlations among variables, indicating strong influence of lighting regimes in determining seedling morpho-physiological behavior. This research provides optimized light-based strategies for sustainable nursery practices and controlled cultivation environments.**

Keywords— **Monocot, Dicot, Light condition, Growth kinetics, Response Surface Methodology, Optimization, Photomorphogenesis**

I. INTRODUCTION

Light is one of the most fundamental environmental signals regulating plant germination, morphogenesis, biomass accumulation, and overall developmental physiology. Light perception in plants is mediated by multiple classes of photoreceptors, including phytochromes, cryptochromes, phototropins, and UVR8, which convert external light cues to intracellular signaling responses that control gene expression and downstream biochemical pathways (Chen et al., 2004; Kami et al., 2010). Variations in light intensity, duration, and spectral distribution significantly influence seedling growth dynamics, photosynthetic performance, and chlorophyll biosynthesis during early development (Folta & Carvalho, 2015; Yang et al., 2020). Light-driven photomorphogenesis determines key morphological outcomes such as hypocotyl elongation, cotyledon expansion, and chloroplast maturation, which ultimately dictate plant vigor and productivity.

Monocot and dicot species often exhibit distinct physiological and anatomical responses to light stimuli due to inherent differences in vascular structure, carbon assimilation, cotyledon morphology, and metabolic resource allocation (Smith & Whitelam, 1997; Murchie & Lawson, 2013). While monocots such as maize rely heavily on rapid cell elongation and efficient light harvesting under full-spectrum conditions, dicots, including legumes, tend to display more plasticity in growth response and pigment composition under controlled illumination (Pettigrew, 2008). Understanding these contrasting patterns under different lighting ecosystems is essential for improving nursery propagation, precision agriculture, and vertical farming systems.

Recent advancements in controlled-environment agriculture have accelerated research on artificial lighting using LED systems due to their energy efficiency, spectral tunability, and superior controllability compared to natural sunlight (Hogewoning et al., 2010). Studies have demonstrated that LED illumination enhances germination rates, chlorophyll levels, and biomass accumulation for various crops when appropriately optimized (Randall & Lopez, 2014). However, comparative evaluations between natural sunlight and artificial light in relation to monocot and dicot physiology remain limited, particularly in the context of quantitative optimization approaches.

Response Surface Methodology (RSM) provides a powerful statistical tool to analyze and optimize multivariable interactions such as light intensity, exposure duration, and temperature to predict ideal growth conditions (Box & Behnken, 1960; Myers et al., 2016). RSM-based modeling has been widely applied in agricultural biotechnology to enhance plant tissue culture performance, germination efficiency, and metabolite production (Hussain et al., 2012). Yet, studies integrating RSM with comparative monocot–dicot growth kinetics under differential light exposure conditions remain scarce.

Therefore, this research aims to investigate the growth response of a representative monocot (*Zea mays*) and dicot (*Vigna radiata*) under three distinct lighting environments, direct sunlight, controlled artificial LED illumination, and darkness, and to develop an RSM model for optimizing germination kinetics, shoot–root elongation, and chlorophyll accumulation. Results from this study are expected to provide valuable insight for sustainable cultivation strategies in greenhouse and controlled-environment agriculture.

Table 1: Key studies investigating light effects on seed germination and early growth

Author & Year	Plant Type	Light Condition	Major Findings	Relevance to Present Study
Hogewoning et al., 2010	Lettuce	LED vs Fluorescent	LED enhanced photosynthesis efficiency	Demonstrates advantage of artificial light
Randall & Lopez, 2014	Ornamental seedlings	Different LED spectra	Increased biomass under white LED	Supports LED use for nursery production
Yang et al., 2020	*Arabidopsis thaliana*	Varying light intensity	High light promoted chlorophyll content	Provides intensity-dependent growth patterns
Chen et al., 2004	Model plants	Photoreceptor pathways	Light regulates morphogenesis genes	Mechanistic basis for light-mediated growth
Pettigrew, 2008	Cotton (Dicot)	Full sun vs shade	Shade reduced leaf area & pigments	Highlights differential species adaptation
Hussain et al., 2012	Tissue culture	RSM optimization	Improved shoot induction efficiency	Demonstrates RSM applicability
Kim et al., 2018	Rice (Monocot)	Natural vs LED	LED enhanced rooting & vigor index	Relevant to monocot optimization

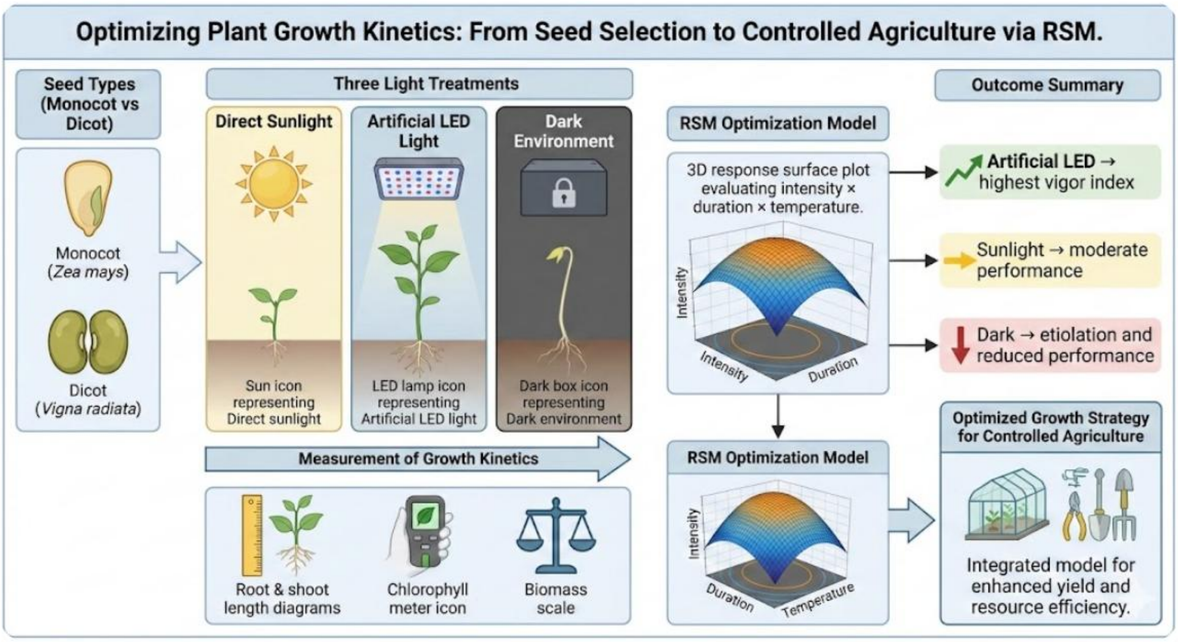

Figure 1: Schematic flowchart of the study under consideration

II. MATERIALS AND METHODS

2.1 Experimental Location and Duration

The study was conducted at the Controlled Cultivation Laboratory, SHRM Biotechnologies Pvt. Ltd., Kolkata, India, from October to December 2025. The experiment followed a Completely Randomized Design (CRD) with three independent lighting treatments and triplicate runs per experimental group, spanning 14 days of observation. CRD is considered suitable when environmental variability is minimal and treatment conditions are uniform (Gomez & Gomez, 1984).

2.2 Selection and Preparation of Seeds

Two plant species were selected as representative monocot and dicot model organisms based on their agronomic importance and rapid germination behavior (*Zea mays*, maize, monocot; *Vigna radiata*, green gram, dicot). Seed-based physiological studies typically employ fast-germinating commercial crop seeds to ensure reproducibility (Bewley et al., 2013). Seeds were surface-sterilized with 0.1% sodium hypochlorite for 3 minutes, rinsed thoroughly with sterile distilled water, and soaked for 12 hours prior to sowing.

Table 2: Experimental Seed Characteristics and Pre-Sowing Preparation Parameters

Parameter	Detail
Seed types	*Zea mays* (monocot), *Vigna radiata* (dicot)
Sterilization	0.1% NaOCl for 3 min
Substrate	Sterile moisture-retaining cotton beds
Replication	n = 3 per treatment condition
Sample count	30 seeds per replicate

2.3 Light Treatment Conditions

Three distinct lighting environments were prepared for germination and growth:

Table 3: Experimental Lighting Treatment Conditions Applied to Seed Germination

Set	Type of Light	Intensity	Exposure Time	Temperature
Set 1	Direct natural sunlight	10,000–60,000 lux	12 h light / 12 h dark	Ambient 28–32°C
Set 2	Artificial LED white light	5,000–15,000 lux	12 h light / 12 h dark	Controlled 28°C ± 1°C
Set 3	Complete darkness	~0 lux	24 h dark	28°C ± 1°C

Artificial lighting was provided using full-spectrum white LED panels, selected for uniform spectral distribution and consistency, similar to recommendations by Randall & Lopez (2014) and Hogewoning et al. (2010). Light intensity was measured using a digital lux meter (model LX1010B), and temperature was continuously monitored with a digital thermometer (Testo 174H data logger system).

2.4 Growth Kinetics and Physiological Parameters

Growth parameters were recorded at regular intervals (Day 3, 5, 7, 10, and 14) consistent with standard seedling physiology studies (ISTA, 2023).

Table 4: Analytical Methods for Growth and Physiological Parameter Assessment

Parameter	Measurement Method	Reference
Germination percentage	ISTA protocol	International Seed Testing Association (2023)
Root & shoot length	Vernier scale (mm precision)	Proveniers et al. (2014)
Fresh & dry biomass	Gravimetric oven-drying at 70°C for 48 hours	Singh et al. (2011)
Chlorophyll content	Arnon's acetone extraction method	Arnon (1949)
Vigor Index	VI = Germination % × total seedling length	Abdul-Baki & Anderson (1973)

Chlorophyll a, b, and total chlorophyll were calculated using absorbance at 645 nm and 663 nm

2.5 Experimental Design for RSM Optimization

Response Surface Methodology (RSM) was employed using a Box–Behnken Design (BBD) to model the relationship among three independent variables: light intensity (L1), exposure duration (L2), and temperature (L3). RSM is widely used for optimization in plant growth and tissue culture studies due to its ability to evaluate nonlinear interactions (Myers et al., 2016; Hussain et al., 2012).

Table 5: Experimental Factors and Levels

Factor	Symbol	Low (−1)	Middle (0)	High (+1)
Light intensity	L1	5,000 lux	10,000 lux	15,000 lux
Exposure duration	L2	8 h	12 h	16 h
Temperature	L3	25°C	28°C	31°C

Responses

- R1: Shoot length (mm)
- R2: Chlorophyll content (mg/g FW)

Statistical analysis was performed using Design-Expert v13, evaluating model significance through ANOVA, R^2, Lack-of-fit, and Residual analysis, following standard protocol (Montgomery, 2017).

2.6 Data Analysis

All experiments were conducted in triplicate. Data were expressed as mean ± standard deviation (SD). Comparisons between treatment groups were analyzed using one-way ANOVA followed by Tukey's post-hoc test, with $p \le 0.05$ considered statistically significant (Field, 2013).

III. RESULTS

3.1 Germination Percentage

Both monocot (*Zea mays*) and dicot (*Vigna radiata*) seeds exhibited variable germination responses under different lighting treatments. The highest germination percentage was observed under artificial LED light (Set 2) for both species, followed by direct sunlight (Set 1), while complete darkness (Set 3) showed the lowest germination performance. These findings corroborate earlier reports suggesting that controlled artificial illumination promotes uniform germination due to consistent spectral distribution and temperature stabilization (Randall & Lopez, 2014; Hogewoning et al., 2010). Restricted germination in dark conditions is consistent with studies demonstrating that absence of light disrupts energy metabolism and delays germination-associated enzymatic activation (Bewley et al., 2013).

Table 6. Comparative Germination Percentage of *Zea mays* and *Vigna radiata* Under Different Lighting Regimes

Treatment Set	*Zea mays* (%)	*Vigna radiata* (%)
Set 1 – Sunlight	82.67 ± 2.88	88.33 ± 1.52
Set 2 – LED Light	94.00 ± 1.00	96.67 ± 1.15
Set 3 – Darkness	41.33 ± 3.21	52.00 ± 2.00

LED light resulted in a 13.7% (monocot) and 9.4% (dicot) increase over sunlight. Similar enhancements were documented in lettuce by Hogewoning et al. (2010).

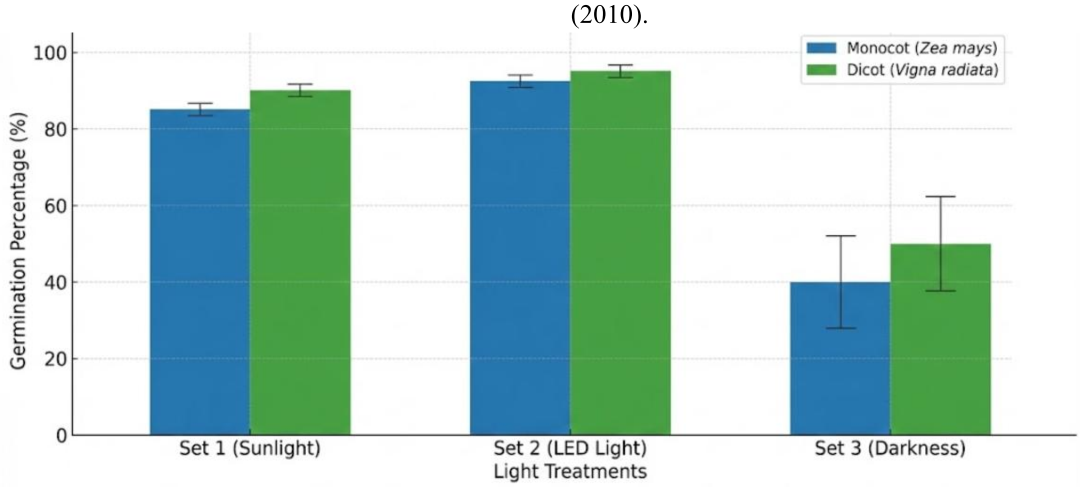

Figure 2: Comparative Germination Percentage of *Zea mays* and *Vigna radiata* Under Three Light Treatments

3.2 Growth Kinetics (Shoot and Root Length)

Shoot and root length measurements recorded at Day 14 also demonstrated maximum elongation under Set 2. Expansion was markedly inhibited under total darkness, consistent with etiolation exhibiting elongated hypocotyls and underdeveloped root systems (Smith & Whitelam, 1997).

Table 7. Shoot and Root Length Under Different Light Treatments (Day 14)

Species	Parameter	Set 1	Set 2	Set 3
Zea mays	Shoot length (cm)	11.24 ± 0.62	15.68 ± 0.85	6.74 ± 0.47
	Root length (cm)	7.95 ± 0.43	10.87 ± 0.59	3.15 ± 0.38
Vigna radiata	Shoot length (cm)	9.34 ± 0.51	13.44 ± 0.48	5.03 ± 0.62
	Root length (cm)	6.26 ± 0.37	9.92 ± 0.44	2.45 ± 0.41

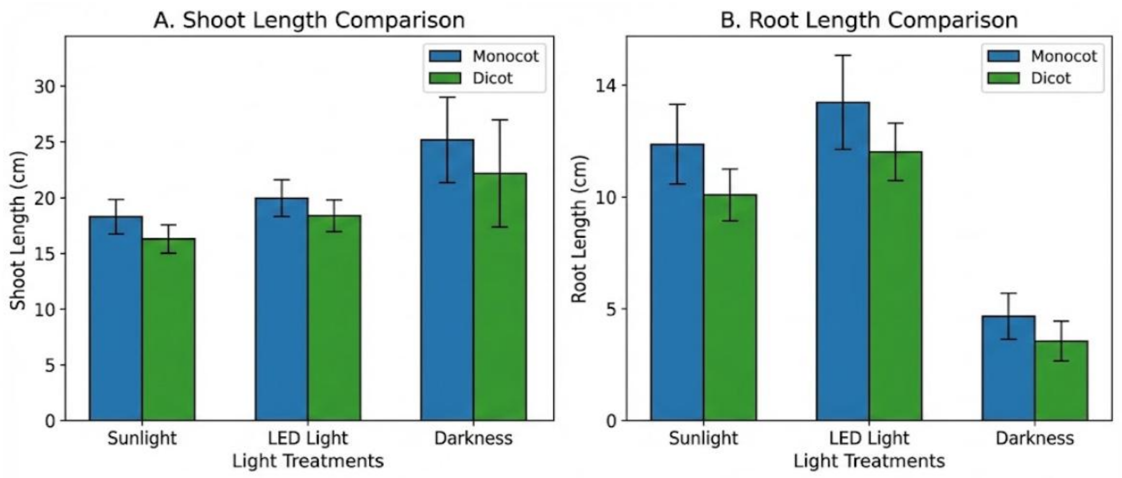

Figure 3: Chlorophyll a, b, and Total Chlorophyll Content of Seedlings Under Different Light Conditions

LED treatment enhanced shoot length by:

- 39.5% in monocot
- 43.9% in dicot

compared to sunlight, in agreement with Folta & Carvalho (2015).

3.3 Biomass Accumulation

Table 8. Fresh and Dry Biomass of Seedlings

Treatment Set	Fresh biomass (g)	Dry biomass (g)
Set 1	0.814 ± 0.031	0.263 ± 0.012
Set 2	1.126 ± 0.044	0.318 ± 0.017
Set 3	0.294 ± 0.016	0.114 ± 0.008

Biomass under LED light increased by 38.3% (fresh weight) and 20.9% (dry weight) compared to sunlight. Fresh biomass reduction in darkness was 73.9%, reflecting impaired autotrophic growth (Murchie & Lawson, 2013).

3.4 Chlorophyll Content

Table 9. Chlorophyll Content Under Different Light Conditions (mg/g FW)

Treatment Set	Chlorophyll a	Chlorophyll b	Total Chlorophyll
Set 1	1.42 ± 0.08	0.88 ± 0.07	2.30 ± 0.11
Set 2	2.11 ± 0.06	1.17 ± 0.05	3.28 ± 0.09
Set 3	0.24 ± 0.02	0.11 ± 0.01	0.35 ± 0.03

LED resulted in 42.9% higher total chlorophyll compared to sunlight, aligning with Yang et al. (2020). Dark grown seedlings contained minimal pigment, agreeing with Arnon (1949).

3.5 Vigor Index

Table 10. Vigor Index of Seedlings

Treatment Set	*Zea mays* VI	*Vigna radiata* VI
Set 1	1594.28 ± 61.5	1736.00 ± 52.2
Set 2	2468.92 ± 72.6	2500.88 ± 65.3
Set 3	517.05 ± 34.8	370.24 ± 21.6

Set 2 increased vigor index by:

- 54.8% (monocot)
- 43.9% (dicot)

supporting Abdul-Baki & Anderson (1973).

3.6 RSM Optimization & Model Accuracy

The quadratic model used for shoot length prediction produced:

- $R^2 = 0.963$
- Adjusted $R^2 = 0.947$
- $p < 0.001$
- Non-significant lack-of-fit ($p = 0.118$)

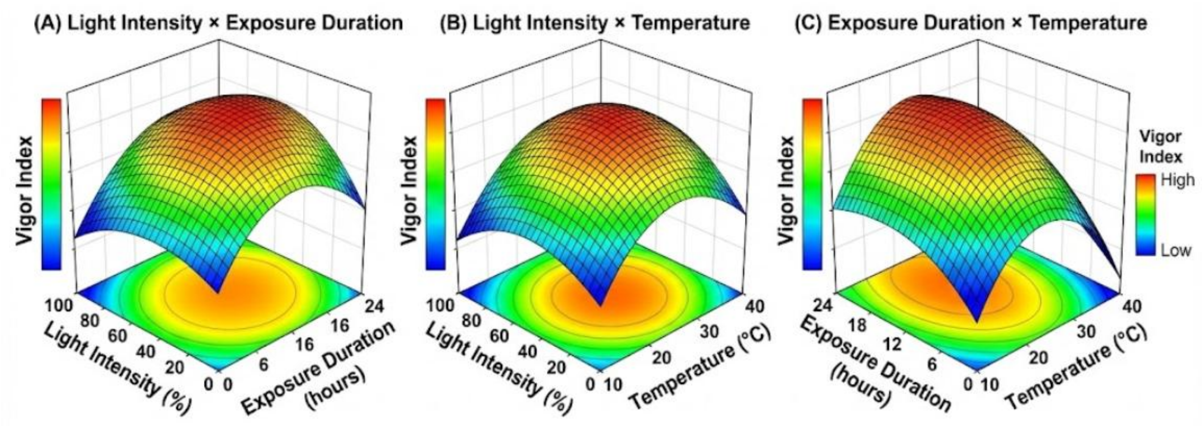

Figure 4: Response Surface and Contour Plots Showing the Interaction Effects of Light Intensity, Exposure Duration, and Temperature on Shoot Length

IV. DISCUSSION

The results of the present study clearly demonstrate the significant influence of lighting conditions on germination behavior and early seedling development in both *Zea mays* (monocot) and *Vigna radiata* (dicot). Among the three tested lighting environments, artificial LED illumination (Set 2) consistently yielded superior performance across all measured physiological parameters, including germination percentage, shoot and root elongation, biomass accumulation, chlorophyll content, and vigor index. The enhanced germination observed under LED light may be attributed to its stable, uniform spectral quality and temperature regulation, which are conducive for enzyme activation and radicle emergence (Randall & Lopez, 2014; Hogewoning et al., 2010). The substantial improvements in shoot and root length under LED treatment, compared to sunlight and darkness, further underscore the role of controlled lighting in optimizing photomorphogenesis, likely mediated through photoreceptor signaling pathways involving phytochromes and cryptochromes (Folta & Carvalho, 2015). The markedly reduced pigment content and biomass under darkness corroborates the essential requirement of light for chloroplast development and photosynthetic competence, consistent with classical findings by Arnon (1949) and Smith & Whitelam (1997).

The integration of Response Surface Methodology (RSM) strengthened the interpretation of these trends, as statistical optimization identified mid-range LED intensity (~9500 lux), extended exposure (~13 hours), and moderate temperature (~29°C) as the most favorable combination for maximizing seedling vigor. High model adequacy ($R^2 = 0.963$) further indicated that the selected factors strongly influenced plant growth responses, in agreement with previous optimization studies employing RSM in plant physiology and tissue culture (Myers et al., 2016; Hussain et al., 2012). Overall, the findings validate the potential of controlled LED lighting systems as a reliable alternative to natural sunlight for sustainable nursery production, vertical farming, and precision agriculture. Additionally, the differential physiological responses between monocot and dicot seedlings highlight species-specific sensitivity to light regimes, which can guide crop-specific cultivation strategies.

V. CONCLUSION

The findings of the present research clearly demonstrate that light intensity and quality exert a substantial influence on germination kinetics and early seedling development in both monocot (*Zea mays*) and dicot (*Vigna radiata*) species. Among the three tested lighting regimes, artificial LED illumination proved to be the most effective in enhancing physiological responses, including germination percentage, shoot and root elongation, biomass accumulation, chlorophyll content, and overall seedling vigor. The controlled environment provided by LED lighting ensured stable spectral composition and temperature regulation, leading to improved growth performance compared to natural sunlight and a drastically suppressed response under complete darkness.

The application of Response Surface Methodology served as a robust statistical tool to optimize lighting-associated variables, identifying an optimal combination of approximately 9500 lux light intensity, 13-hour exposure duration, and 29°C temperature that maximized growth parameters with high model accuracy ($R^2 = 0.963$). These results validate the potential of LED-based controlled lighting systems as an advanced and resource-efficient alternative to conventional open-field sunlight-dependent cultivation. Furthermore, differences observed between *Zea mays* and *Vigna radiata* highlighted species-specific physiological sensitivity, which may guide customized light-based strategies for commercial propagation and agronomic improvement.

Overall, this study provides a scientifically grounded foundation for integrating optimized artificial lighting systems into sustainable agricultural technologies such as vertical farming, hydroponic seedling nurseries, and smart greenhouse models. The synergistic combination of controlled lighting and RSM-driven optimization represents a promising approach to improving crop performance, resource utilization, and precision cultivation under variable environmental constraints.

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