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MICROENCAPSULATION OF PGPM AND ITS EFFECT ON PH AND EC DYNAMICS IN THE RHIZOSPHERE OF DIFFERENT CROPS AND IN SITU MONITORING WITH ELECTROCHEMICAL SENSORS

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Abstract: The functional efficiency of plant growth-promoting microorganisms (PGPM) in real soil conditions depends on their stability, viability, and release kinetics in the rhizosphere. The present study evaluated a consortium of microencapsulated PGPMs under a completely randomized factorial design, integrating in situ electrochemical monitoring of pH, electrical conductivity (EC, dS m^{-1}), and soil temperature (°C), together with the early morphogenic response of four contrasting crops (*Pisum sativum* L., *Zea mays* L., *Triticum aestivum* L., and *Phaseolus vulgaris* L.). The physicochemical variables were recorded at six time points (10–59 days after application, DAA), while leaf number and height were evaluated at three sequential time points after initial inoculation. The general linear model indicated that pH dynamics were dominated by the temporal effect ($F_{5,456}$ = 56.16; p < 0.0001; R^2 = 0.4058), with a progressive alkaline shift of Δ = 0.84 units between 10 and 59 DPA, without significant Crop × Time interaction, suggesting parallel trajectories between species. EC showed less structuring (R^2 = 0.1424), although with significant interaction ($F_{15,456}$ = 2.18; p = 0.0064), evidencing interspecific dependence in ionic dynamics and a biphasic pattern with an intermediate maximum at 31 DDA. Temperature showed the highest proportion of explained variance (R^2 = 0.8104), with highly significant effects of Cultivation and its interaction with time, indicating microenvironmental modulation dependent on the plant species. In morphogenic terms, the number of leaves showed exceptional statistical adjustment (R^2 = 0.9893), dominated by the genotypic effect, while height showed greater temporal sensitivity (R^2 = 0.8111), consistent with a progressive physiological response following rhizospheric colonization. The integration of electrochemical and morphological data confirms that microencapsulation induced a gradual modification of the ionic and protonic equilibrium of the soil-plant system, with time-dependent and species-modulated effects. These results demonstrate that the controlled release of microencapsulated PGPM generates functional kinetics consistent with mineralization and differential absorption processes, and that in situ electrochemical monitoring is a robust tool for characterizing the edaphic dynamics associated with controlled-release bio-inputs.

Keywords: microencapsulation, electrochemical sensors, rhizosphere

INTRODUCTION

The sustainability of contemporary agricultural systems depends on the efficient integration of biological and physicochemical processes that regulate soil dynamics and plant productivity. Agricultural intensification based exclusively on mineral fertilization has led to soil imbalances, loss of microbial biodiversity, and decreased nutrient use efficiency. In this context, plant growth-promoting microorganisms (PGPM) represent a biotechnological alternative aimed at improving nutrient availability, modulating hormonal processes, and strengthening resilience to abiotic stress (Kumar et al., 2023; Laishram et al., 2025). Recent studies show that targeted manipulation of the rhizosphere microbiome can increase crop physiological efficiency and contribute to sustainable agricultural management schemes (Kumar et al., 2023).

However, the effectiveness of PGPMs in field conditions is highly dependent on

their survival and establishment in the rhizosphere. Factors such as competition with native microbiota, temperature fluctuations, desiccation, and soil heterogeneity limit the functional persistence of inoculants. In response to these limitations, microencapsulation has emerged as a technological strategy that protects cell viability and regulates release kinetics using biodegradable polymer matrices, favoring gradual and sustained release dependent on soil conditions (Bashan et al., 2023). This approach allows microbial release to be synchronized with the physiological dynamics of the plant, reducing initial losses due to rapid diffusion.

From a soil perspective, pH and electrical conductivity (EC) are integrative indicators of the chemical functioning of the soil-plant system. pH controls ion speciation and nutrient availability, while EC reflects the total concentration of dissolved solutes and root absorption dynamics. Processes such as nitrification, differential assimilation of NH_4^+ and NO_3^-, and root exudation can induce progressive shifts in the proton equilibrium in the rhizosphere (Zhang et al., 2022). Root architecture and nutrient capture efficiency further influence differentiated temporal trajectories of EC among plant species (Lynch, 2022).

Conventional assessment of these variables is based on destructive determinations of soil-water extracts, which limits temporal resolution and prevents the capture of transient events associated with controlled release or differential absorption. In contrast, recent advances in electrochemical sensors allow continuous in situ monitoring of pH and EC with high sensitivity and reproducibility, providing dynamic information without altering soil structure (Eldeeb et al., 2023; Kim et al., 2024). The integration of these technologies into precision agriculture schemes has expanded the ability to characterize rhizospheric processes in real time under controlled experimental conditions (Mansoor et al., 2025).

Additionally, soil temperature acts as a central metabolic modulator, regulating microbial respiration, enzymatic activity, and the rate of nutrient transformation. Thermal variations induced by differences in vegetation cover can significantly modify biological reaction rates and, in , the kinetics of release and establishment of encapsulated microbial consortia (Bradford et al., 2022).

Despite advances in microencapsulated formulations and electrochemical monitoring technologies, there remains a gap in recent literature that integrates the controlled release of PGPM with temporal in situ monitoring of edaphic variables and comparative evaluation of morphogenic response in contrasting crops. Most studies address these components independently, limiting understanding of the functional kinetics of the soil-microorganism-plant system.

The present study evaluates the controlled release of a consortium of microencapsulated plant growth-promoting microorganisms (PGPM) and its effect on the temporal dynamics of pH, electrical conductivity (EC), and soil temperature using *in situ* electrochemical sensors. Simultaneously, the early morphogenic response in four crops with contrasting physiology is analyzed, with the aim of relating the physicochemical changes in the rhizosphere to the initial response of the plants.

The central hypothesis is that microencapsulation promotes microbial survival by reducing osmotic shock and early mortality, allowing an active population to be

maintained for a longer period of time. As a result, a progressive modification of the ionic and protonic equilibrium of the soil-plant system is expected, with effects that are time-dependent and modulated by the plant species. Within this framework, it is proposed that treatment with microencapsulated PGPM will show a stronger and more consistent temporal correlation between pH and EC fluctuations, indicating simultaneous and coupled modulation of rhizosphere chemistry by a functionally sustained microbial community. Likewise, it is expected that the joint dynamics of pH and EC in this treatment will remain within a favorable range for nutrient availability (e.g., slightly acidic pH and moderate EC) for a longer period of time compared to the other treatments.

MATERIALS AND METHODS

Experimental units and plant establishment

The experimental units consisted of inert plastic pots containing previously homogenized soil to reduce variability associated with structural and chemical heterogeneity of the substrate. Each pot was considered an independent experimental unit for statistical purposes. Twenty units were established per crop, totaling eighty experimental units (n = 80).

Sowing was carried out directly in the substrate, and after emergence, manual thinning was performed to maintain one plant per pot, ensuring uniform density and minimizing intraspecific competition. The incorporation of the Crop factor into the experimental structure responded to physiological and architectural differences and potential patterns of rhizospheric interaction between species, allowing for a formal evaluation of their contribution to the variability observed in the physicochemical and morphogenic variables of the system.

Experimental design

The study was conducted under a completely randomized design with a crossed factorial structure, in which four agricultural species—*Pisum sativum* L., *Zea mays* L., *Triticum aestivum* L., and *Phaseolus vulgaris* L.— were evaluated as a function of the time elapsed after the initial application of a microencapsulated consortium of plant growth-promoting microorganisms (PGPM). The factorial structure allowed us to estimate the main effects of Crop and Days After Application (DAA), as well as their interaction, within an analytical framework consistent with general linear models.

For the physicochemical variables of the soil (pH, electrical conductivity, and temperature), six evaluation times were established (10, 24, 31, 38, 45, and 59 DDA), which provided sufficient temporal resolution to model the progressive kinetics of the encapsulated system and capture gradual shifts in the proton and ion equilibrium. This sampling frequency was consistent with the structure of degrees of freedom used in the subsequent statistical analysis.

In the case of morphogenic variables—number of fully developed leaves and plant height—three sequential evaluations were performed after the initial inoculation, with the aim of characterizing the early response associated with the rhizospheric establishment of the bacterial consortium and

its effect on the initial growth dynamics of the crops.

Consortium preparation and microencapsulation

The microbial consortium was composed of heterotrophic bacteria and halotolerant actinomycetes selected for their plant growth-promoting potential. The strains were grown individually under controlled conditions until the late exponential phase, adjusted to standardized concentrations (CFU mL^{-1}), and then combined for the final formulation.

Microencapsulation was performed by entrapment in a biodegradable polymer matrix; alginate, previously dissolved in a buffer solution with controlled pH and ionic strength, was evaluated as the encapsulating material. The microbial suspension was homogeneously incorporated into the matrix, and the mixture underwent controlled gelation/cross-linking in a $CaCl_2$ solution, allowing the formation of microcapsules with physical cell entrapment. Subsequently, the microcapsules were washed and dried under controlled conditions to stabilize the formulation.

Microbial viability before and after encapsulation was verified by plate counting and metabolic activity assays, ensuring the functional preservation of the consortium.

For the experimental application, the microencapsulated formulation was reconstituted in sterile water and applied to the substrate at a dose equivalent to 5 $L{\cdot}ha^{-1}$, adjusted to the volume of soil per pot. The application was carried out by controlled saturation until runoff, ensuring homogeneous distribution. This scheme allowed the progressive release of the consortium and its effect on the ionic and proton dynamics of the soil-microorganism-plant system to be evaluated.

Determination of soil physicochemical variables

The dynamics of pH, electrical conductivity (EC, dS m^{-1}), and soil temperature were evaluated using a system of continuous measurement electrochemical sensors installed directly in each experimental unit. Prior to the establishment of the trial, the sensors were calibrated using certified standard solutions for pH (standard buffers) and electrical conductivity, as well as traceable thermal references, in order to ensure instrumental accuracy, analytical stability, and inter-unit reproducibility.

The devices were inserted at a uniform depth within the substrate profile in all pots, ensuring homogeneous contact with the soil matrix and reducing the influence of local moisture or temperature gradients. The variables were recorded at regular time intervals throughout the experimental period using an automated digital data acquisition and storage system, generating continuous time series for each experimental unit.

In order to validate the in situ measurements and maintain comparability with conventional methodologies, pH and EC were also determined in soil-water extract (80 g : 50 mL) using distilled water. After a stabilization period, pH was measured with a calibrated digital potentiometer and EC with a previously verified conductometer.

Evaluation of morphogenic variables

The number of fully developed leaves was quantified by direct counting in each

experimental unit, considering only those leaves with complete leaf expansion and defined morphological differentiation. Plant height was determined as the linear distance from the base of the stem, at substrate level, to the apical meristem, using a calibrated millimeter scale to ensure measurement accuracy.

The evaluations were carried out at three consecutive times after the initial application of the microencapsulated consortium, which allowed the early growth dynamics to be characterized and the morphogenic response associated with rhizosphere establishment and the progressive metabolic activity of the bacterial consortium to be modeled.

Statistical analysis

Statistical analysis was performed using general linear models (GLM) with the PROC GLM procedure implemented in SAS Studio (SAS Institute Inc., Cary, NC, USA). For each dependent variable (pH, electrical conductivity, soil temperature, number of leaves, and plant height), a factorial model with fixed effects of Crop, days after application (DAA), and their interaction (Crop × DAA) was adjusted according to the defined experimental structure.

Effect estimates were obtained using Type III sums of squares, which allowed for the evaluation of adjusted effects independent of the order of entry of the factors in the model. Statistical significance was determined at a critical level of $\alpha = 0.05$.

When significant effects were detected, multiple comparisons between adjusted means (LSMeans) were performed using the Tukey–Kramer test, controlling the Type I error r experiment-wise. In addition, the coefficient of determination (R^2), mean square error (MSE), and F statistic were reported as indicators of model fit and robustness.

The inclusion of the interaction term allowed for a formal evaluation of the presence of parallel or divergent temporal trajectories between species, providing a consistent inferential basis for interpreting soil–microorganism–plant dynamics.

RESULTS AND DISCUSSION

pH dynamics in the microencapsulated PGPM release system

The general linear model explained 40.6% of the total pH variability (R^2 = 0.4058; MSE = 0.1986), indicating a moderate temporal structure of the system. The effect of days after application (DAA) was highly significant ($F_{5,456} = 56.16$; $p < 0.0001$), constituting the main determinant of the change in pH. The Cultivation effect was also significant, although to a lesser ex-

Source	gl	SS	MS	F	p
Cultivation	3	1.8721	0.6240	3.14	0.0251
DDA	5	55.7582	11.1516	56.16	<0.0001
Crop×DDA	15	4.2219	0.2815	1.42	0.1345

Table 1. ANOVA for pH (SS Type III)

Source: SAS STUDIO 2025

tent ($F_{3,456}$ = 3.14; p = 0.0251), while the interaction between Crop and DDA was not significant ($F_{15,456}$ = 1.42; p = 0.1345), indicating parallel temporal trajectories between species (Table 1).

Comparisons of means showed moderate differences between crops. Corn (8.787 ± 0.057) and wheat (8.777 ± 0.057) had higher values than peas (8.629 ± 0.057), with beans in an intermediate position. The magnitude of the temporal effect was considerably greater: pH increased from 8.261 ± 0.073 at 10 DDA to 9.101 ± 0.073 at 59 DDA (Δ = 0.84 units), a value close to double the RMSE (0.446), confirming biological relevance as well as statistical significance (Table 2).

The progressive alkaline shift is consistent with mineralization and microbial nitrogen transformation processes. The activity of plant growth-promoting microorganisms (PGPM) can alter the rhizosphere microenvironment through differential assimilation of NH_4^+ and NO_3^-, affecting the proton balance of the system (Richardson et al., 2009). Root exudation is also a primary modulator of rhizosphere pH, with variations depending on the functional type of plant (Canarini et al., 2019). In systems with biodegradable polymers, the gradual degradation of the encapsulating matrix modifies the chemical environment over time, affecting local ion exchange (Liu et al., 2021).

Electrical conductivity and ion dynamics

The model explained 14.24% of the total variability in electrical conductivity (EC) (R^2 = 0.1424; MSE = 0.0465), indicating greater residual heterogeneity with respect to pH. The Cultivation effect was not significant ($F_{3,456}$ = 0.38; p = 0.7676), while DDA was significant ($F_{5,456}$ = 8.38; p < 0.0001). The Cultivation×DDA interaction was significant ($F_{15,456}$ = 2.18; p = 0.0064), evidencing differential temporal dependence between species (Table 3).

The adjusted means showed average homogeneity between crops (0.460–0.488 dS m^{-1}). Temporally, a maximum was observed at 31 DDA (0.586 ± 0.036), followed by a progressive decrease up to 59 DDA (Table 4).

The intermediate pulse is consistent with controlled release systems with an initial phase of rapid diffusion followed by matrix degradation-dependent release (Shaviv, 2005; Trenkel, 2010). The significant interaction suggests that differential nutrient uptake between crops modulated the residual ionic concentration, a phenomenon associated with variations in root architecture and uptake efficiency (Lynch, 2019). Values remained below 1 dS m^{-1}, ruling out potentially phytotoxic salt accumulation.

Thermal modulation of the system

Temperature showed the highest statistical structuring (R^2 = 0.8104; MSE = 1.24505). The Crop effect was highly significant ($F_{3,456}$ = 320.46; p < 0.0001), exceeding the DDA effect in magnitude ($F_{5,456}$ = 91.04; p < 0.0001). The interaction was also significant ($F_{15,456}$ = 35.50; p < 0.0001) (Table 5).

Comparisons of means showed a clear separation between species, with peas (23.74 ± 0.14 °C) at the upper end and corn (19.40 ± 0.14 °C) at the lower end (Δ = 4.34 °C) (Table 6).

Factor	Level	LSMean ± SE	Group
Crop	Corn	8.787 ± 0.057	a
	Wheat	8.777 ± 0.057	a
	Beans	8.721 ± 0.057	ab
	Pea	8.629 ± 0.057	b
DDA	59	9.101 ± 0.073	a
	31–45	8,808–8,988	ab
	10–24	8,261–8,263	c

Table 2. Comparison of pH means (Tukey, α = 0.05)

Source: SAS STUDIO 2025

Source	gl	SS	MS	F	p
Cultivation	3	0.05297	0.01766	0.38	0.7676
DDA	5	1.94728	0.38946	8.38	<0.0001
Crop×DDA	15	1.51949	0.10130	2.18	0.0064

Table 3. ANOVA for EC (SS Type III)

Source: SAS STUDIO 2025

Factor	Level	LSMean ± SE	Group
Crop	All	0.460–0.488	a
DDA	31	0.586 ± 0.036	a
	10–38	0.493–0.496	ab
	45–52	0.452	b
	24	0.394	c

Table 4. Comparison of EC means (Tukey)

Source: SAS STUDIO 2025

Source	gl	SS	MS	F	p
Cultivation	3	1,196,976	398,992	320.46	<0.0001
DDA	5	566,748	113,350	91.04	<0.0001
Cultivation×DDA	15	662,953	44.197	35.50	<0.0001

Table 5. ANOVA for Temperature (SS Type III)

Source: SAS STUDIO 2025

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Thermal differences of this magnitude can exponentially modify microbial metabolic activity according to thermodynamic principles derived from the Arrhenius equation, where increases of 10 °C can double the rate of biological reaction (Davidson & Janssens, 2006). Temperature regulates microbial respiration and nutrient transformation in the soil, directly affecting mineralization processes and nutrient availability (Allison et al., 2010). Consequently, the crop acts as a microenvironmental modulator of the encapsulated system's performance.

Morphogenic dynamics of the number of leaves induced by halophilic biostimulation

The general linear model explained 98.93% of the total variability in the number of leaves (R^2 = 0.9893; MSE = 2.3491; RMSE = 1.533), indicating an exceptional statistical fit and minimal residual variance. The overall model was highly significant ($F_{11,227}$ = 1905.07; $p < 0.0001$). Under Type III sums of squares, the main effects of Cultivation ($F_{3,227}$ = 6267.24; $p < 0.0001$), days after initial application (DAIA) ($F_{2,227}$ = 421.65; $p < 0.0001$), and their interaction ($F_{6,227}$ = 215.29; $p < 0.0001$) were significant (Table 7).

The Crop effect explained the largest proportion of the total variation, indicating that the leaf architecture inherent to each species is the main structural determinant. However, the significance of the DDA factor confirms a progressive response after the initial application, consistent with a cumulative process of bacterial rhizosphere colonization. The significant interaction indicates non-parallel temporal trajectories between species.

The adjusted means showed complete statistical separation between crops and between evaluation times (Table 8).

The increase of 6.93 leaves between DDA 1 and DDA 3 represents more than four times the RMSE, confirming biologically relevant magnitude. The greater response in peas suggests greater morphogenic plasticity and efficiency in PGPR-induced hormonal signaling. Plant growth-promoting bacteria have been documented to synthesize indoleacetic acid (IAA), stimulate cell division, and improve nutrient absorption, promoting leaf emission (Vessey, 2003; Glick, 2012). In halotolerant strains, osmotic regulation and phytohormone production enhance aerial growth under conditions of moderate salt stress (Egamberdieva et al., 2017).

Response in plant elongation dependent on time post-application

The model explained 81.11% of the total variability in height (R^2 = 0.8111; MSE = 10.2243; RMSE = 3.198). The overall model was significant ($F_{11,227}$ = 88.62; $p < 0.0001$). Under SS Type III, the effects of Crop ($F_{3,227}$ = 27.24; $p < 0.0001$), DDA ($F_{2,227}$ = 396.91; $p < 0.0001$) and their interaction ($F_{6,227}$ = 16.02; $p < 0.0001$) were significant (Table 9).

In contrast to the number of leaves, height was mainly determined by the temporal factor, whose magnitude greatly exceeded the genotypic effect. This result indicates that cell elongation responded predominantly to physiological dynamics after bacterial inoculation (Table 10).

The increase of 14.22 cm between DDA 1 and DDA 3 is equivalent to

Factor	Level	LSMean ± SE	Group
Crop	Pea	23.74 ± 0.14	a
	Beans	22.24 ± 0.14	b
	Wheat	21.26 ± 0.14	c
	Corn	19.40 ± 0.14	d

Table 6. Comparison of means Temperature (Tukey)

Source: SAS STUDIO 2025

Source	gl	SS	MS	F	p
Cultivation	3	44167.49	14,722.50	6267.24	<0.0001
DDA	2	1981.03	990.52	421.65	<0.0001
Crop × DDA	6	3034.52	505.75	215.29	<0.0001

Table 7. ANOVA for number of leaves (SS Type III)

Source: SAS STUDIO 2025

Effect Crop				DDA effect		
Crop	LSMean	Group		DDA	LSMean	Group
Chícharo	35.28	a		3	15.74	a
Beans	5.95	b		2	11.06	b
Corn	3.65	c		1	8.81	c
Wheat	2.60	d				

Table 8. Comparison of means for number of leaves (Tukey–Kramer, α = 0.05)

Source: SAS STUDIO 2025

Source	gl	SS	MS	F	p
Cultivation	3	835.63	278.54	27.24	<0.0001
DDA	2	8116.32	4058.16	396.91	<0.0001
Crop × DDA	6	982.52	163.75	16.02	<0.0001

Table 9. ANOVA for height (SS Type III)

Source: SAS STUDIO 2025

Effect Culture				Effect DDA		
Crop	LSMean	Group		DDA	LSMean	Group
Corn	30.72	a		3	34.81	to
Chí-charo	28.72	b		2	28.88	b
Wheat	27.32	bc		1	20.59	c
Beans	25.61	c				

Table 10. Comparison of means for height (Tukey–Kramer)

Source: SAS STUDIO 2025

4.4×RMSE, confirming physiological relevance. The literature indicates that various PGPR synthesize gibberellins and express ACC-deaminase, reducing stress-associated ethylene and promoting cell elongation (Glick, 2014; Kang et al., 2014). The time-dependent response is consistent with bacterial establishment processes and progressive hormonal modulation.

Physiological integration and host–microorganism specificity

The consistent significance of the Culture × DDA interaction in both variables indicates that biostimulation does not act uniformly but depends on the physiological compatibility between the host and the bacterial consortium. The number of leaves was dominated by the genotypic component, while height showed greater temporal sensitivity, suggesting differentiated physiological mechanisms.

From a mechanistic perspective, leaf emission depends mainly on cell division in apical meristems, a process regulated by auxins and cytokinins, whose synthesis can be stimulated by PGPR (Vessey, 2003; Glick, 2012). In contrast, cell elongation is associated with the action of gibberellins and reduction of inhibitory ethylene by bacterial ACC-deaminase (Glick, 2014).

Halotolerant strains also improve ionic homeostasis and nutrient absorption efficiency under variable osmotic conditions, which increases stomat nd conductance and photosynthetic activity, affecting cumulative longitudinal growth (Egamberdieva et al., 2017).

The greater response observed in peas for number of leaves and in corn for height suggests that the root architecture and specific photosynthetic efficiency of each crop modulate the magnitude of the bacterial effect, a phenomenon consistent with studies on functional specificity in plant-microbiome interactions (Backer et al., 2018).

In agronomic terms, the high F values, the clear separation in multiple comparisons, and the magnitude of the increases relative to the RMSE indicate that halophilic biostimulation produced consistent and reproducible morphological changes, with effects dependent on species and time after initial application.

CONCLUSIONS

The controlled-release system of microencapsulated plant growth-promoting microorganisms (PGPM) demonstrated functional dynamics consistent with progressive matrix degradation and active rhi-

zosphere establishment, as evidenced by in situ electrochemical monitoring of pH, electrical conductivity (EC), and system temperature.

The pH dynamics were mainly determined by the time factor, with a progressive alkaline shift of $\Delta = 0.84$ units between 10 and 59 days after application (DAA), a magnitude close to twice the mean square error. The absence of significant Cultivation × DDA interaction indicates that the temporal pattern was structurally parallel between species, suggesting that microencapsulated release kinetics and microbial nitrogen transformation processes dominated the system response over interspecific variability. This behavior confirms that PGPM-induced mineralization and modification of the rhizospheric proton balance are central mechanisms of encapsulation performance.

Electrical conductivity showed a biphasic response characteristic of controlled-release systems, with an intermediate maximum pulse followed by progressive stabilization. Although the average effect of the crop was not significant, the temporal interaction was, showing that differential nutrient absorption modulated the residual ionic concentration. The permanence of values below 1 dS m^{-1} rules out potentially phytotoxic salt accumulation, confirming that the microencapsulated system maintains osmotic stability within agronomically safe ranges.

Temperature showed the greatest statistical structuring of the system, with a dominant effect of the crop and significant temporal interaction. Thermal differences of up to 4.34 °C between species imply substantial variations in microbial metabolic rates, given that thermal increases of this magnitude can exponentially modify soil respiration and mineralization. Consequently, the crop acts as a microenvironmental modulator of the encapsulated system's performance, indirectly affecting release kinetics and nutrient transformation.

In morphogenic terms, the number of leaves was predominantly determined by the genotypic component of the crop, while height responded ly to the temporal dynamics following bacterial application. The significant interaction in both variables confirms host-microorganism functional specificity. Foliar emission is associated with auxin and cytokinin regulation stimulated by PGPM, while plant elongation reflects the action of gibberellins and ACC-deaminase-mediated ethylene reduction. The greater temporal sensitivity observed in height suggests that the hormonal mechanisms induced by the bacterial consortium operate progressively as rhizospheric colonization advances.

The integration of physicochemical and morphological variables demonstrates that microencapsulated release not only modifies the edaphic microenvironment but also generates a consistent and quantifiable plant physiological response. The consistency between alkaline displacement, controlled ion dynamics, and morphogenic response confirms that the encapsulated system maintains active biological functionality during the evaluated period.

Taken together, the results validate that PGPM microencapsulation is an effective strategy for gradually modulating the rhizospheric environment, minimizing abrupt saline pulses, and promoting time-dependent plant growth. The use of in situ electrochemical sensors allowed the actual kinetics of the system to be captured, providing solid experimental evidence of the chemical stability, osmotic safety, and physiological efficacy of the encapsulation under field conditions.

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