

OPTIMIZATION OF MICROORGANISM-ENRICHED BIO-COATED CLAY GRANULES FOR SUSTAINABLE PLANT GROWTH USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT: This study developed and optimized a microbial-enriched compost powder designed to enhance the growth performance of Red Cos lettuce using Response Surface Methodology (RSM). Three plant growth-promoting bacteria—*Azotobacter* sp., *Bacillus* spp., and *Azotobacter vinelandii*—were incorporated into compost powder and applied to high-porosity fired clay granules as the growth medium. A Box-Behnken Design was employed to evaluate individual and interactive effects of microbial concentrations on plant dry weight. ANOVA confirmed that the quadratic regression model was highly significant ($p < 0.0001$), with strong predictive capacity ($R^2 = 0.9973$; Adjusted $R^2 = 0.9925$) and an insignificant lack-of-fit. All microbial factors significantly influenced biomass production, with *A. vinelandii* exhibiting the most significant effect, followed by *Azotobacter* sp. and *Bacillus* spp. Response surface and contour plots revealed clear synergistic interactions among the variables and identified a distinct optimal region. The optimal formulation—0.19% *Azotobacter* sp., 1.84% *Bacillus* spp., and 0.39% *A. vinelandii*—yielded the highest observed dry weight (2.14 ± 0.04 g), consistent with model predictions. Confirmation experiments showed that unbalanced microbial levels led to inferior growth responses, underscoring the importance of optimized ratios. The findings establish that microbial consortia integrated into compost powder and applied via porous clay granules can substantially improve plant biomass while supporting environmentally sustainable production systems. This optimized formulation provides a promising basis for further development of microbially enhanced growth media for leafy vegetables.

Keywords: Bio-coated clay, *Azotobacter*, *Bacillus*, Response surface methodology, Sustainable agriculture

1. INTRODUCTION

Sustainable agriculture increasingly requires plant growth substrates that minimize environmental impacts while maintaining crop productivity. Traditional materials such as peat moss have long been used due to their favorable physicochemical properties; however, peatland extraction poses ecological concerns, including habitat loss, carbon emissions, and long-term degradation [1]. These challenges highlight the need for renewable, low-impact growth media. Recent studies show that porous clay-based substrates provide adequate aeration, moisture retention, and structural stability, positioning them as promising alternatives for horticultural and agricultural applications [2]. When combined with bioactive microbial components, such substrates can also reduce dependency on chemical fertilizers and support circular nutrient management systems [3].

Plant growth-promoting microorganisms (PGPMs) contribute to sustainable production by enhancing nutrient acquisition, stimulating root development, and improving resilience to environmental stress [4–7]. *Azotobacter* sp. supports

biological nitrogen fixation [4], *Bacillus* spp. facilitate phosphate solubilization and nutrient mobilization [5], and *Azotobacter vinelandii* provides strong nitrogen-fixing and biofilm-forming capacities that improve microbial persistence in the rhizosphere [7]. Incorporating these microorganisms into clay-based carriers improves survival and enables controlled release at the root zone, promoting more efficient plant responses than conventional fertilizers [8].

Response Surface Methodology (RSM) offers a statistically robust framework for optimizing multivariable agricultural systems. Its ability to quantify individual and interaction effects makes it effective for formulating microbial products and optimizing amendments [9]. The Box-Behnken Design (BBD) is particularly efficient, requiring fewer runs while capturing nonlinear and interaction effects [10]. Applying RSM to bio-coated clay systems enables precise determination of microbial ratios governing plant growth responses.

This research introduces a novel integration of a microbial-enriched compost powder with fired porous clay granules as a dual-function growth medium and microbial carrier. Its originality lies in

the systematic optimization of a multi-strain microbial consortium using RSM combined with a structurally engineered clay-based delivery system. Unlike conventional biofertilizers, this approach enables controlled microbial distribution, enhanced stability, and consistent plant response. The study validates microbial synergy within a compost–clay matrix, establishing a platform for sustainable plant production systems and advancing practical applications of microbial-based growth media.

Building upon prior work demonstrating the suitability of fired clay granules as carriers for nitrogen-fixing bacteria [8], this study expands the concept by integrating multiple PGPMs into a compost-based formulation. Red Cos lettuce (*Lactuca sativa* var. *longifolia*) was selected as a model leafy vegetable due to its sensitivity to nutrient availability and relevance to controlled-environment cultivation. By using RSM to optimize the concentrations and interactions of *Azotobacter* sp., *Bacillus* spp., and *A. vinelandii*, the study aims to identify an effective microbial-enriched compost formulation that maximizes biomass while supporting environmentally responsible cultivation. The outcomes offer data-driven evidence for developing sustainable microbial-based growth media suitable for broader agricultural and horticultural applications.

2. RESEARCH SIGNIFICANCE

This study presents a novel microbial-enriched compost powder optimized through Response Surface Methodology to enhance Red Cos lettuce growth. By integrating *Azotobacter* sp., *Bacillus* spp., and *A. vinelandii* onto porous clay granules, it uniquely evaluates synergistic microbial interactions using a Box–Behnken Design. The optimized consortium significantly boosts biomass, demonstrating an innovative, sustainable approach to developing next-generation microbially enhanced growth media for leafy vegetable production.

3. MATERIALS AND METHODS

3.1 The Experimental Design

This study investigates the effects of microbial supplementation in compost powder on plant growth when cultivated in clay granules. The independent variables are the concentrations of *Azotobacter* sp. (0.13–0.67 %w/w), *Bacillus* spp. (0.07–0.33 %w/w), and *A. vinelandii* (1.3–2.7 %w/w), while plant dry weight is the dependent variable. Controlled factors include compost composition, plant type, environmental conditions (light, water, temperature, humidity), clay granule properties (size, porosity, water-holding capacity), and experiment duration. The variable ranges are summarized in Table 1.

Table 1. Levels, actual and coded experimental independent variables for microbial supplementation in compost powder on the growth of Red Cos lettuce

Variables	Coding	Unit	Levels		
			-1	0	+1
<i>Azotobacter</i> sp.	X_1	%w/w	0.4	0.13	0.67
<i>Bacillus</i> spp.	X_2	%w/w	0.07	0.2	0.33
<i>A. vinelandii</i>	X_3	%w/w	1.3	2	2.7

3.2 The statistical analysis

Statistical analysis was performed using a Box-Behnken Design (BBD) under Response Surface Methodology (RSM) to evaluate interactions among three variables. Design-Expert® Version 13 was used for A one-way Analysis of Variance (ANOVA), response optimization, and visualization via contour and 3D surface plots, providing insights into how the inputs influenced plant growth (Table 2).

Table 2. Design matrix of the experiments along with the corresponding experimental and predicted values for the growth of Red Cos lettuce.

Run	Variables			Response*	
	X_1	X_2	X_3	Dry weight (g)	
	(%w/w)	(%w/w)	(%w/w)	Observed value	Predicted value
1	0.13	0.2	2.7	1.77	1.77
2	0.13	0.33	2	1.77	1.77
3	0.4	0.33	2.7	1.85	1.85
4	0.67	0.2	1.3	1.95	1.95
5	0.4	0.2	2	2.14	2.13
6	0.67	0.2	2.7	1.88	1.87
7	0.4	0.07	2.7	1.77	1.78
8	0.67	0.07	2	1.85	1.85
9	0.13	0.07	2	1.89	1.88
10	0.4	0.33	1.3	1.90	1.89
11	0.13	0.2	1.3	1.93	1.94
12	0.4	0.2	2	2.12	2.13
13	0.4	0.2	2	2.14	2.13
14	0.67	0.33	2	1.93	1.94
15	0.4	0.07	1.3	1.98	1.98

Note: *The dry weight data of Red Cos Lettuce after 60 days of planting

The regression analysis yielded a second-order polynomial equation used to predict plant growth as a function of microbial supplementation levels. This equation takes the general form:

$$y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \quad (1)$$

where y represents the predicted response (dry weight), X_1 , X_2 , and X_3 The coded levels of the

independent variables, and the coefficients represent the quadratic and interaction effects. This model enabled precise evaluation of the individual and combined effects of the microbial inputs on plant growth.

3.3 The Confirmation Experiments

A set of seven confirmation experiments was conducted to validate the predictive accuracy of the response surface model. These included: (1) a control without microbial addition, (2–5) low and high levels of individual microbial inputs, (6) a center point representing average values, and (7) an optimized formulation derived from numerical optimization. Each treatment involved precise concentrations of *Azotobacter* sp., *Bacillus* spp., and *A. vinelandii* incorporated into compost powder and applied to high-porosity clay granules as the plant growth medium.

Red Cos lettuce seedlings were grown in a regulated environment for 60 days (Fig. 2). Each treatment was replicated three times. When it came time to harvest, the growth performance of the plants was evaluated through the measurement of the plant dry weight (g). Statistical evaluations were carried out to analyze the means of the treatments. ANOVA accompanied by Tukey's Honestly Significant Difference (HSD) test was employed to identify notable differences between treatments, using a 95% confidence level ($p < 0.05$). [11].

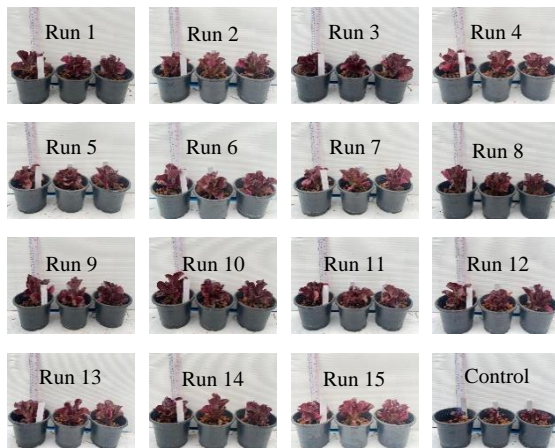


Fig. 1 Growth performance of Red Cos lettuce seedlings under the 15 Box–Behnken Design experimental treatments and the control.

3.4 High Porous Clay Granule Preparation

High-porous clay granules were prepared following the method described in [8], incorporating 15% (w/w) sawdust waste into the raw clay mixture. A water solution containing 30-35% water was added to improve plasticity for shaping. The granules were manually formed using the soft-mud paving

technique, resulting in diameters of 1.0-1.5 cm. The formed granules were sun-dried for three days before being fired at 900°C to enhance their structural integrity and porosity.

3.5 Microbial Preparation

The selected microbial strains—*Azotobacter* sp., *Bacillus* spp., and *A. vinelandii*—were prepared under controlled laboratory conditions to ensure consistency and viability prior to application. Each strain was cultured in 6000 mL fermentation vessels containing 1800 mL of sterilized nitrogen-free medium supplemented with potassium metabisulfite (KMS). This medium composition supports the growth of diazotrophic and plant growth-promoting bacteria by eliminating external nitrogen sources and encouraging endogenous nitrogen fixation pathways. The cultures were incubated for five days under continuous shaking at room temperature, a condition that promotes adequate aeration and homogeneous nutrient distribution throughout the fermentation vessels.

Upon completion of incubation, the bacterial suspensions were standardized by adjusting the optical density to $OD_{600} = 1$. This normalization step ensured that each microbial strain was applied at a consistent cell concentration, thereby reducing variability during the subsequent bio-coating process. Establishing uniform cell density is essential for comparative evaluation across experimental treatments and for ensuring reproducibility of microbial loading onto the compost powder and clay granules. The prepared suspensions were then immediately used for bio-coating to maintain microbial activity and minimize physiological shifts associated with prolonged storage.

3.6 Compost Powder Production

The compost powder used in this study was formulated from organic residues selected to ensure a balanced nutrient composition and a suitable carbon-to-nitrogen (C/N) ratio for microbial enrichment. The raw materials consisted of food waste (40–55%), cricket manure (15–25%), dried *Samanea saman* leaves (15–20%), and molasses (8.5–15%). This mixture provides both readily degradable substrates and stable organic matter, supporting microbial activity during composting and aligning with recommended practices for producing high-quality organic fertilizers [12]. Maintaining an appropriate C/N ratio is essential for optimizing microbial metabolism and ensuring adequate conversion of organic substrates into nutrient-rich compost.

Composting was carried out in a 3×5 meter chamber for 60 days with periodic turning to ensure uniform aeration and moisture distribution. After maturation, the compost was shade-dried for three

days, mechanically shredded, and sieved to obtain a fine powder. This standardized particle size was critical for achieving homogeneous mixing with microbial suspensions and ensuring uniform coating on the high-porosity clay granules used as the plant growth medium. The physical characteristics of the resulting microbial-enriched compost formulations are shown in Fig. 2, which illustrates consistency and morphology across treatments.

To ensure regulatory compliance and suitability for biological inoculation, the compost powder was analyzed in accordance with the official procedures mandated by the Ministry of Agriculture and Cooperatives (Thailand, 2559; 2551). As shown in Table 3, the powder sample demonstrates physicochemical characteristics that align with the established standards for organic fertilizers and with the functional requirements of a microbial carrier. The near-neutral pH and balanced salinity profile provide a conducive environment for microbial survival while minimizing potential plant stress during application. The C/N ratio corresponds to that of fully stabilized compost, indicating adequate decomposition of organic matter without the risk of nitrogen immobilization.



Fig. 2 Characteristics of microbial-enriched compost powder formulations based on the Box-Behnken Design

The macronutrient composition reflects typical values of mature compost derived from mixed organic feedstocks, affirming that the substrate offers baseline fertility before microbial supplementation. Measures of compost stability—particularly the substantial proportion of humified organic matter—further verify that decomposition proceeded to completion in accordance with regulatory expectations. The high germination index, surpassing commonly accepted maturity thresholds, confirms the absence of phytotoxic compounds and supports its suitability for use in plant-based assays and microbial formulation work. The lack of physical contaminants and a uniform particle-size distribution contribute to

consistent mixing behavior and facilitate reliable microbial coating on clay granules. Collectively, these attributes confirm that the compost powder meets both regulatory and functional criteria essential for producing high-quality microbial-enriched formulations.

Table 3. Physicochemical properties of compost powder

Parameter	Mean (\pm SD)
pH	6.80 \pm 0.14
Moisture content (%)	19.45 \pm 0.78
Total Nitrogen (%)	2.80 \pm 0.14
Total Phosphorus (%)	1.20 \pm 0.00
Total Potassium (%)	1.50 \pm 0.14
C/N ratio	15.50 \pm 0.71
EC (dS/m)	13.60 \pm 0.14
Organic Carbon (%)	44.70 \pm 0.57
Organic Matter (%)	48.35 \pm 1.20
Sodium (%)	0.535 \pm 0.007
Germination Index (%)	87.55 \pm 0.86
Plastic/Glass	Not detected

Note: Analytical measurements were obtained from official reports issued by the Office of Agricultural Research and Development Region 2, Ministry of Agriculture and Cooperatives, Thailand, following standardized procedures for organic fertilizer analysis (MOAC, 2559; 2551).

4. RESULT AND DISCUSSION

4.1 Regression Model Fitting Using the Box-Behnken Design (BBD)

The analysis of variance (ANOVA) summarized in Table 4 demonstrates that the fitted quadratic regression model is highly statistically significant, with a p -value of the model less than 0.0001. This indicates that the observed variation in the dry weight of Red Cos lettuce is primarily attributable to the effects of the selected microbial input variables and their interactions, rather than random experimental error. The high F -value further reinforces the strength of the relationship between the model and the response variable.

The model's coefficient of determination implies that approximately 99.73% of the total variation in plant dry weight can be explained by the fitted model. This exceptionally high R^2 value signifies a near-perfect fit between the predicted and actual data points, confirming that the model captures the key trends and effects of the independent variables on the growth response. All three main effects—*Azotobacter* sp. (X_1), *Bacillus* spp. (X_2), and *A. vinelandii* (X_3)—were statistically significant ($p < 0.0002$), with *A. vinelandii* contributing the most substantial impact ($F = 224.04$, $p < 0.0001$). Significant two-way interaction effects were

observed between X_1X_2 and X_2X_3 . At the same time, the quadratic terms (X_1^2 , X_2^2 , and X_3^2) exhibited highly significant effects ($p < 0.0001$), indicating curvature in the response surface and supporting the appropriateness of the second-order model. Moreover, the lack-of-fit test was insignificant ($p = 0.5929$), confirming that the model fits the data adequately and that the residual variance is attributable primarily to pure error rather than model misspecification.

Table 4. Analysis of variance (ANOVA) for the model regression representing.

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	0.22	9	0.0245	207.31	< 0.0001
X_1	0.01	1	0.0157	132.61	< 0.0001
X_2	0.01	1	0.0108	91.21	0.0002
X_3	0.03	1	0.0265	224.04	< 0.0001
$X_1 X_2$	0.0100	1	0.0100	84.51	0.0003
$X_1 X_3$	0.0020	1	0.0020	17.11	0.0090
$X_2 X_3$	0.0064	1	0.0064	54.08	0.0007
X_1^2	0.0652	1	0.0652	551.25	< 0.0001
X_2^2	0.0728	1	0.0728	615.22	< 0.0001
X_3^2	0.0513	1	0.0513	433.85	< 0.0001
Residual	0.0006	5	0.0001		
Lack of Fit	0.0003	3	0.0001	0.8125	0.5929
Pure Error	0.0003	2	0.0001		
Cor Total	0.2214	14			
R^2	0.9973				
Adjusted R^2	0.9925				

4.2 Optimization of Compost Powder Formulation for Microbial-Enriched Compost Powder Formulations

To examine the interaction effects of the three microbial components—*Azotobacter* sp. (X_1), *Bacillus* spp. (X_2), and *A. vinelandii* (X_3)—on the dry weight of Red Cos lettuce, contour plots and three-dimensional response surface plots were generated from the quadratic regression model. The visualizations confirm a well-defined optimal region and demonstrate the synergistic impact of the microbial formulations on plant biomass (Fig. 3). Fig. 3a illustrates the interaction between *Azotobacter* sp. and *Bacillus* spp., while *A. vinelandii* was fixed at its central value (2.0% w/w).

The results show that increasing both *Azotobacter* sp. and *Bacillus* spp. Concentrations up to their mid-range significantly enhance dry weight. The predicted maximum dry weight in this interaction was approximately 2.14 g, confirming a strong synergistic effect. Fig. 3b presents the interaction between *Azotobacter* sp. and *A. vinelandii*, with *Bacillus* spp. held constant. Similar to the previous interaction, a convex surface is evident, with the optimum occurring at mid-range concentrations of both X_1 and X_3 . This indicates that *Azotobacter* sp., a nitrogen-

fixer, and *A. vinelandii*, another diazotroph with biofilm-forming capacity, complement each other in promoting plant growth. Fig. 3c depicts the interaction between *Bacillus* spp. and *A. vinelandii* while keeping *Azotobacter* sp. constant. The plots

4.3 Confirmation of the Optimized Microbial-Enriched Compost Powder Formulation

The confirmation experiments were conducted to validate the predictive accuracy and practical applicability of the optimized microbial-enriched compost powder formulation identified through the response surface model. Seven treatments—representing the control, low-level single-factor variations, high-level variations, the center point, and the optimized ratios—were evaluated to determine whether the model’s predicted optimum could be reproduced under controlled cultivation conditions. As shown in Table 5, the optimized formulation consisting of 0.19% *Azotobacter* sp., 1.84% *Bacillus* spp., and 0.39% *A. vinelandii* produced the highest dry weight (2.14 ± 0.04 g), demonstrating complete agreement with the model’s predicted maximum response.

Table 5. The confirmation experiments for the growth of Red Cos lettuce.

Run	Variables			Response
	<i>Azotobacter</i> sp. (% w/w)	<i>Bacillus</i> spp. (% w/w)	<i>A. vinelandii</i> (% w/w)	Dry weight (g)
1	0	0	0	1.98 ± 0.02^{ab}
2	0.4	0.07	2	1.89 ± 0.01^c
3	0.13	0.07	1.3	1.98 ± 0.02^{ab}
4	0.67	0.33	2	1.97 ± 0.07^{ab}
5	0.13	0.33	2.7	1.85 ± 0.05^c
6	0.13	0.2	2	2.14 ± 0.06^a
7	0.19	1.84	0.39	2.14 ± 0.04^a

The center-point treatment exhibited comparable performance (2.14 ± 0.06 g), reinforcing the stability of the response surface around the optimal region. In contrast, treatments containing imbalanced microbial concentrations—whether excessively low or high—resulted in reduced plant biomass, with dry weights ranging from 1.85 to 1.98 g. These outcomes align with the significant quadratic terms identified in the model, indicating that deviations from optimal microbial ratios negatively affect plant growth. The magnitude and consistency of these differences highlight the system's sensitivity to microbial proportions rather than to absolute concentrations.

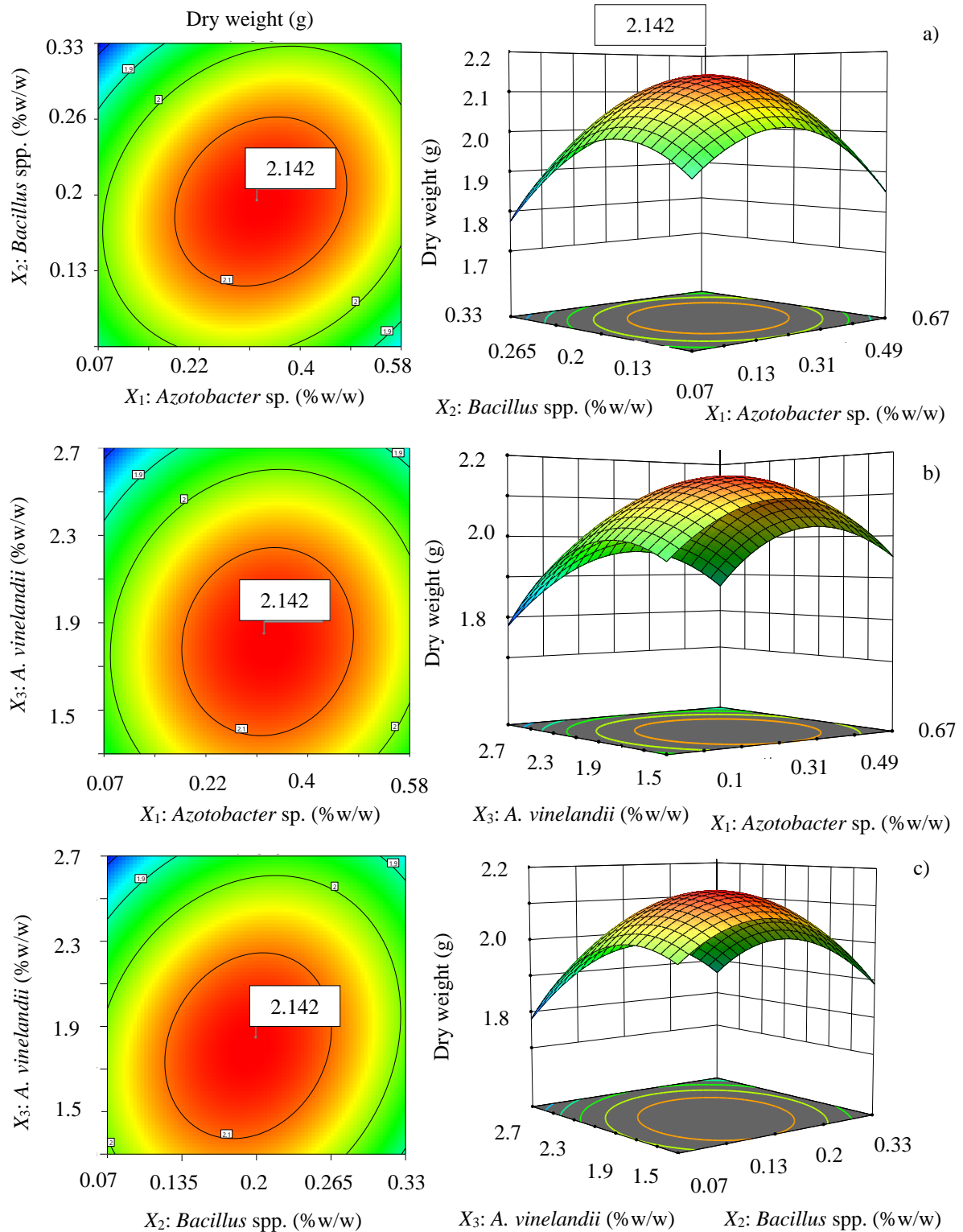


Fig. 3. Contour and 3D response surface plots illustrate microbial inputs' interactive effects on the dry weight of Red Cos lettuce: (a) *Azotobacter* sp. (X_1) \times *Bacillus* spp. (X_2); (b) *Azotobacter* sp. (X_1) \times *A. vinelandii* (X_3); (c) *Bacillus* spp. (X_2) \times *A. vinelandii* (X_3).

The clear distinction in biomass production across the seven validation treatments also demonstrates the

practical significance of the model's interaction terms. Treatments 2 and 5, which contained disproportionately low or high levels of one or more

microbial components, yielded the lowest biomass values, underscoring the necessity of maintaining a balanced combination of nitrogen-fixing and phosphate-solubilizing microorganisms. This experimentally verified trend supports the conclusion that microbial synergy is highly dependent on the relative contribution of each strain within the formulation.

Furthermore, the alignment between observed and predicted values across all treatments confirms the reliability of the response surface model for determining optimal microbial compositions in compost-based carriers. The consistency of results across replicates also reflects the reproducibility of the formulation process and the suitability of fired porous clay granules as a stable delivery medium for the microorganisms. Collectively, these findings provide strong empirical evidence that the optimized formulation is both statistically valid and practically effective, firmly establishing its potential as a high-performance microbial enrichment strategy for plant cultivation systems.

4.4 Discussion

This study demonstrates the effectiveness of microbial-enriched compost powder in enhancing the growth performance of Red Cos lettuce, with the optimized formulation yielding significant improvements in plant dry weight. The close agreement between predicted and experimental results confirms the robustness of the response surface model, as reflected by the high coefficient of determination ($R^2 = 0.9973$, Adj. $R^2 = 0.9925$). These findings indicate that the fitted quadratic model successfully captured the contributions of the microbial variables and their interactions, supporting its applicability for formulation optimization.

Among the three microbial components, *A. vinelandii* exerted the strongest influence on plant biomass accumulation, consistent with its well-documented capacity for nitrogen fixation and biofilm formation [7]. *Azotobacter* sp. and *Bacillus* spp. also played substantial roles, contributing nitrogen fixation and phosphate solubilization, respectively [4–6]. The combined effects of these microorganisms resulted in synergistic enhancement of plant growth, aligning with earlier reports that microbial consortia commonly outperform single-strain inoculants by improving nutrient uptake efficiency and promoting rhizosphere functionality [13]. The significant interaction and quadratic terms observed in the regression model further underscore the importance of maintaining balanced microbial ratios, as deviations from the optimized concentrations led to reduced plant responses.

The response surface visualizations provided additional insights into these synergistic trends, revealing well-defined optimum regions across the

microbial concentration ranges. Treatments containing either excessively high or low microbial levels exhibited noticeably lower biomass production than the optimized or center-point formulations, emphasizing that plant growth is highly sensitive to microbial composition and proportionality rather than total microbial input alone.

The optimized microbial-enriched compost powder also integrates successfully with fired porous clay granules, which serve as stable carriers capable of supporting microbial viability and allowing uniform distribution throughout the growth medium [8]. The compatibility between the compost formulation and the clay granules suggests that this approach offers practical advantages over conventional fertilizers, particularly in terms of handling ease, dry storage potential, and controlled microbial delivery. Moreover, the enhanced plant response observed in this study highlights the potential of combining compost-based substrates with beneficial microorganisms as part of broader sustainable agriculture strategies.

Overall, the findings validate the use of Response Surface Methodology for optimizing microbial-enriched compost formulations and demonstrate the promise of microbial consortia in improving plant biomass production. The evidence indicates that appropriately balanced microbial inputs, when applied onto structurally stable clay granules, can provide an effective alternative to chemical fertilizers and contribute to environmentally responsible plant production systems.

5. CONCLUSION

This study successfully established and optimized a microbial-enriched compost powder formulation incorporated onto fired porous clay granules to enhance the growth performance of Red Cos lettuce. Using Response Surface Methodology with a Box–Behnken Design, the research systematically quantified the individual and interactive effects of *Azotobacter* sp., *Bacillus* spp., and *A. vinelandii* on plant biomass accumulation. The resulting regression model demonstrated excellent predictive accuracy, as indicated by the high determination coefficients ($R^2 = 0.9973$; Adj. $R^2 = 0.9925$) and an insignificant lack-of-fit, confirming that the model effectively captured the key trends governing plant growth responses.

The optimized microbial formulation—0.19% *Azotobacter* sp., 1.84% *Bacillus* spp., and 0.39% *A. vinelandii*—yielded the highest observed dry weight (2.14 ± 0.04 g), aligning closely with model predictions. Confirmation experiments further showed that deviations from these optimized ratios consistently resulted in reduced plant performance, underscoring the importance of balanced microbial compositions rather than maximal dosages. The strong synergistic effects identified through the

response surface analysis also highlight the functional complementarity among nitrogen-fixing and phosphate-solubilizing microorganisms.

The effective integration of the optimized compost formulation with fired clay granules demonstrates an added advantage, as the granules provide structural stability, support microbial adhesion, and ensure uniform distribution within the growth substrate. This combined system offers practical benefits for dry storage, handling, and controlled microbial release, distinguishing it from conventional organic or chemical fertilizers.

Collectively, the findings provide robust experimental evidence that microbial consortia, when delivered through a standardized compost–clay carrier, can significantly improve plant biomass production while supporting sustainable cultivation practices. The optimized formulation identified in this study serves as a validated foundation for advancing microbial-based growth media for leafy vegetables and related agricultural applications.

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