International Journal of GEOMATE, March, 2026 Vol.30, Issue 139, pp.106-115
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2026.139.g15269
Geotechnique, Construction Materials and Environment

DEVELOPMENT AND OPTIMIZATION OF MICROBIAL COMPOST POWDER FOR CLAY PELLETS: TOWARD A FUNCTIONAL AND MARKETABLE GROWING MEDIA

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ABSTRACT: This study presents the development and optimization of a microbial-enriched compost powder applied as a bioactive coating on porous fired-clay pellets, designed as a functional growing-media carrier derived from agricultural residues. The clay pellets were fabricated from locally sourced clay incorporating 15 wt% corn cob as a pore-forming additive and fired at 900°C to generate a lightweight porous ceramic matrix suitable for microbial attachment. Key physical and mechanical properties of the pellets, including firing shrinkage, water absorption, apparent porosity, bulk density, and compressive strength, were quantitatively evaluated to verify structural integrity and carrier performance. The compost powder was enriched with three functionally distinct microbial groups—phosphate-solubilizing, antagonistic, and nitrogen-fixing microorganisms—and their proportions were optimized using Response Surface Methodology based on a Box–Behnken Design. Butterhead lettuce was employed as a model plant to validate the functional response of the integrated carrier–coating system. The optimized formulation (0.7% phosphate solubilizers, 0.235% antagonists, and 2.7% nitrogen fixers, w/w) produced a shoot dry weight of 2.83 g, in close agreement with the model-predicted value of 2.84 g ($R^2 = 0.9938$). The results demonstrate that biomass-modified fired-clay pellets can provide a mechanically stable and porous carrier platform for microbial compost coatings, while statistical optimization supports effective tuning of biological inputs within a fixed engineered matrix. The integrated system shows potential as a waste-derived functional material relevant to sustainable growing media and environmental engineering applications.

Keywords: Porous fired clay pellet; Biomass pore-forming additive; Microbial-enriched compost coating; Sustainable growing media; Environmental materials engineering

1. INTRODUCTION

In recent years, growing attention has been directed toward sustainable and resource-efficient solutions across agriculture, materials engineering, and environmental management. This shift is primarily driven by increasing concerns over organic waste accumulation, soil degradation, and the environmental burdens associated with conventional production systems. Although chemical fertilizers remain effective in improving crop productivity, their long-term and intensive use has been widely associated with nutrient leaching, disruption of soil microbial communities, and increased greenhouse gas emissions [1,2]. These challenges have prompted research efforts to develop integrated approaches that combine waste valorization with functional materials design and biologically based processes to support long-term sustainability.

Microbial-enriched composts derived from food and agricultural residues represent one such approach, offering a pathway for transforming organic waste into value-added soil amendments. These composts incorporate beneficial microorganisms that contribute to nutrient mobilization, plant growth stimulation, and suppression of soil-borne pathogens [3,4]. Functional microbial groups, including phosphate-solubilizing bacteria, nitrogen-fixing microorganisms, and antagonistic strains, play complementary roles in improving nutrient availability and maintaining rhizosphere stability [4]. Despite these advantages, the direct application of microbial composts often faces practical limitations, such as uneven nutrient release, microbial wash-off, and reduced stability during storage and field application.

To address these limitations, increasing attention has been given to engineered mineral carriers that enhance microbial retention and enable controlled release. Fired clay pellets have been widely investigated as carrier materials due to their mechanical stability, durability, and adaptable pore structure. When organic pore-forming agents are incorporated into clay matrices, internal porosity can be tailored through thermal decomposition during firing. In this context, agricultural waste biomass has been extensively used as a sacrificial additive in clay-based materials. During firing, biomass decomposes and volatilizes, creating interconnected pore networks that reduce bulk density and enhance water absorption while maintaining adequate structural integrity [8–10,12]. These properties make corn-cob-modified fired-clay pellets suitable for use as lightweight growing media components and microbial carrier materials.

Previous studies have demonstrated that fired clay granules can serve as effective carriers for nitrogen-fixing bacteria, preserving microbial viability during storage and supporting subsequent colonization in soil environments [5]. Such findings indicate that clay-based materials can serve not only as passive structural media but also as functional components in biologically active systems. However, most existing studies have examined microbial formulation and carrier material development as separate research domains. Microbial optimization studies typically emphasize agronomic outcomes, whereas materials-oriented research focuses primarily on physical and mechanical properties without explicitly linking these characteristics to biological functionality.

As a result, a research gap remains in the integrated design and optimization of microbial-enriched compost formulations combined with engineered porous clay carriers [5,8-10], particularly when both components are derived from waste materials. In addition, limited attention has been given to applying statistically robust optimization techniques to balance microbial composition and functional system performance in such integrated carrier systems.

Response Surface Methodology (RSM) provides a robust statistical framework for multivariable optimization [6]. RSM enables the evaluation of individual and interaction effects among multiple factors and has been widely applied in process optimization and materials engineering. Nevertheless, its application to optimizing functional microbial consortia within engineered clay-based carrier systems remains limited.

Therefore, the objective of this study was to develop and optimize a microbial-enriched compost powder intended for application to corn cobs-modified fired-clay pellets, designed as an engineered growing-media component. The functional microbial groups: phosphate-solubilizing, antagonistic, and nitrogen-fixing microorganisms, were selected based on their complementary roles in nutrient cycling and biological stability. Their proportions were optimized using RSM with a BBD, and butterhead lettuce (*Lactuca sativa*) was used as a model plant to validate the functional performance of the engineered carrier system. In addition, the feasibility of the integrated system was examined from a materials utilization and sustainability perspective, with emphasis on waste valorization and low-energy processing.

2. RESEARCH SIGNIFICANCE

This study presents an integrated materials-biological approach to developing a waste-derived growing media system by combining porous fired-clay pellets with statistically optimized microbial compost coatings. Unlike previous studies that address carrier materials and microbial formulations separately, this work links pellet pore engineering, mechanical stability, and microbial functionality within a single design framework. Response Surface Methodology is applied to systematically optimize functional microbial groups under a fixed engineered carrier, enabling performance tuning without altering material structure. The results demonstrate a scalable, low-energy strategy for transforming agricultural residues into functional environmental materials with clear relevance to sustainable agriculture and circular bioeconomy practices.

3. MATERIALS AND METHODS

3.1 Preparation of Microbial Compost Powder

The microbial compost powder was prepared through a controlled aerobic composting and post-processing procedure designed to produce a stable, fine-particle material suitable for surface coating on corn cob-modified fired-clay pellets. Key operational parameters governing the composting and microbial enrichment steps were maintained within established ranges, as summarized in Table 1.

Table 1 Key operational parameters for aerobic food-waste composting and microbial enrichment.

Parameter	Optimal Range	Purpose
pH	6.0-7.0	Supports microbial activity and stability
Moisture content (%)	55-60	Prevents anaerobic conditions
C/N ratio	20:1-30: 1	Promotes balanced biodegradation
Temperature	55–65°C (thermophilic)	Enhances decomposition and pathogen reduction
Turning Frequency	Every 3–5 days	Improves aeration and uniform composting
Microbial Load	10^7–10^8 CFU*/g	Ensures effective biological performance

*Note: *CFU (Colony-Forming Unit)*

Food waste was collected from local fresh markets and food retail sources and manually sorted to remove non-biodegradable contaminants such as plastics, glass, and packaging materials. The biodegradable fraction, consisting mainly of fruit and vegetable residues, was reduced in size by shredding or chopping to increase surface area and promote uniform biodegradation. The processed waste was mixed with bulking agents, including dry leaves and animal manure, to adjust the C/N ratio and improve aeration. At the same time, molasses was added as an auxiliary carbon source to stimulate microbial activity during the initial composting stage [1,2,11].

Aerobic composting was conducted under ambient conditions, with periodic turning every 3–5 days to maintain oxygen availability and prevent anaerobic zones. Composting proceeded for approximately 45 days, during which the temperature gradually stabilized, and the material exhibited a homogeneous appearance indicative of compost maturity [11,13]. This maturation step ensured adequate stabilization of organic matter before powder processing and microbial inoculation.

After maturation, the compost was dried under controlled conditions to reduce moisture content while minimizing thermal stress. The dried material was subsequently milled and sieved to obtain particles with a size below 2 mm. This particle size range was selected to facilitate uniform adhesion to clay pellet surfaces and to reduce agglomeration during subsequent coating operations [4,5].

The compost powder was then inoculated with selected functional microorganisms, including *Bacillus* spp., *Azotobacter* spp., and *Azotobacter vinelandii*. These microbial groups were selected based on their complementary roles in nutrient solubilization, nitrogen fixation, and biological stabilization [7,11]. Inoculation was performed after compost maturation to minimize thermal and competitive stress on the introduced strains, and was followed by gentle mixing to ensure a homogeneous microbial distribution.

To preserve microbial viability and improve storage stability, the inoculated compost powder was subjected to low-temperature drying at temperatures below 40°C, thereby reducing residual moisture without compromising microbial activity [7,11]. The final product was packaged and stored under dry conditions, with moisture content maintained at or below 12%, to ensure consistency during subsequent coating onto corn cobs-modified clay pellets. The microbial compost powder was formulated as a functional coating material rather than a bulk soil amendment, optimized for adhesion, stability, and biological performance when integrated with engineered porous clay pellets. This formulation supports the combined materials–biological system evaluated in this study and aligns with the development of sustainable growing-media components [5,9,10].

3.2 Production of Corn Cob-Modified Fired Clay Pellets

In this study, pellet preparation was deliberately restricted to a single, pre-selected condition: 15 wt% (w/w) corn cob incorporated into the clay mixture and fired at 900°C to maintain a consistent carrier platform for coating and plant-growth experiments. The selected condition was based on prior screening in biomass-templated fired-clay systems, in which higher biomass loading generally promotes pore development after firing. In contrast, the 900°C firing level provides sufficient ceramic consolidation without excessive closure of accessible pores [8-10].

3.2.1 Preparation of Corn Cob Additive and Clay Feedstock

Corn cob residues were processed to obtain a uniform pore-forming additive. As illustrated in Fig. 1, the corn cob was first milled and then sieved to reduce particle-size variation and improve dispersion during mixing. Raw clay was prepared by sieving to remove coarse impurities and to provide a consistent feedstock for pellet forming.

Fig. 1 Preparation of the corn cob pore-forming additive for pellet fabrication: (a) raw corn cob residues, (b) milled corn cob particles, and (c) sieved corn cob fraction used for mixing with clay.

3.2.2 Mixing, Forming, Drying, and Firing

Processed clay and the prepared corn cob additive were dry-mixed until visually homogeneous. Water addition was controlled within 30–35% to support hand-forming while limiting cracking during drying. The plastic mass was shaped into granules with a target diameter of approximately 1.0–1.5 cm, which provided a practical compromise between shaping consistency and thermal stability.

After forming, the pellets were sun-dried for three days to reduce the likelihood of drying. The dried pellets were then fired at 900°C (with a holding period at the peak temperature) and allowed to cool naturally to room temperature before storage under dry conditions. The overall production workflow is shown in Fig. 2, highlighting the key steps of mixing, controlled water addition, and pellet forming before firing. The resulting pellets prepared under this single condition were used throughout the coating and plant-growth experiments reported in this study.

Fig. 2 Production steps of corn cob–modified fired clay pellets (15 wt% corn cob; 900°C): (a) dry mixing of sieved clay and prepared corn cob additive, (b)

controlled water addition to obtain a formable paste, and (c) pellet forming before drying and firing.

3.2.3 Physical Analysis

The physical and mechanical properties of the corn cob–modified fired clay pellets were evaluated through firing shrinkage, water absorption, apparent porosity, bulk density, and compressive strength, followed by [5] and [9]. All measurements were conducted in triplicate (n = 3) and reported as mean ± standard deviation.

Linear firing shrinkage was determined by measuring specimen length after drying (L_d) and after firing (L_f). The firing shrinkage (%) was calculated as:

$$\text{Firing shrinkage (\%)} = \frac{\mathrm{L_d - L_f}}{\mathrm{L_d}} \times 100 \quad (1)$$

Water absorption was determined from the oven-dry mass (D, g) and the saturated surface-dry mass (W, g). Water absorption (%) was calculated as:

$$\text{Water absorption (\%)} = \frac{\mathrm{W - D}}{\mathrm{D}} \times 100 \quad (2)$$

Apparent porosity represents the fraction of open pores relative to the total specimen volume and was calculated using an Archimedes-based approach. Here, D is the oven-dry mass (g), W is the saturated surface-dry mass (g), and S is the suspended mass in water (g). Apparent porosity (%) was computed as:

$$\text{Apparent porosity (\%)} = \frac{\mathrm{W - D}}{\mathrm{W - S}} \times 100 \quad (3)$$

Bulk density was calculated from the oven-dry mass (D, g) and the apparent volume represented by $W - S$ (cm^3), derived from Archimedes' displacement. Bulk density (g cm^{-3}) was calculated as:

$$\text{Bulk density } (\mathrm{gcm^{-3}}) = \frac{\mathrm{D}}{\mathrm{W - S}} \quad (4)$$

Compressive strength was evaluated using the maximum applied load at failure (P, N) divided by the loaded cross-sectional area (A, mm^2). Compressive strength (MPa) was calculated as:

$$\text{Compressive strength (MPa)} = \frac{\mathrm{P}}{\mathrm{A}} \quad (5)$$

where P is the applied load at failure (N), and A is the loading area (mm^2)

3.2.4 Scanning Electron Microscopy

The structure of the fired clay granules was determined and analyzed using a scanning electron microscope, Hitachi Tabletop SEM TM-3000 (Hitachi High Technology Corp., Tokyo, Japan). The entire surface of each sample was treated with ethanol to remove any grease, ensuring images of the highest quality could be obtained.

3.3 Plant Growth Trials

The plant growth trials were conducted to evaluate the agronomic efficacy of microbial-enriched compost powder in enhancing crop performance, improving soil quality, and increasing yield. The experimental design followed a structured protocol that incorporated RSM with BBD to optimize the proportions of three functional microbial groups in the compost formulation. Butterhead lettuce was selected for testing due to its rapid growth cycle and sensitivity to soil amendments. The range and levels of the independent variables for microbial supplementation in compost powder on the growth of Butterhead lettuce are shown in Table 2. The plant was harvested after 60 days, and the dry weight was analyzed.

Table 2 Levels, actual and coded experimental independent variables for a microbial-enriched compost powder on the growth of butterhead lettuce

Variables	Coding	Unit	Levels		
			-1	0	+1
Phosphate-solubilizing bacteria concentration	X_1	%w/w	0.1	0.4	0.7
Antagonistic bacteria concentration	X_2	%w/w	0.07	0.235	0.4
Nitrogen-fixing bacteria concentration	X_3	%w/w	1.3	2	2.7

3.4 Statistical Analysis

For statistical calculations, the test factors (χ_i) were coded as x_i according to the following transformation equation, Eq. (6)

$$x_i = (\chi_i - \chi_0)/\Delta\chi_i \quad (6)$$

where x_i: the coded value for the variable, χ_i is the actual value of the independent variables, χ_0 is the actual value of χ_i at the center point, and $\Delta\chi_i$ is the step change value.

The response variable was fitted to a quadratic polynomial model (Eq. (7)) to relate it to the independent variables. The general form of the predictive polynomial quadratic equation is as follows.

$$Y_i = \beta_0 + \Sigma\beta_i\chi_i \; \Sigma\beta_{ii}\chi_i^2 + \Sigma\beta_{ij}\chi_i\chi_j \quad (7)$$

where Y_i is the predicted response, χ_i is the parameters, β_0 is the constant, β_i is the linear coefficients, β_{ii} is the squared coefficients, and β_{ij} is the cross-product coefficient.

Data collected from the growth trials were subjected to statistical evaluation using Design-Expert® version 13 (Stat-Ease Inc., USA). The analysis employed ANOVA for a quadratic model to assess the significance of treatment effects ($p < 0.05$). Model fitness was verified using lack-of-fit tests, adjusted R^2, and predicted R^2 values. Key factors considered in the BBD included: χ_1 : Phosphate-solubilizing bacteria concentration (%), χ_2 : Antagonistic bacteria concentration (%), and χ_3 : Nitrogen-fixing bacteria concentration (%). Response optimization and visualization via contour and 3D surface plots provide insights into how the inputs influenced plant growth (Table 3).

The primary response variable was shoot dry weight, with leaf number and plant height as secondary indicators. Response surface plots were generated to visualize factor interactions and to determine the optimal microbial-enriched compost powder formulation. Tukey's HSD post hoc test was conducted to identify statistically significant differences between treatments. The application of RSM enabled the prediction of optimal microbial ratios, which were subsequently validated through experimental results to confirm model accuracy and agronomic relevance [6].

Table 3 Design matrix of the experiments along with the dry weight of butterhead lettuce.

Run	Variables (%w/w)			Response		±S.D.**
	χ_1	χ_2	χ_3	Dry weight* (g)		
				Observed mean	Predicted mean	
1	0.4	0.235	2	2.53	2.56	0.019
2	0.4	0.4	2.7	2.35	2.38	0.029
3	0.4	0.235	2	2.58	2.56	0.019
4	0.7	0.235	1.3	2.12	2.14	0.029
5	0.7	0.07	2	2.83	2.84	0.029
6	0.1	0.4	2	2.46	2.45	0.029
7	0.4	0.4	1.3	1.89	1.90	0.029
8	0.1	0.235	2.7	2.16	2.15	0.029
9	0.1	0.07	2	2.15	2.18	0.029
10	0.4	0.235	2	2.58	2.56	0.019
11	0.4	0.07	1.3	2.25	2.22	0.029
12	0.7	0.4	2	2.35	2.32	0.029
13	0.7	0.235	2.7	2.44	2.44	0.029
14	0.4	0.07	2.7	2.32	2.31	0.029
15	0.1	0.235	1.3	1.90	1.90	0.029

*Note: *60-day butterhead lettuce planting; **Standard Deviation*

3.5 Prototype feasibility assessment and quality verification.

The feasibility of the microbial compost powder as a product-ready formulation was assessed at a semi-pilot handling scale by verifying the practicality of unit operations (drying, milling/sieving, packaging, and storage) and by confirming key physicochemical and phytotoxicity-related indicators through external laboratory testing. A representative powder sample was submitted for analysis covering pH, moisture content, total N–P–K, C/N ratio, electrical conductivity, organic carbon/organic matter, sodium, germination index, and physical contaminants (plastic/glass, gravel), including sieve-size conformity. The analytical procedures followed the official methods specified by the Ministry of Agriculture and Cooperatives (B.E. 2559) and the Organic Fertilizer Analysis Manual (B.E. 2551).

4. RESULTS AND DISCUSSION

4.1 Physical and Engineering Characteristics of Corn Cob-Modified Fired Clay Pellets

Corn cob–modified fired clay pellets were fabricated by incorporating 15 wt% corn cob (w/w) into the clay mixture and firing at 900°C to obtain a porous ceramic carrier. The microstructure in Fig. 3 indicates the presence of intra-particle voids and a rough internal morphology, consistent with pore development driven by the thermal decomposition and burnout of the biomass additive during firing.

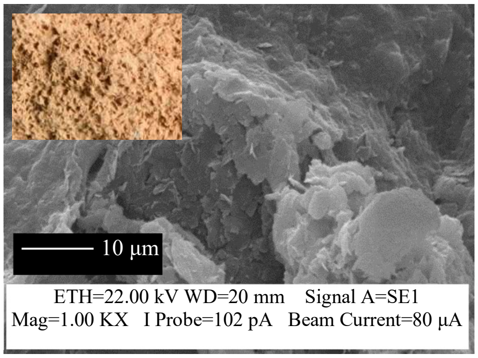

Fig. 3 Microstructure of corn cob–modified fired clay pellets (15 wt% corn cob, 900°C) showing intra-particle porosity and pore-wall morphology; insets show representative pellet appearance and porous surface texture.

This pore-forming mechanism suggests higher accessible pore volume and moisture uptake, while the sintered clay framework preserves structural integrity. Similar pore-forming behavior and the resulting balance between porosity, water absorption, and mechanical strength have also been reported on waste-modified fired clay materials, confirming the engineering relevance of biomass burnout as a pore-generation mechanism [8–10]. The physical and mechanical properties are summarized in Table 4 (mean ± S.D., n = 3). The pellets showed a firing shrinkage of 8.94 ± 0.28%, indicating that densification during firing was sufficient to consolidate the clay matrix without eliminating the pore space created by biomass burnout. This balance is reflected in the measured water absorption (12.77 ±1.61%) and apparent porosity (28.34 ±1.73%), indicating that a substantial fraction of the pore network remained open and accessible to water. The bulk density (1.54 ± 0.05 g cm^{-3}) confirms the lightweight character of the pellets associated with pore formation, which is advantageous for applications requiring reduced unit weight and improved air–water balance in granular carriers.

Despite the increased porosity, the pellets retained a compressive strength of 27.50 ±1.90 MPa, indicating that the sintered clay skeleton provided adequate mechanical resistance for handling and subsequent coating operations [5, 9, 10]. Accordingly, this pellet condition was selected as the fixed carrier platform for the subsequent microbial-coating formulation and RSM-based optimization.

Table 4 Physical and mechanical properties of corn cob–modified fired clay pellets obtained (mean ± S.D., n = 3).

Physical properties	Measured value	±S.D.
The firing shrinkage (%)	8.94	0.28
The water absorption (%)	12.77	1.61
The apparent porosity (%)	28.34	1.73
The bulk density (g cm^{-3})	1.54	0.05
The compressive strength (MPa)	27.50	1.90

4.2 Optimization of Microbial Consortium Composition using RSM

Following the engineering characterization of the porous fired-clay carrier, the microbial-enriched compost powder was statistically optimized to maximize plant-response performance within the same application framework. A BBD within RSM was used to evaluate the effects of three microbial inputs—phosphate-solubilizing microorganisms (χ_1), antagonistic microorganisms (χ_2), and nitrogen-fixing microorganisms (χ_3)—on butterhead lettuce shoot dry weight, using a quadratic polynomial model as the analytical basis [6] (Table 5) (Fig. 4). In this context, optimization represents performance tuning of the integrated carrier–bioactive coating system.

The ANOVA results (Table 5) confirmed that the quadratic model was highly significant, indicating that the model explained the systematic variability in the response across the investigated design space. The coefficient of determination was high ($R^2 = 0.9938$). The adjusted R^2 (0.9827) and predicted R^2 (0.9254) were also in good agreement.

Therefore, the model can be considered reliable for prediction within the studied ranges. The lack-of-fit was not significant ($p = 0.3989$), suggesting no evidence of unmodeled systematic error relative to the experimental noise captured by the replicated center points (pure error). Collectively, these diagnostics indicate that the high R^2 is not merely an artifact of overfitting but reflects strong model adequacy for the current experimental domain; however, extrapolation beyond the tested factor ranges should be avoided.

Table 5 Analysis of variance (ANOVA) for the model regression

Source	Sum of Squares	df	Mean Square	*F*-value	*P*-value	
Model	0.9293	9	0.1033	89.14	< 0.0001	Sig.
X_1	0.1431	1	0.1431	123.55	0.0001	
X_2	0.0313	1	0.0313	26.98	0.0035	
X_3	0.1540	1	0.1540	132.96	< 0.0001	
$X_1 X_2$	0.1560	1	0.1560	134.70	< 0.0001	
$X_1 X_3$	0.0009	1	0.0009	0.7770	0.4184	
$X_2 X_3$	0.0380	1	0.0380	32.83	0.0023	
X_1^2	0.0246	1	0.0246	21.26	0.0058	
X_2^2	0.0043	1	0.0043	3.72	0.1116	
X_3^2	0.3940	1	0.3940	340.15	< 0.0001	
Residual	0.0058	5	0.0012			
Lack of Fit	0.0041	3	0.0014	1.65	0.3989	not sig.
Pure Error	0.0017	2	0.0008			
Cor Total	0.9351	14				
R^2	0.9938					
Adjusted R^2	0.9827					

Regarding individual effects, χ_3 exhibited the strongest contribution, followed by χ_1, while χ_2 also remained significant. This ranking implies that nitrogen availability and phosphorus mobilization were dominant drivers of biomass accumulation in the tested system, consistent with reported plant–microbe functional roles [13]. Notably, interaction terms revealed synergistic behavior between χ_1 and χ_2 ($\chi_1\chi_2$) and between χ_2 and χ_3 ($\chi_2\chi_3$), whereas $\chi_1\chi_3$ was not significant. Such interaction patterns support the practical rationale for consortium-based formulations in which complementary functions and antagonism-mediated stabilization can enhance overall performance beyond additive effects [13].

The curvature of the response was primarily governed by the quadratic term of χ_3 (χ_3^2), indicating a pronounced non-linear dependence on nitrogen-fixer loading, while χ_1^2 was significant and χ_2^2 was not significant. The response surface and contour plots (Fig. 4) visualize these interaction–curvature features and highlight an operating region that maximized dry weight. The optimal microbial composition predicted by the quadratic model was $\chi_1 = 0.70\%$ (w/w), $\chi_2 = 0.235\%$ (w/w), and $\chi_3 = 2.70\%$ (w/w), yielding a predicted shoot dry weight of 2.84 g. Experimental validation produced 2.83 g, demonstrating close agreement and confirming the adequacy of the selected quadratic model for optimization within the investigated factor space.

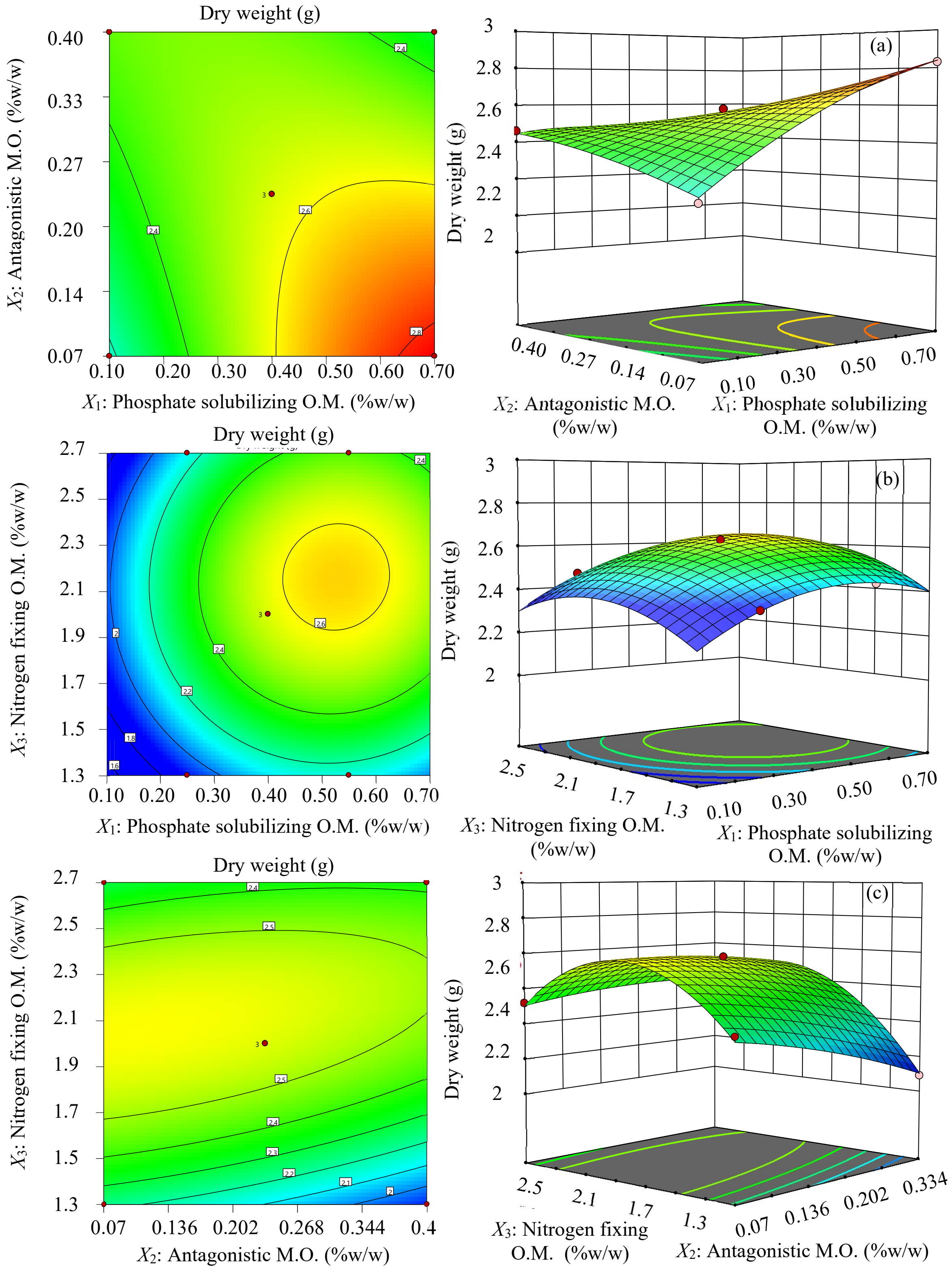

Fig. 4 Contour and 3D response surface plots showing the interactive effects of microbial inoculation levels on lettuce shoot dry weight. (a) X_1 (phosphate-solubilizing microorganisms) × X_2 (antagonistic microorganisms); (b) $X_1 \times X_3$ (nitrogen-fixing microorganisms); and (c) $X_2 \times X_3$. Variables are expressed as % (w/w).

4.3 Prototype Quality Characteristics of the Microbial Compost Powder

To support product feasibility beyond process-level description, the microbial compost powder prototype was externally characterized using standard fertilizer/organic fertilizer analytical procedures.

The reported parameters covered basic physicochemical properties, macronutrient contents, phytotoxicity-oriented screening, and physical contaminants. The results are summarized in Table 6.

Table 6 Quality indicators of the microbial compost prototype (mean ± S.D., n = 3).

Parameter	Unit	Mean (±SD)
pH	-	6.80 ± 0.20
Moisture Content (75°C, 20 h)	(%)	20.00 ± 0.18
Total Nitrogen	(%)	2.70 ± 0.30
Total Phosphorus	(%)	1.20 ± 0.02
Total Potassium	(%)	1.60 ± 0.04
C/N ratio	-	16/1 ± 0.41
Electrical Conductivity (EC)	(dS/m)	13.70 ± 0.03
Organic Carbon	(%)	45.10 ± 1.57
Organic Matter	(%)	49.20 ± 1.10
Sodium	(%)	0.54 ± 0.006
Germination Index	(%)	86.94 ± 1.16
Plastic/Glass	-	Not detected

The microbial compost prototype exhibited a near-neutral pH and a C/N ratio, indicating an organic matrix consistent with a stabilized compost-derived formulation suitable for handling as a finished product. The sample also showed relatively high organic carbon and organic matter, confirming that the formulation remained organic-rich. With respect to nutrient-bearing characteristics, the reported totals were 2.7% N, 1.2% P, and 1.6% K (Table 6).

The germination index in Table 6 provides an additional screening indicator suggesting limited phytotoxicity under the applied test conditions, supporting the suitability of the prototype for plant-associated applications when used at appropriate dosages within the engineered carrier system. Importantly, physical contaminants were not detected (plastic/glass: not detected; gravel: 0), and sieve-size conformity was reported as 100%, indicating effective feedstock sorting and post-processing control—practical quality attributes that become increasingly important during scale-up and batch-to-batch standardization.

4.4 Application Potential Feasibility and Application Potential

The proposed system combines a porous fired-clay carrier and a microbial-enriched compost powder to deliver functional microorganisms in a physically stable format. From an engineering perspective, the carrier platform provides the handling durability and moisture–air balance typically required for granular media, even though the microbial coating aims to enhance nutrient mobilization and biological suppression functions relevant to low-chemical cultivation [5,8-10]. In this study, the pellet condition selected as the fixed carrier (15 wt% biomass additive, fired at 900°C) exhibited an accessible pore network and maintained compressive resistance suitable for coating, storage, and field handling, which aligns with the principles of porous ceramic design using burnout pore-formers and residue valorization. Recent publications further demonstrate that fired clay products incorporating agricultural or polymeric wastes can achieve favorable porosity–strength relationships suitable for environmental and civil engineering applications, reinforcing the broader applicability of the proposed carrier system beyond agronomic use [8-10, 18]. The approach is also consistent with prior work demonstrating fired clay granules as viable microbial carriers under practical handling conditions [5,19-23].

Beyond conventional soil amendment use, the materials-oriented design of the porous pellets supports broader environmental and civil engineering relevance where granular porous media are required. Potential application contexts include engineered growing media components for green roofs, bioretention or infiltration layers, and reclamation substrates where lightweight granules, pore-mediated moisture storage, and mechanical robustness are desirable traits. In such settings, carrier stability and the ability to retain bioactive agents can be advantageous for sustaining performance under intermittent wetting–drying and transport stresses. Importantly, the system targets waste-to-resource conversion by using organic residues and biomass additives, thereby supporting circular-economy strategies in clay-based products and addressing the sustainability concerns associated with intensive chemical fertilizer use [1,2,15].

Feasibility at a product-handling level was supported by semi-pilot workflow verification, including drying, milling/sieving, packaging, and storage steps, together with external laboratory characterization of key physicochemical and phytotoxicity-related indicators.

The prototype powder showed a near-neutral pH and a stabilized compost-like C/N ratio, and the germination index provided an additional screening indicator suggesting limited phytotoxicity under the applied test conditions. Practical quality attributes relevant to scale-up were also demonstrated, including the absence of detected physical contaminants and conformity to the specified sieve-size fraction, which are essential for batch-to-batch standardization and user acceptance in real deployment. These handling and quality-control considerations are consistent with broader guidance on biofertilizer formulation and the need for regulated quality standards in microbial products [7,14].

Nevertheless, to strengthen the environmental engineering positioning, the next revision stage should explicitly address two aspects often scrutinized for field-deployable bio-carrier materials: (i) leaching-related risks from the carrier and coated system under relevant exposure conditions, and (ii) biosafety/identity clarity of the microbial groups used, including storage stability and viability retention as a function of time. These elements are repeatedly highlighted in the microbial biofertilizer literature as critical for translating laboratory efficacy into reliable field performance and regulatory readiness [16,17]. Accordingly, future work should incorporate standardized leaching evaluation and time-based viability checks on the coated pellets; until such data are available, the claims should be framed as application potential supported by materials performance and prototype quality indicators rather than as fully validated environmental-impact outcomes [1,2,10].

5. CONCLUSION

This study demonstrates an integrated approach to developing a waste-derived microbial compost powder combined with a porous fired-clay carrier engineered using biomass as a pore-forming additive. Incorporation of corn cob into the clay matrix and firing at 900°C produced pellets with a balanced combination of apparent porosity, water absorption, bulk density, and compressive strength, confirming their suitability as a mechanically stable carrier for bioactive coatings.

Statistical optimization of the microbial-enriched compost powder using Response Surface Methodology enabled systematic evaluation of the interactions among phosphate-solubilizing, antagonistic, and nitrogen-fixing microorganisms. The optimized formulation resulted in a validated plant-growth response, serving as functional evidence that the engineered carrier–coating system can effectively support biological activity without compromising structural integrity.

While the present work focuses on laboratory-scale characterization and validation, the findings highlight the potential of porous fired-clay pellets as multifunctional carriers that integrate materials engineering principles with biological functionality. Limitations related to long-term microbial viability, nutrient release kinetics, and environmental leaching behavior are acknowledged and warrant further investigation. Overall, the proposed system provides a materials-oriented framework for converting agricultural residues into functional growing-media components relevant to sustainable construction and environmental engineering contexts.

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