Improving Coral Sand Properties and Plant Growth Using GTM25 Substrate

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Abstract

Coral sand has considerable potential for agricultural utilization in coastal and island regions; however, its low organic matter content, poor nutrient retention, weak aggregation, and limited biological activity severely constrain plant growth. This study evaluated the effectiveness of GTM25 organic substrate in improving the physicochemical, microstructural, and biological properties of coral sand and its effects on mustard green (*Brassica juncea* L.) growth under greenhouse conditions. Coral sand was amended with GTM25 at five incorporation levels (0%, 5%, 10%, 15%, and 20% v/v) in a completely randomized design with three replications. GTM25 application progressively reduced soil pH from 8.12 to 7.02, while increasing organic matter from 0.48% to 4.55%, total nitrogen from 0.06% to 0.34%, and electrical conductivity from 141 to 3046 µS/cm. SEM observations revealed organic–mineral interactions characterized by surface coating and particle aggregation, and EDX analysis confirmed carbon enrichment together with the incorporation of P, K, Si, and S into the coral sand matrix. These structural and chemical modifications were accompanied by marked microbial proliferation: total bacterial abundance increased from 3.70 to 6.89 $\log_{10}$ CFU g^{-1}, with concurrent stimulation of nitrogen-fixing, cellulolytic, and phosphate-solubilizing bacteria. The improved substrate functionality translated into enhanced plant growth, with fresh biomass increasing from 15.22 to 71.83 g $plant^{-1}$ and dry biomass from 1.59 to 4.44 g $plant^{-1}$ ($p < 0.001$). Among the tested formulations, the 15% GTM25 incorporation level provided the most balanced improvement in fertility, microbial activity, and crop performance, provided the most balanced improvement in fertility, microbial activity, and crop performance among the incorporation rates evaluated, providing preliminary evidence for the agricultural rehabilitation of coral-derived sandy substrates.

Keywords

Brassica juncea; coastal and island agriculture; coral sand amendment; functional microbial groups; GTM25 substrate.

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Introduction

Coral sand, formed from the long-term weathering and biological accumulation of calcareous marine sediments, is widely distributed across tropical coastal and island regions (Xu & Zhuge, 2016). Under increasing pressure from land scarcity and food security challenges, coral-derived substrates have attracted growing attention as a potential resource for agricultural development in coastal and remote island areas (Chen *et al.*, 2026). However, their agricultural utilization remains severely constrained by inherently unfavorable physicochemical properties, including extremely low organic matter content, poor nutrient retention, excessive permeability, weak water-holding capacity, and unstable structure. Being predominantly composed of calcium carbonate particles with high porosity and irregular morphology, coral sand also exhibits strong alkalinity and limited biological activity, which collectively restrict plant establishment and long-term substrate fertility (Chen *et al.*, 2026; Xu & Zhuge, 2016). Recent ecological studies have further demonstrated that nutrient availability and microbial colonization are among the principal limiting factors for vegetation development on tropical coral islands (Shi *et al.*, 2025; Wang *et al.*, 2023).

To overcome these limitations, several amendment strategies have been investigated. Mineral-based approaches, particularly the incorporation of bentonite and other clay materials, have been shown to enhance cation exchange capacity, porosity, water retention, and nutrient-holding capacity of coral sandy substrates (Nguyen *et al.*, 2025). In parallel, biological approaches have gained increasing attention because of their sustainability and ability to simultaneously modify soil structure and microbial activity. For instance, exopolysaccharide-producing microorganisms such as *Bacillus velezensis* have been reported to enhance particle aggregation, improve water retention, and alleviate salt stress in coral sandy soils through the formation of stable particle associations (Le *et al.*, 2025).

Beyond mineral and microbial amendments, organic substrate incorporation has emerged as a particularly promising strategy for the rehabilitation of degraded sandy soils. Carbon-rich amendments such as compost, biochar, and bio-organic substrates can substantially improve soil aggregation, cation exchange capacity, water retention, and nutrient dynamics in coarse-textured soils (Agegnehu *et al.*, 2017; Blanco-Canqui, 2017; Burrell *et al.*, 2016). A recent systematic review further confirmed that biochar consistently improves nutrient cycling and crop productivity in sandy-textured soils (Bekchanova *et al.*, 2024), while long-term field experiments have shown sustained improvements in pH, porosity, and aggregate stability of sandy soils under organic amendment management (Aranyos, 2025). Importantly, organic amendments also stimulate microbial proliferation and shape soil microbial community structure, with notable effects on functional groups involved in nitrogen, carbon, and phosphorus cycling (Cong *et al.*, 2025; Tao *et al.*, 2024; Timofeeva *et al.*, 2023). The formation of organic–mineral associations within amended substrates has further been identified as a key mechanism underlying improvements in water retention, nutrient availability, and aggregate stability (Aranyos, 2025; Tao *et al.*, 2024).

Despite these advances, knowledge specifically addressing organic substrate-based rehabilitation of coral sand remains limited. Most previous studies have focused on mineral sandy soils or separately investigated mineral, organic, and microbial amendments, whereas the integrated effects of multifunctional organic substrates on the physicochemical, structural, biological, and agronomic properties of coral sand remain poorly understood. Unlike conventional compost or biochar, GTM25 combines organic matter, mineral nutrients, and beneficial microorganisms within a single amendment, potentially enabling the simultaneous improvement of nutrient availability, microbial activity, and organo–mineral interactions in coral sand. However, the effectiveness of such an integrated amendment for improving coral sand functionality and supporting crop growth has not been systematically evaluated. Therefore, this study aimed to provide a comprehensive assessment of GTM25 as a multifunctional amendment for the rehabilitation of coral-derived sandy substrates under coastal and island conditions.

To address these gaps, this study evaluated GTM25 - an organic substrate enriched with organic matter, mineral nutrients, and beneficial microbial inoculants - as an amendment for coral sand. We hypothesized that GTM25 would simultaneously improve the physicochemical, microstructural, and biological properties of coral sand by enhancing organic matter accumulation, modifying particle interactions, stimulating beneficial microbial groups, and improving nutrient availability, thereby promoting plant growth under coral sandy conditions. Mustard greens (*Brassica juncea* L.) were selected as the test crop because of their short growth cycle, well-documented sensitivity to substrate fertility and salinity, and importance as a leafy vegetable in coastal and island agriculture in Vietnam and across Southeast Asia. The specific objectives of this study were to: (i) evaluate the effects of GTM25 incorporation on the physicochemical properties of coral sand; (ii) investigate microstructural and elemental modifications using SEM and EDX analyses; (iii) assess changes in total and functional microbial abundance; and (iv) determine the effects of GTM25 on the growth and biomass production of mustard greens. The findings provide new evidence on the potential of

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integrated organic substrate amendments for improving the agricultural suitability of coral-derived sandy substrates under coastal and island conditions.

Material and methods

Material

GTM25 is an organic substrate developed by the Joint Vietnam–Russia Tropical Science and Technology Research Center (No. SH.Đ1.01/25). It is produced from composted sugarcane by-products supplemented with mineral nutrients, humic substances, and beneficial microorganisms, including nitrogen-fixing, cellulolytic, and phosphate-solubilizing bacteria. The main physicochemical and biological characteristics of GTM25 are presented in Table 1.

Table 1. Physicochemical and biological characteristics of the GTM25 substrate

No.	Analytical Parameter	Unit	Value
1	pH	–	7.25 ± 0.12
2	Moisture content	%	28.2 ± 1.6
3	Porosity	%	71.5 ± 2.1
4	Organic matter (OM)	%	37.70 ± 2.5
5	Total N	%	1.91 ± 0.09
6	Total P	%	1.12 ± 0.08
7	Total K	%	1.32 ± 0.11
8	Total bacteria	CFU/g	6.6×10^7
9	Nitrogen-fixing bacteria	CFU/g	2.1×10^6
10	Cellulolytic bacteria	CFU/g	3.4×10^7
11	Phosphate-solubilizing bacteria	CFU/g	2.8×10^6

GTM25 functions through multiple mechanisms, including improvement of structure, enhancement of water-holding capacity, nutrient supply, stimulation of beneficial microorganisms, and gradual improvement of biological activity in coral sand.

Coral sand used in this study was collected from a coastal area in Khanh Hoa Province, central Vietnam. Prior to use, the sand was air-dried, gently homogenized, and passed through a 2-mm sieve to remove debris and large fragments.

Mustard greens (Brassica juncea L.) were used as the test crop. Uniform seedlings with four to five fully expanded true leaves were selected.

Experimental Design

The experiment was conducted under greenhouse conditions at the Faculty of Agronomy, Vietnam National University of Agriculture. Environmental conditions during the experiment were as follows: temperature ranged from 28 to 35 °C, relative humidity from 50% to 70%, and light intensity exceeded 6000 lux.

A completely randomized design (CRD) with five treatments and three replications was applied. Each treatment consisted of three pots, with one pot considered an experimental replicate. Treatments consisted of coral sand amended with GTM25 at incorporation rates of 0% (Control), 5% (CT1), 10% (CT2), 15% (CT3), and 20% (CT4) (v/v).

Plastic pots were filled with equal volumes of substrate mixture to maintain uniform root-zone conditions across treatments. Mustard green seedlings were cultivated for 35 days under identical management conditions. Irrigation was applied manually twice daily to maintain consistent substrate moisture.

Analytical methods

Physicochemical analysis

pH was measured in a soil-water suspension (1: 5, w/v) using a calibrated pH meter.

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EC was assessed using a handheld EC meter (Hana 901, Taiwan), with each formula measured three times

Organic matter (OM) content was determined using the Walkley-Black dichromate oxidation method.

Total nitrogen (N) was analyzed using the Kjeldahl digestion method.

Microstructural and elemental characterization

Surface morphology and elemental composition of coral sand before and after GTM25 amendment were examined using Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray spectroscopy (EDX).

Surface microstructure of the samples was examined using a HITACHI S-4800 scanning electron microscope. Prior to analysis, the samples were oven-dried and coated with a thin platinum conductive layer to minimize surface charging and improve image quality. Elemental composition analysis was conducted using the Energy Dispersive X-ray (EDX) method on an MS-7001F device (Jeol, Tokyo, Japan).

Determination of microbial populations

Microbial populations were enumerated using the serial dilution and plate count method. Total bacteria were cultured on Plate Count Agar according to TCVN 11039-1:2015. Nitrogen-fixing, cellulolytic, and phosphate-solubilizing bacteria were enumerated on Ashby, Hans, and Pikovskaya media, respectively, according to TCVN 6166:2002, TCVN 6168:2002, and TCVN 6167:1996. Plates were incubated at 28-30 °C for 2-5 days, and microbial abundance was expressed as $\log_{10}$ CFU g^{-1} dry substrate.

Plant growth measurement

Plant growth parameters were recorded periodically during the experimental period.

Leaf number was determined weekly by counting fully developed leaves per plant. Measurements were conducted in triplicate, with plants randomly selected from each replicate.

SPAD Index: Leaf chlorophyll content was estimated using a SPAD-502 chlorophyll meter (Konica Minolta, Japan). Measurements were obtained from two fully expanded young leaves per plant using three plants per replicate, and average values were calculated.

Fresh and dry biomass: Fresh biomass was determined immediately after harvest (35 days after transplanting). Samples were subsequently oven-dried at 70 °C for 48 h to a constant weight to determine dry biomass.

Statistical analysis

All data were subjected to analysis of variance (ANOVA) to evaluate the effects of GTM25 incorporation rates. Treatment means were compared using Tukey's HSD test at a significance level of $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA).

Results

GTM25 incorporation induced significant physicochemical, microstructural, elemental, and biological changes in coral sand, which collectively contributed to enhanced plant growth and biomass production.

Effects of GTM25 substrate on physicochemical properties of coral sand

GTM25 application markedly modified the chemical properties of coral sand (Table 2). Substrate pH decreased progressively from 8.12 in the unamended control to 7.02 in CT4, indicating a clear shift from strongly alkaline toward near-neutral conditions. Concurrently, organic matter content increased nearly tenfold (from 0.48% to 4.55%), total nitrogen rose from 0.06% to 0.34%, and electrical conductivity increased from 141 to 3046 µS cm^{-1} as the amendment rate increased from 0% to 20%. The most pronounced changes were observed at CT3 and CT4, where organic matter, total nitrogen, and EC values were higher than in the control, indicating substantial improvement in the chemical fertility of the originally nutrient-poor coral substrate.

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Table 2. Physicochemical properties of coral sand as affected by GTM25 substrate

Treatment	pH	OM (%)	EC (µS/cm)	Total N (%)
Control	8.12 ± 0.09	0.48 ± 0.03	141.00 ± 17.10	0.06 ± 0.01
CT1	7.66 ± 0.08	1.23 ± 0.08	999.33 ± 56.23	0.10 ± 0.02
CT2	7.26 ± 0.08	2.21 ± 0.08	1665.0 ± 151.14	0.17 ± 0.03
CT3	7.15 ± 0.06	3.78 ± 0.09	2437.0 ± 152.40	0.26 ± 0.06
CT4	7.02 ± 0.07	4.55 ± 0.10	3046.0 ± 55.56	0.34 ± 0.05

Values are presented as mean ± standard deviation (n = 3).

Microstructural and elemental characteristics of coral sand under GTM25 treatment

SEM observations revealed pronounced changes in the surface morphology and microstructure of coral sand following GTM25 application (Figure 1). The untreated coral sand exhibited a loose and discontinuous structure characterized by large interparticle voids and weak particle association. After GTM25 incorporation, organic coatings and fine particulate materials progressively accumulated on the sand surface, resulting in increased particle connectivity and gradual modification of the pore structure.

At low amendment levels (CT1 and CT2), localized aggregation and partial pore filling were observed around the sand particles. More distinct structural modification occurred in CT3, where the organic phase appeared more uniformly distributed, forming a relatively interconnected porous network. In contrast, CT4 exhibited stronger aggregation and denser clustering of particles, with some regions showing reduced pore continuity.

EDX spectra further indicated progressive changes in elemental composition following GTM25 application. Compared with the untreated coral sand, amended treatments showed increased carbon-related signals together with the appearance and enrichment of nutrient-associated elements, while calcium-related peaks became less dominant at higher amendment levels.

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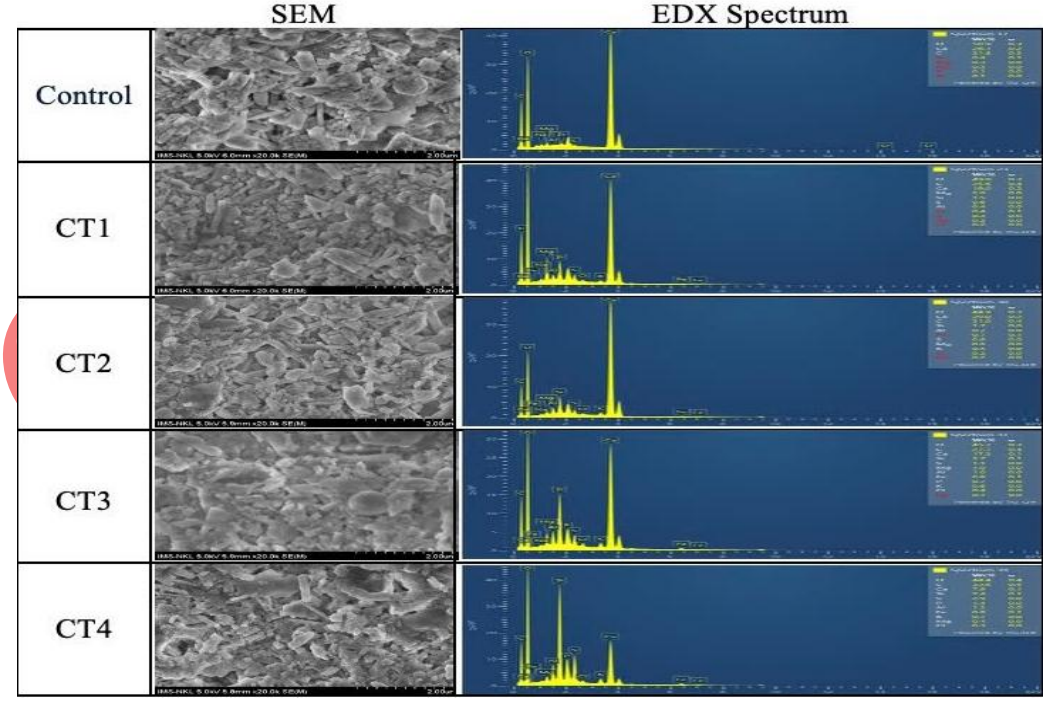

Figure 1. SEM micrographs and corresponding EDX spectra of coral sand under different GTM25 incorporation levels.

Microbial abundance in coral sand under GTM25 amendment

GTM25 application significantly increased microbial populations across all four functional groups examined (Figure 2). Total bacterial abundance rose from 3.70 $\log_{10}$ CFU g^{-1} in the control to 6.89 and 6.92 $\log_{10}$ CFU g^{-1} in CT3 and CT4, respectively, representing an increase of more than three orders of magnitude.

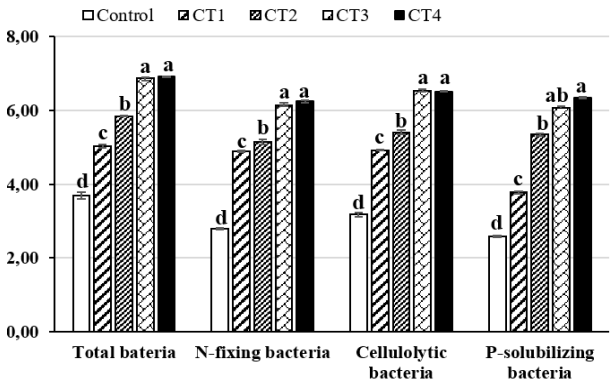

Figure 2. Abundance of Total bacteria, Nitrogen-fixing bacteria (N-fixing bacteria), Cellulolytic bacteria, and Phosphate-solubilizing bacteria (P-solubilizing bacteria) in coral sand under different GTM25 incorporation levels.

Similar trends were observed for the three functional groups: nitrogen-fixing bacteria increased from 2.79 to 6.24 $\log_{10}$ CFU g^{-1}, cellulolytic bacteria from 3.18 to 6.54 $\log_{10}$ CFU g^{-1}, and phosphate-solubilizing bacteria from 2.58 to 6.34 $\log_{10}$ CFU g^{-1} between the control and CT4. The most pronounced increases occurred between the control and CT3, while differences between CT3 and CT4 were minimal across all microbial groups, suggesting a saturation effect in microbial proliferation at higher GTM25 incorporation rates.

Effects of GTM25 amendment levels on plant growth and yield

Leaf development was enhanced by GTM25 incorporation throughout the cultivation period (Figure 3a). All GTM25-amended treatments showed greater leaf production from week 3 onward compared with the control. By week 5, leaf number per plant reached 17.0 in both CT3 and CT4, compared with 12.7 in the control - an increase of approximately 34%.

The SPAD index showed distinct temporal patterns among treatments (Figure 3b). In the unamended control, SPAD values declined progressively from 38.4 at week 1 to 31.2 at week 5, reflecting limited nutrient availability and gradual chlorophyll loss under coral sand conditions. In contrast, all GTM25-amended treatments maintained higher SPAD values throughout the cultivation period. CT3 consistently exhibited the highest SPAD index, peaking at 46.5 in week 3 and remaining elevated (40.1) at week 5. CT4 showed a similar early-stage increase but a more pronounced decline in later weeks, possibly reflecting nutrient or osmotic imbalance at the highest GTM25 incorporation level

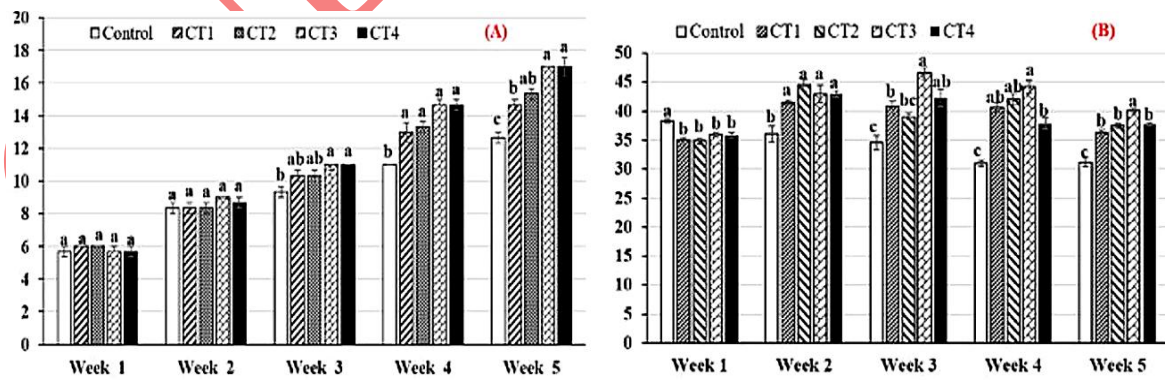

Figure 3. Effects of GTM25 incorporation levels on (A) leaf number and (B) SPAD index of mustard greens (*Brassica juncea* L.) during the 5-week cultivation period.

Values are presented as mean ± standard deviation (n = 3). Different letters indicate significant differences among treatments at $p < 0.05$.

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Fresh and dry biomass were significantly affected by GTM25 incorporation (Table 3; $p < 0.001$). Fresh weight increased progressively from 15.22 g plant^{-1} in the control to 35.02, 51.03, 68.28, and 71.83 g plant^{-1} in CT1, CT2, CT3, and CT4, respectively. Dry biomass followed a similar overall trend, increasing from 1.59 g plant^{-1} in the control to a maximum of 4.44 g plant^{-1} in CT3. Notably, although fresh weight was statistically similar in CT3 and CT4, dry biomass in CT4 (4.13 g plant^{-1}) was slightly lower than in CT3, indicating that increasing the organic input beyond 15% did not translate into greater dry matter accumulation. Visual comparison among treatments at harvest further confirmed the marked enhancement in plant size and canopy development with increasing GTM25 incorporation up to CT3 (Figure 4).

Table 3. Fresh and dry biomass of mustard greens as affected by GTM25 incorporation

	Fresh weight (g/plant)	Dry biomass (g/plant)
Control	15.22 ± 0.95**d**	1.59 ± 0.07**c**
CT1	35.02 ± 3.20**c**	3.00 ± 0.25**b**
CT2	51.03 ± 3.67**b**	3.63 ± 0.41**ab**
CT3	68.28 ± 2.80**a**	4.44 ± 0.23**a**
CT4	71.83 ± 0.47**a**	4.13 ± 0.15**a**
F-value	85.41	20.42
P-value	< 0.001	< 0.001

Values are presented as mean ± standard deviation (n = 3). Different letters within a column indicate significant differences at p < 0.05.

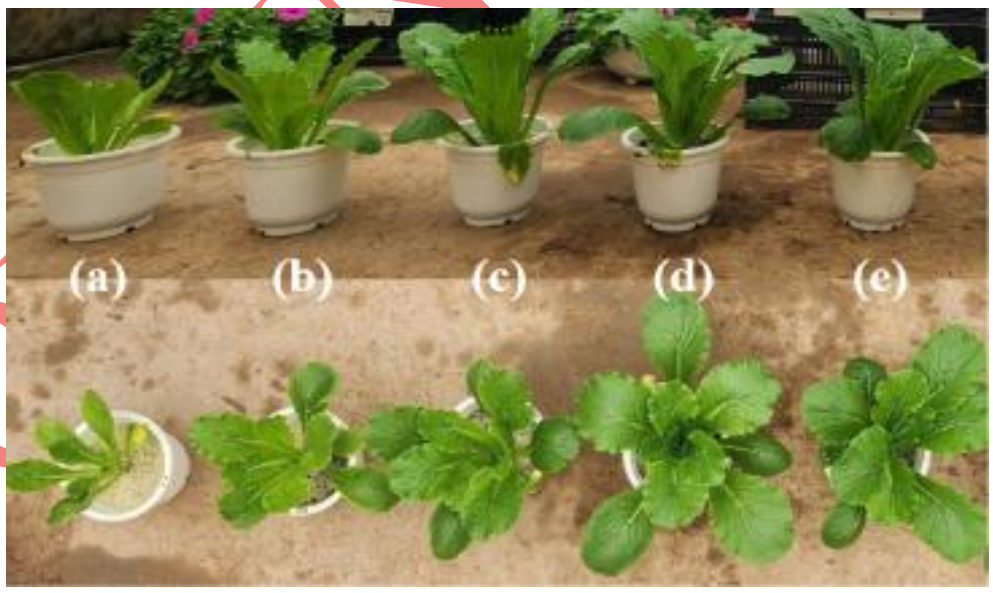

Figure 4. Visual comparison of mustard green (*Brassica juncea* L.) growth in coral sand amended with different GTM25 incorporation rates at harvest (35 days after transplanting): (a) Control, (b) CT1 (5% GTM25), (c) CT2 (10% GTM25), (d) CT3 (15% GTM25), and (e) CT4 (20% GTM25).

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Discussion

The present study demonstrates that GTM25 organic substrate effectively improved the physicochemical, microstructural, elemental, and biological properties of coral sand, leading to enhanced mustard green growth. The dose-response pattern indicated that 15% GTM25 incorporation provided the most balanced substrate functionality, whereas higher incorporation levels produced diminishing benefits in several growth and biological indicators.

The progressive reduction of substrate pH from 8.12 to 7.02 with increasing GTM25 incorporation reflects a typical response of carbonate-rich alkaline substrates to organic amendments. Organic matter decomposition releases low-molecular-weight organic acids and CO_2, which promote dissolution of carbonate minerals and gradually reduce alkalinity (Chen *et al.*, 2022). The marked increases in organic matter (0.48 - 4.55%) and total nitrogen (0.06 - 0.34%) indicate substantial enrichment of carbon and nutrient pools within the originally nutrient-poor coral sand and are consistent with previous reports on biochar- and compost-amended sandy soils (Aranyos, 2025; Blanco-Canqui, 2017). The simultaneous increase in EC from 141 to 3046 µS cm^{-1} reflects a greater concentration of soluble ions following GTM25 incorporation and is consistent with the increased organic matter and nutrient contents of the amended substrate. The increase in EC is likely associated with the release of soluble nutrients from the organic and mineral components of GTM25 during decomposition. Although higher EC may indicate improved nutrient availability in the short term, elevated EC has also been reported to influence plant physiological responses under certain growing conditions (Ding *et al.*, 2018). In the present study, the highest EC was observed in CT4. Although fresh and dry biomass did not differ significantly between CT3 and CT4, no further improvement in plant growth was observed at the highest incorporation rate. Because the experiment lasted only 35 days under greenhouse conditions, the long-term implications of increased EC on substrate quality and plant growth could not be evaluated. Future field studies are therefore needed to monitor EC dynamics under repeated GTM25 application and to assess their long-term effects on substrate quality and crop performance. The pH plateau observed in CT3 and CT4 is consistent with the residual carbonate buffering capacity of coral sand, which moderates further acidification despite increasing organic inputs (Oyebiyi *et al.*, 2026). This buffering effect likely maintained the substrate pH within a near-neutral range, creating favorable conditions for nutrient availability and microbial activity.

SEM observations revealed a progressive transition from a discontinuous sand matrix to a more coherent, aggregated surface structure with increasing GTM25 incorporation, consistent with previous studies on organic-amended coarse-textured soils (Burrell *et al.*, 2016; Tao *et al.*, 2024). The observed organic surface coatings suggest the formation of early-stage organo-mineral associations capable of improving substrate stability and nutrient retention. EDX analysis provided complementary surface-level information, showing a decrease in calcium content from 26.1% to 7.9% and a corresponding increase in carbon content from 21.8% to 32.6%. In addition, nutrient-associated elements such as K, P, Si, and S became more evident in the amended formulations. These changes support the interpretation that GTM25 progressively modified the carbonate-dominated surface through organic enrichment and partial mineral dissolution. Because EDX reflects localized surface composition, further bulk elemental analyses would be useful to confirm absolute changes in substrate chemistry. Such organo–mineral associations have been reported to enhance nutrient retention and organic matter stabilization in amended coarse-textured soils (Wang *et al.*, 2026). The denser clustering observed at CT4 may also have restricted pore continuity, partly explaining the reduction in dry biomass at this amendment level.

GTM25 incorporation substantially stimulated all four culturable microbial groups, with total bacterial abundance increasing from 3.70 to approximately 6.89 log_{10} CFU g^{-1}. Similar increases were observed for nitrogen-fixing, cellulolytic, and phosphate-solubilizing bacteria, indicating strong enhancement of microbial activity and nutrient transformation

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potential within the amended substrate (Bekchanova *et al.*, 2024; Cong *et al.*, 2025). Organic amendments are known to stimulate microbial proliferation by supplying carbon substrates and improving microsite conditions in sandy soils. The marked increase in phosphate-solubilizing bacteria is particularly important in carbonate-rich substrates, where phosphorus is commonly immobilized as Ca-phosphate complexes. Organic acids produced by microorganisms may reduce local pH and increase phosphate solubility, thereby improving nutrient availability (Timofeeva *et al.*, 2023). The relatively small microbial increase between CT3 and CT4 suggests a saturation effect at high amendment levels, where additional organic input no longer proportionally enhances microbial proliferation. The concurrent stimulation of nitrogen-fixing and cellulolytic bacteria further suggests that GTM25 promoted biological nitrogen input and organic matter turnover, thereby enhancing nutrient cycling within the amended substrate (Xiao *et al.*, 2025).

The convergence of physicochemical, structural, microbial, and plant growth responses indicates that 15% GTM25 provided the most favorable overall performance among the incorporation rates evaluated in this study, rather than representing a true optimum, because higher incorporation rates were not examined. Although the 20% treatment further increased organic matter, total nitrogen, and electrical conductivity, these changes were not accompanied by additional improvements in plant growth. Fresh biomass did not differ significantly between CT3 and CT4, whereas dry biomass was slightly lower and the SPAD index declined during the later growth stage in CT4. SEM observations also revealed a denser particle arrangement at the highest incorporation rate, while microbial abundance increased only marginally between CT3 and CT4. These findings suggest that additional GTM25 incorporation beyond 15% provided limited agronomic benefits under the conditions of this study. Increased EC and changes in substrate structure may have contributed to this response, although the underlying mechanisms cannot be confirmed because substrate physical properties, root characteristics, and plant physiological responses were not directly measured. Therefore, the 15% incorporation rate should be considered the best-performing treatment among those tested, and further studies under a wider range of incorporation rates and long-term field conditions are required before an optimal application rate can be established (Ding *et al.*, 2018).

The study evaluated GTM25 as an integrated amendment, and the individual contributions of organic matter, mineral nutrients, and microbial inoculants were not separated experimentally. In addition, microbial populations were assessed using culture-dependent plate counting methods targeting selected functional groups. Although these methods provided useful information on cultivable microorganisms associated with nutrient cycling, they did not characterize the overall microbial community structure or diversity. Future studies incorporating molecular approaches, such as high-throughput amplicon sequencing, would provide a more comprehensive understanding of microbial responses to GTM25 application. Furthermore, the experiment was conducted under greenhouse conditions using a single crop species and one coral sand source over a relatively short cultivation period (35 days). Therefore, further field-scale studies evaluating long-term substrate stability, water retention, and crop-specific responses under coastal and island environments are required. Nevertheless, the consistent improvements observed across physicochemical, structural, biological, and agronomic indicators provide preliminary evidence supporting the potential of GTM25 for the rehabilitation of coral-derived sandy substrates.

Conclusion

This study showed that GTM25 substantially improved the physicochemical, structural, elemental, and biological properties of coral-derived sandy substrates, resulting in enhanced mustard green growth under greenhouse conditions. GTM25 reduced substrate alkalinity, increased organic matter and nutrient contents, promoted organo–mineral associations, and

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stimulated beneficial microbial groups involved in nutrient cycling.

Among the tested incorporation rates, 15% GTM25 (v/v) provided the most favorable overall improvement in substrate quality, microbial activity, and plant performance under the conditions of this study. Higher incorporation rates did not result in further improvements in plant growth, suggesting that increasing the amendment rate beyond 15% provided limited additional benefits under the experimental conditions.

Overall, the findings provide preliminary evidence that GTM25 can improve the agricultural suitability of coral-derived sandy substrates under greenhouse conditions. Further studies under field conditions and across a wider range of crops are needed to validate the long-term effectiveness of this approach.

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Data Availability Statement: *The data supporting the findings of this study are available from the corresponding author upon reasonable request*

Statement on the use of Generative AI: *The authors declare that AI tools were used only for language editing/formatting, and not for generating scientific content. All data, analyses, and interpretations were performed and verified by the authors, who take full responsibility for the manuscript.*

Conflict of interest statement: *The authors declare that there are no conflicts of interest related to this article.*

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