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Bio-VegeGrout for soil strength enhancement: Effects of fermentation period on mechanical performance and microstructural characteristics

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A R T I C L E I N F O

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Bio-VegeGrout (BVG)
Vegetable fermentation
Soil stabilization
Sustainable grouting material

A B S T R A C T

This study investigates the potential of fermented Bio-VegeGrout (BVG) as a sustainable grouting agent made from vegetable waste for improving the strength of clayey silt soil, highlighting its value in waste management. The waste vegetables were fermented for different periods (7 to 35 days) to evaluate the influence of fermentation duration on soil strength and microbial succession. Unconfined compressive strength (UCS) testing, scanning electron microscopy (SEM), pH and conductivity measurements, and bacterial community analysis based on 16S rRNA gene sequencing were conducted. Soil treated with 30-day fermented BVG liquid achieved the highest UCS of 0.55 ± 0.05 MPa, compared to 0.24 ± 0.09 MPa at 7 days. The untreated soil could not withstand the test and failed immediately, highlighting the strengthening effect of BVG treatment of any fermentation duration. SEM observations revealed denser particle aggregation and reduced spaces between soil particles in samples treated with longer fermentation periods. High-throughput sequencing demonstrated clear shifts in bacterial community composition across fermentation periods and after soil treatment. The strength enhancement is likely associated with organic-assisted stabilization through fermentation-induced physicochemical interactions, and improved interparticle bonding within the soil matrix. These findings demonstrate that vegetable waste-derived BVG can provide a sustainable approach for soil strengthening and circular waste utilization.

1. Introduction

Soil serves as the primary supporting medium for infrastructure development and directly influences the safety, durability and service life of engineered structures. However, many natural soils exhibit low strength and high susceptibility to erosion, which limits their suitability for construction applications (Shinde et al., 2024). To address these limitations, soil stabilization techniques have been widely implemented to improve mechanical performance and durability. Historically practiced since ancient civilizations, modern soil stabilization encompasses physical, chemical or mechanical modification approaches aimed at enhancing strength, durability, and load-bearing capacity (Sim et al., 2024).

Conventional soil stabilization techniques commonly rely on cementitious binders or chemical additives. While effective, these approaches are often associated with high economic cost, significant carbon emissions, and environmental concerns. At the same time, large quantities of agricultural and food waste are generated globally,

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creating increasing challenges for sustainable waste management (Afolayan et al., 2019; Daud Nik Norsyahariati et al., 2016). Improper disposal of these residues may lead to environmental problems such as air and water pollution, greenhouse gas emission, and pressure on landfill systems. Consequently, increasing attention has been directed toward the reuse and valorization of agricultural and organic wastes as alternative materials in engineering applications (Pourakbar et al., 2015; Rama Subbarao et al., 2011).

The incorporation of waste-derived materials into soil stabilization has shown promising potential for improving soil engineering properties while reducing environmental impact. For instance, bagasse ash has been reported to significantly improve soil strength (43.58%) and bearing capacity (41.52%) when used as a partial stabilizing agent (Kharade et al., 2009). Among various organic waste streams, vegetable waste from markets, food processing, and households represents a significant but underutilized resource that could potentially be converted into value-added materials through biological processes such as fermentation (Aït-Kaddour et al., 2024).

More recently, bio-based soil improvement techniques have emerged as environmentally conscious alternative to conventional grouting systems (Gidebo et al., 2023; Jamaldar et al., 2025; Liu et al., 2024). Such biological approaches include the use of fermentation products to modify soil properties through biochemical transformations (Afolayan et al., 2019; Duong et al., 2021; Munirwan et al., 2021). Unlike conventional cementitious grouting, bio-derived stabilizers can influence soil behaviour through physicochemical interactions, organic binding effects, or microstructural rearrangement, offering a potentially lower-carbon pathway for ground improvement. Compared to standard geotechnical treatments, including microbial induced carbonate precipitation, BVG has several potential economic benefits, it valorises a waste product and offers potential economic benefits including reduced costs as there is no equipment of expertise required to maintain cultures of precipitating bacteria. Furthermore, there are no costs associated with the purchase of calcium or urea as it relies on waste vegetable material. Like microbially induced carbonate precipitation, BVG treatment can be applied by liquid injection and the costly soil mixing associated with other types of soil treatment, including waste fibre stabilization and lime-based treatment, are not required.

Previous studies have investigated the use of vegetable-derived grouting materials, referred to as Bio-VegeGrout (BVG), as sustainable soil strengthening agents. For example, fermented BVG liquid combined with polyethylene terephthalate (PET) waste improved slope stability in pylon foundations by increasing soil shear resistance by about 33% (Abdul Azam et al., 2024a). In peat soil, BVG enhanced unconfined compressive strength (UCS) by up to 449% after eight weeks of curing, with an optimum content reported at around 15% BVG to solid content (Abdul Azam et al., 2024b). Approximately 15% BVG content was confirmed as giving the maximum strength in another study using silty clay soil (Abdul Azam et al., 2024c). In marine deposit soils, increasing BVG content (10–50%) resulted in improved shear strength and reduced permeability, enhancing resistance to liquefaction (Baharuddin et al., 2013). In addition, studies on phyllite residual soil reported that a BVG content of 20% with an appropriate curing period provided optimal improvement in soil strength and permeability due to microbial activity (Omar et al., 2016). These findings indicate that BVG treatment, typically applied within a range of 10 to 25%, with optimal performance often observed between 15% and 20%, improves soil mechanical strength but does depend on soil type and conditions.

Based on these findings, a BVG liquid content of 20% was selected in this study to ensure adequate binder distribution and workable soil conditions. Previous studies applied BVG in combination with additional stabilizing materials or focused on a range of different soil types, but the effect of BVG liquid in clayey silt soil and in particular, the influence of fermentation period on soil strength development and microbial community changes remain unclear. Therefore, this study advances the work on BVG by testing its potential on clayey soils and optimising the fermentation period to maximise efficiency of the process. Emphasis is placed on understanding how fermentation period influences mechanical performance and soil microstructure. This study aims to evaluate the relationship between fermentation-controlled transformations and soil strength development. The findings of this study contribute to advancing sustainable soil stabilization strategies through agricultural waste valorisation and circular resource utilization.

2. Materials and methods

2.1. Soil sample

Raw soil sample was obtained from a location in Simpang Pulai, Perak (Fig. 1). The study area is located at 4.83953° N, 101.82142° E and is characterized by hilly terrain. Regional studies conducted in nearby areas indicate that elevations typically range between 500 m and 2000 m above sea level (Yusoff et al., 2016). The site consists of moderately steep slopes (40°–45°). Approximately 10 kg of soil was collected from the study area and used for UCS testing and sample characterization.

2.2. Preparation and characterization of BVG for soil stabilization

Vegetable waste was collected from Pasar Borong Selangor, Seri Kembangan, Selangor, Malaysia. Five vegetables, namely long bean, spinach, cucumber, water spinach and cabbage, were mixed at a fresh mass ratio of 2:2:2:2:1, following our previous study (Abdul Azam et al., 2024a). The vegetables were cut into smaller pieces, thoroughly mixed, and divided equally into six 2 L plastic containers (1.31 ± 0.08 kg per container). Mineral water was then added to half fill each container to 1 L, resulting in a total mass of 1.75 ± 0.04 kg per container, indicating an average of 440 mL water added. No microbial inoculum was added to the containers, fermentation relied on the microorganisms associated with the vegetables. The containers were tightly sealed and allowed to ferment under ambient laboratory conditions (20–22 °C) for 7, 14, 21, 28, 30 or 35 days. During fermentation, liquid was gradually produced from vegetable waste, with the volume increasing as the fermentation period progressed, as shown in Fig. 2. The fermented vegetable waste liquid obtained from this process is hereafter referred to as BVG liquid.

The BVG liquid obtained after 30 days of fermentation was selected for further analysis of its physical and chemical properties. BVG liquid exhibited a greenish-brown colour and low viscosity. Its pH and conductivity were measured using an ISOLAB analyser for all samples across the fermentation periods. Concentrations of heavy metals and other elements listed in Table 1 were determined using inductively coupled plasma mass spectrometry (ICP-MS). Additional physical and chemical properties of BVG liquid were analysed using the methods summarized in Table 1.

2.3. Preparation of soil modifications for stabilization enhancement

The soil collected from the study area was maintained under ambient laboratory conditions (20–22 °C) to allow gradual natural moisture loss prior to specimen preparation. The soil was gently crushed by hand to disaggregate soil clumps while avoiding significant alteration of the original particle size. For each fermentation period, BVG was added at 20% of the soil weight and thoroughly mixed to ensure homogeneity.

The sample preparation procedure was adapted from previous research on BVG-based soil stabilization (Abdul Azam et al., 2024a). The treated soil mixtures were placed into PVC pipes with an internal diameter of 40 mm and a height of 80 mm and lined with parchment paper to facilitate sample removal, as shown in Fig. 3. All samples were subjected to UCS testing in accordance with British Standard BS 1377 Part 7. The same mould dimensions, soil mass, BVG dosage (20% by soil weight), compaction procedure, and curing condition were maintained for all samples to minimize variability during UCS testing. Regardless of

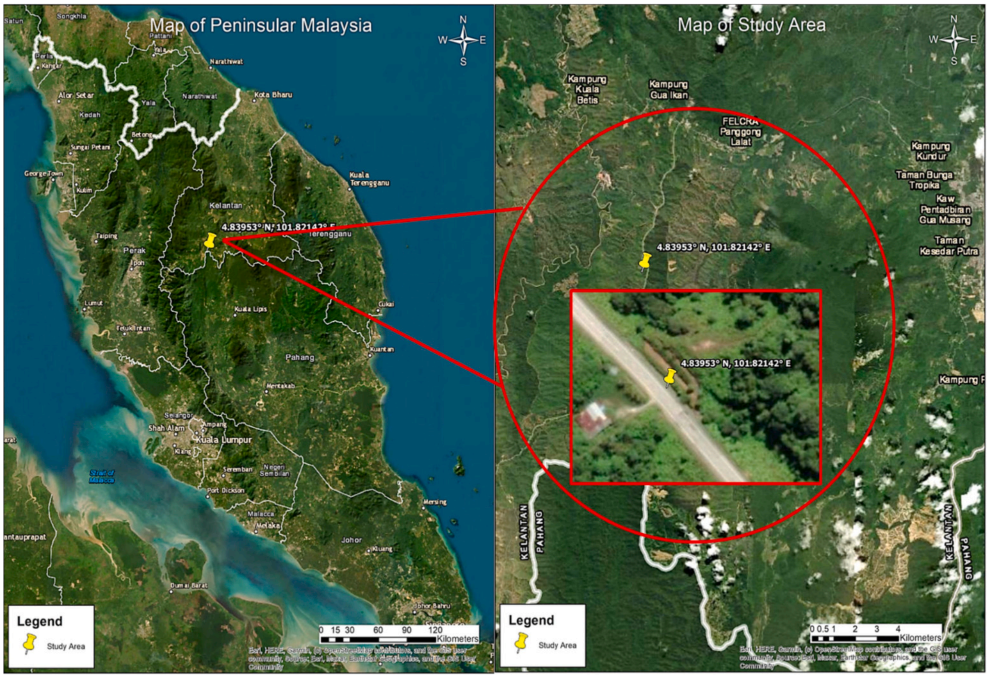

Fig. 1. Location of study area for soil sample preparation. The sampling site in Simpang Pulai, Perak (right) is show with its location within Malaysia (left). Base map imagery modified from Google Earth (©Google).

Fig. 2. Separation process of vegetable waste after fermentation period showing the fermentation vessel (left), the vegetable waste recovered after fermentation (centre) and liquids recovered from fermentations of 28 and 35 days.

Table 1
Method used to determine physical and chemical properties of BVG liquid after 30 days of fermentation.

Analysis	Unit	Method
Viscosity	Pa·s	Falling sphere viscometer
Elemental analysis	mg/L	ICP-MS
Heavy metal analysis	mg/L	ICP-MS
Total organic carbon	mg/L	APHA 5310 B
Total inorganic carbon	mg/L	APHA 5310 B
Ammoniacal nitrogen (NH_3–N)	mg/L	APHA 4500 – NH_3 B&F[a]
Total Kjeldahl nitrogen	mg/L	EPA 351.2 Kjeldahl's method

[a] Note: B&F refers to the borate buffer and phenate method.

the BVG fermentation period (7, 14, 21, 28, 30, and 35 days), all BVG-treated soil samples were cured for a constant period of 28 days under sheltered outdoor ambient conditions to facilitate natural drying prior to analysis.

A control soil was prepared following the same compaction and curing procedures and is herein referred to as SC (soil control). This control sample was solely used as a reference for UCS testing. The treated soil samples were designated as SF7, SF14, SF21, SF28, SF30, and SF35, corresponding to BVG fermentation periods of 7, 14, 21, 28, 30, and 35 days, respectively, where "SF" denotes soil treated with fermented BVG and the number indicates the fermentation period (days).

2.4. Soil characterization and analysis

Several parameters, including pH, electrical conductivity, and moisture content were measured for all BVG-treated soil samples, as well as for fresh raw soil (FRS) collected from the sampling area and SC sample. The FRS sample is the soil used directly without any curing process to characterize the natural soil properties, whereas SC sample was cured under the same conditions as treated samples and served as a control for UCS testing.

For pH and electrical conductivity measurements a 20 g sample was

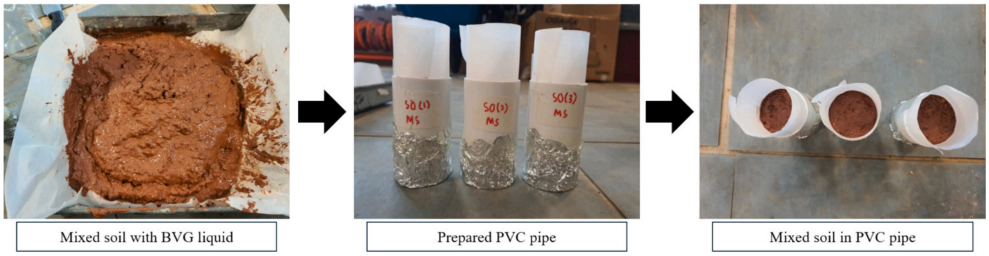

Fig. 3. The process of preparing mixed soils in PVC pipe. Soil was mixed with 20% (*v/w*) BVG (left). PVC pipes were prepared by lining with parchment paper (centre). Soil mixed with BVG was added to the prepared PVC pipes for curing (right).

thoroughly mixed with 20 mL of distilled water to form a homogeneous suspension, which was then left undisturbed for at least 8 h prior to measurement. All measurements were performed in triplicate.

The moisture content of soil samples was determined using approximately 10 g of soil, which was dried in an oven at 105 °C for 24 h. The moisture content was then calculated using Eq. (1).

$$\text{Moisture content } (\%) = \frac{W_i - W_f}{W_i} \times 100\% \qquad (1)$$

where, W_i is initial weight of the sample before drying and W_f is final weight of the sample after drying.

For soil strength analysis, UCS testing was performed using a compression testing machine (Zheijiang Tugong Instrument Co., Ltd) on the BVG-treated soil samples after a curing period of 28 days (Fig. 4). However, SC sample could not be tested, as it failed before any load could be applied, indicating zero cohesion or compressive strength (Fig. 5). The optimum fermentation period was identified based on the highest compressive strength achieved. The UCS test was conducted in accordance with BS 1377:1990, where axial load was applied at a constant rate and measured using integrated dial gauges (proving ring and deformation dials) with a resolution of 0.01 mm until specimen failure.

The soil used in the present study was classified as clayey silt based on its particle size distribution. Particle size distribution analysis was performed according to ASTM D7928 and Atterberg limit, ASTM 4318, showing that the soil consisted of 89.9% silt and 10.1% clay, with no sand or gravel fractions present.

Fig. 5. Sample SC after curing for 28 days before conducting the UCS test. This sample was not treated with BVG liquid and was used as a control.

Each UCS test was performed using three replicate samples for each

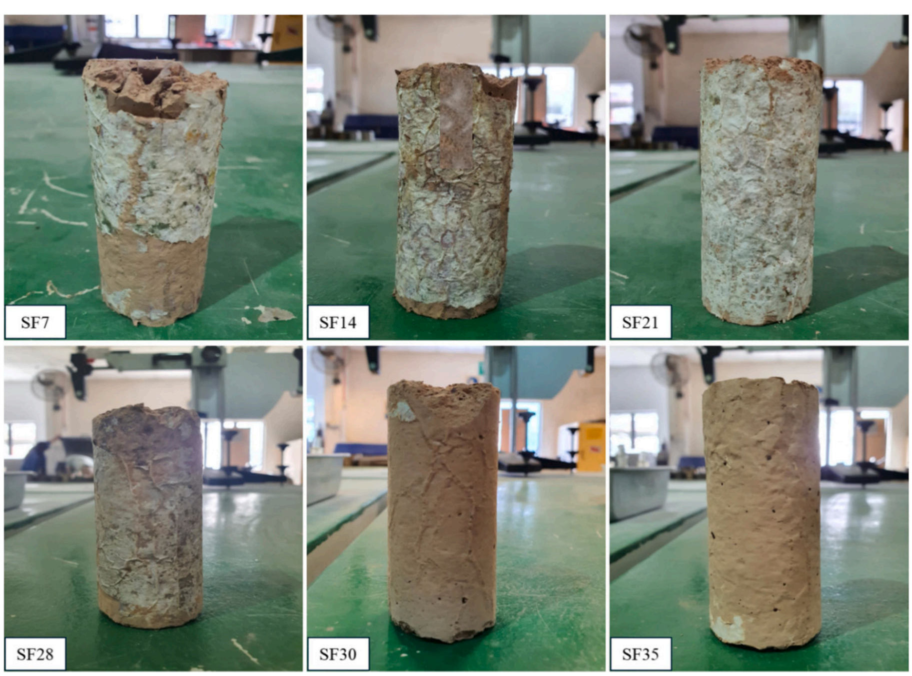

Fig. 4. Samples after curing with BVG of different fermentation periods ranging from 7 (SF7) to 35 days (SF35).

fermentation period. The UCS values were reported as the mean value with standard deviation. Statistical analysis was conducted using Microsoft Excel to evaluate the significance of differences among the fermentation periods. A one-way analysis of variance (ANOVA) was performed to determine whether significant differences existed among the groups (SF7, SF14, SF21, SF28, SF30, and SF35). A two-sample *t*-test was subsequently conducted to compare the statistical difference between SF7 and SF30. A significance level of $p < 0.05$ was used for all statistical analyses.

The morphology of the soil samples was examined using SEM imaging at various magnifications under an accelerating voltage of 10–15 kV. Elemental composition was analysed using energy dispersive X-ray spectroscopy (EDX) equipped with an Oxford X-Max detector. The EDX analysis was performed at an accelerating voltage of 10–15 kV, under standard high-vacuum conditions, to identify elemental composition and changes in soils treated with BVG across different fermentation periods. Fourier Transform Infrared (FT-IR) spectroscopy was performed on selected samples (FRS, SF14 and SF30) to identify the functional groups present in the soil system.

For chemical and microstructural characterization, FRS was used as the baseline reference to represent the natural state of the collected soil. The BVG-treated soil samples were then compared with FRS to evaluate treatment-induced changes in functional groups and soil morphology.

2.5. DNA extraction and sequencing analysis

DNA extraction from selected BVG liquid and treated soil samples was performed using the DNeasy® PowerLyzer® PowerSoil® Kit according to the manufacturer's instructions. For BVG liquid samples, 2 mL of BVG liquid was transferred into a 2 mL Eppendorf tube and centrifuged at 10,000 ×*g* for 2 min. The supernatant was removed and another 2 mL added. This was repeated multiple times until a clearly visible pellet was formed at the bottom of the tube. The resulting pellet was then used for DNA extraction. The BVG liquid DNA samples are referred to as VF7, VF14, VF21, VF28, VF30, and VF35, corresponding to fermentation periods of 7, 14, 21, 28, 30, and 35 days, respectively, where “VF” denotes fermented BVG liquid samples. For soil samples, 0.25 g soil was used directly for DNA extraction. The extracted DNA was stored at −20 °C to −80 °C prior to analysis.

16S rRNA gene sequencing was performed using an Oxford Nanopore Technologies platform. All reagents and software were supplied by Oxford Nanopore Technologies unless otherwise stated. Sequencing was carried out on Flongle flow cells using universal bacterial primers 27F and 1492R and a 16S Barcoding Kit (SQK-16S114.24). DNA libraries were prepared following the manufacturer's protocol with minor modifications, including triplicate PCR amplification, pooled prior to sequencing (total volume of 30 μL) and using 35–40 PCR amplification cycles. The iProof™ High-Fidelity Master Mix (Bio-Rad, CA, USA) was used for PCR amplification. Prepared DNA libraries were loaded directly onto Flongle flow cells for sequencing with MinION Mk1C using MinKNOW v24.11.8. Sequence data was analysed using Epi2Me Labs software using wf-16 s v1.4.0, all parameters were set to default except coverage was changed to 50% and identity was changed to 87% for family level identification (Yarza et al., 2014).

3. Results and discussion

3.1. Analysis of vegetables waste liquid

The BVG liquid exhibited a gradual colour change from light green to greenish-brown over the fermentation periods, as shown in Fig. 6. During fermentation, the breakdown of plant tissues and the diffusion of soluble low molecular-weight compounds, such as sugars and minerals, into the surrounding liquid can occur as a result of microbial activity (Montet et al., 2014). This mass transfer may alter the internal structure and chemical composition of the vegetables and the resulting fermentation liquid. In addition, the production of organic acids during fermentation leads to a decrease in pH, which may contribute to pigment degradation or transformation, particularly for pH-sensitive compounds such as chlorophylls (Janiszewska-Turak et al., 2022).

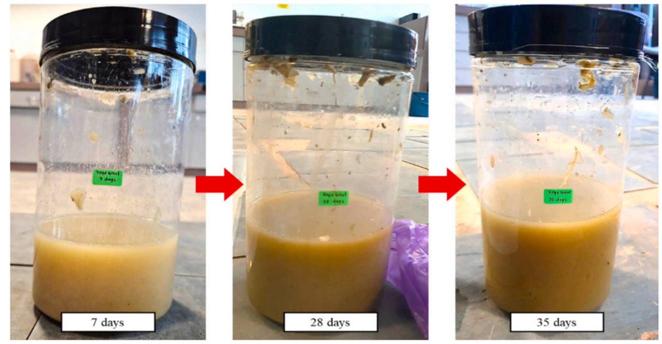

Fig. 6. Colour changes observed in the BVG as fermentation period increases from 7 days to 35 days.

The pH and electrical conductivity of the BVG were measured at the end of each fermentation period (Fig. 7). Conductivity increased with fermentation period, up to 30 days. The pH varied between pH 3.72 and 4.66 throughout the fermentation period, indicating the BVG remained under acidic conditions during fermentation. Such pH variation is expected because fermentation is a dynamic process in which microbial activity and the degradation of organic matter continuously modify the chemical environment through the production and consumption of organic acids (Nakasaki et al., 2019; Zheng et al., 2025). Therefore, the observed pH range reflects the progression of fermentation rather than a constant chemical condition. This acidic pH range is also consistent with vegetable-based lactic acid fermentations, such as kimchi, where acid tolerant fermentative microorganisms, including *Lactobacillus* species (belonging to the family Lactobacillaceae), are often predominant (Rhee et al., 2011; Wieczorek and Drabińska, 2022). In such systems, these microorganisms contribute to maintaining a stable fermentation environment (Bühlmann et al., 2022). Dominance of the bacterial family Lactobacillaceae was observed in this study on day 7, with a change to Enterobacteriaceae becoming the dominant family on day 28 and 30 in the BVG liquid. This microbial succession further supports that the variation in pH reflects the dynamic microbial processes occurring during BVG liquid fermentation. See Fig. 13 and Section 3.4 for further discussion of changes in the bacterial community.

The increase in electrical conductivity with fermentation period indicates the release of soluble ions and metabolites resulting from organic matter degradation. These soluble components, together with

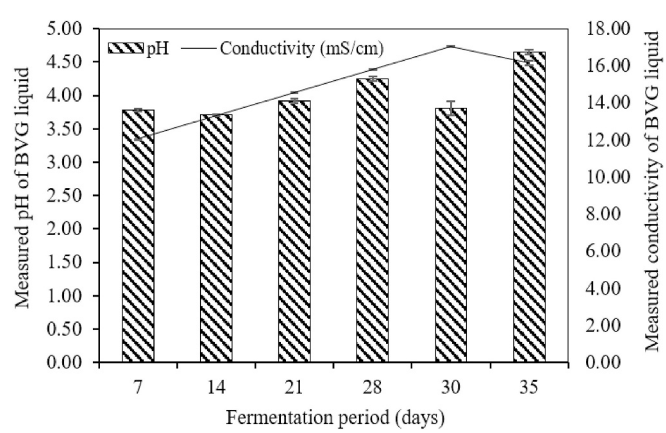

Fig. 7. pH and conductivity of BVG liquid across different fermentation periods. Error bars represent the standard deviation of triplicate measurements (n = 3).

fermentation-derived organic compounds, may influence interactions between organic constituents and soil particles when BVG is applied as a soil stabilizing agent. Song et al. (2026) has reported that organic matter amendments can modify soil surface electrochemical properties through changes in organic carbon fractions, particularly, alkyl C and O-alkyl C, which influence particle interactions and aggregation behaviour. Therefore, the changes in pH and electrical conductivity observed during BVG fermentation may indicate the transformation of organic constituents that contribute to organic-assisted stabilization. The changes in FT-IR bands observed for BVG-treated soils in Fig. 11 further provide indirect evidence of variations in organic functional groups associated with soil-organic interactions. Nevertheless, further detailed quantitative analysis of BVG-derived organic constituents and their interactions with soil particles is required in future studies.

The BVG liquid exhibited a moderate viscosity of 0.7037 Pa·s, which is sufficiently low to facilitate rapid transport through the soil pores. The liquid appeared cloudy, indicating the presence of fine suspended particles and dissolved organic compounds. Such characteristics are commonly observed in fermented vegetable liquids, where soluble metabolites coexist with colloidal and particulate organic matter that remains stably dispersed in the aqueous phase (Christodoulou et al., 2021). The viscosity of the BVG remained relatively stable throughout the fermentation period, suggesting flow behaviour of BVG would be similar regardless of fermentation period. Chemical analysis showed a high total organic carbon concentration of 13,800 mg/L and a low total inorganic carbon content of 10.4 mg/L, indicating that the liquid was dominated by organic constituents derived from vegetables fermentation. Comparable TOC levels (5000 to over 20,000 mg/L) have been reported for organic-rich liquids generated from vegetables residues or compost leachates (Mago et al., 2022; Mohammad et al., 2022). The presence of nitrogenous compounds, including ammoniacal nitrogen (NH_3–N), as shown in Table 2, is consistent with microbial degradation of organic matter under ambient fermentation conditions.

Overall, the BVG liquid exhibited acidic conditions and a nutrient-rich composition typical of food waste derived liquid amendments. It contained high concentrations of macronutrients such as potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), along with trace amounts of micronutrients like copper (Cu) and strontium (Sr), as summarized in the supplementary information (Table S1). These liquids are commonly described as nutrient sources and soil conditioners that influence porosity, water retention, surface interactions, pH balance, and cation exchange capacity (El Barnossi et al., 2021; Lu and Xu, 2021). More recently, it has been suggested that food waste derived amendments may contribute to soil remediation by modifying soil physicochemical conditions, facilitating ionic exchange, and reducing contaminant mobility and bioavailability (Palansooriya et al., 2023).

3.2. Characteristics of fermented soil across different fermentation periods

The pH, conductivity, and moisture content of FRS sample were measured at 5.65, 17.35 mS/cm, and 20.27%, respectively. After 28 days of curing without BVG addition, SC showed a marked decrease in moisture content to 1.66%, while only minor changes in pH and conductivity were observed (Fig. 8). These small differences between FRS and SC reflect the effects of natural curing and moisture loss, without involvement of bio-cementation.

The pH of soils treated with BVG liquid increase with increasing fermentation period. Although the BVG liquid itself is acidic, its interaction with soil results in pH elevation during curing. This increase could result from multiple concurrent processes, including the neutralization and deprotonation of acidic functional groups by soil mineral surfaces, as well as microbial metabolic activity within the treated soil matrix. While BVG liquid introduces organic acids and acidic functional groups, the soil may provide buffering capacity through mineral dissolution and ion exchange reactions, which can locally increase pH during curing. Similar pH evolution in bio-amended soils has been reported in previous studies involving organic waste-soil interactions (Fan et al., 2020; Wu et al., 2020).

Moisture content of the cured soils is presented in Fig. 8. Compared with SC (1.66%), BVG-treated soils retained slightly higher residual moisture contents, ranging from 2.38% to 6.62% after 28 days of curing. However, no monotonic relationship between moisture content and fermentation period was observed. The variations in moisture content among BVG-treated samples are therefore attributed primarily to sample heterogeneity and experimental variability rather than a systematic effect of fermentation duration or bio-cementation processes.

3.3. Effect of BVG liquid on soil strength

The UCS results of the treated soils are presented in Fig. 9. Based on the measurements, the soil treated with BVG fermented for 30 days (SF30) exhibited the highest compressive strength. This result indicates that 30 days represents the optimum fermentation period under the experimental conditions of this study. The SC sample did not sustain the UCS test and failed during loading. Therefore, no measurable UCS value could be obtained for this sample. This behaviour indicates that the untreated soil possessed very low inherent compressive strength under present testing condition. Incorporation of BVG liquid led to a clear improvement in soil strength, with UCS values increasing from 0.24 ± 0.09 MPa for SF7 to a maximum of 0.55 ± 0.05 MPa at 30 days of fermentation, followed by a reduction to 0.25 ± 0.10 MPa at 35 days. The decline in UCS beyond 30 days suggests that prolonged fermentation period may alter the effectiveness of BVG in promoting soil strengthening under the present conditions.

The UCS values of BVG-treated soil exhibited significant variation with fermentation period. Statistical analysis using one-way ANOVA confirmed significant differences among the fermentation periods ($F = 12.93$, $p = 0.0002 < 0.05$) as shown in Table 3. This indicates that fermentation duration significantly influenced the soil strength

Table 2
Physical and chemical properties of BVG liquid after 30 days of fermentation (VF30).

Analysis	Unit	Result
Viscosity (Pa·S)	Pa·s	0.7037
Total organic carbon (TOC)	mg/L	13,800
Total inorganic carbon (TIC)	mg/L	10.4
Ammoniacal nitrogen[a] (NH_3–N)	mg N/L	15.4
Total Kjeldahl nitrogen[a]	mg N/L	1910

[a] Note: Ammoniacal nitrogen refers to the total amount of ammonia (NH_3) plus ammonium ions (NH_4^+) reported in mg/L NH_3-N. Total Kjeldahl Nitrogen refers to the total amount of ammoniacal nitrogen plus total organic nitrogen.

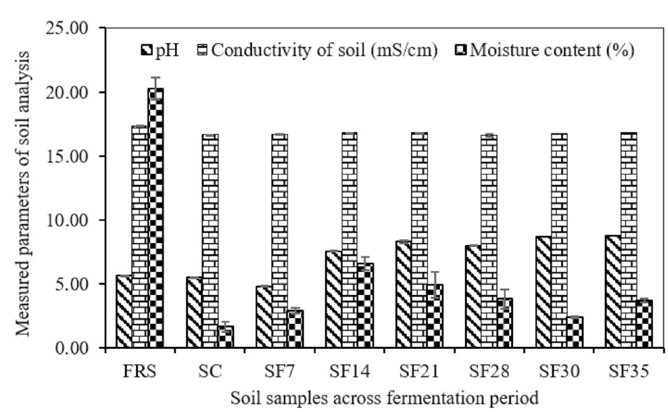

Fig. 8. Variation in pH, electrical conductivity, and moisture content of FRS, SC and BVG-treated soils obtained from different fermentation periods. Error bars represent the standard deviation of triplicate measurements ($n = 3$).

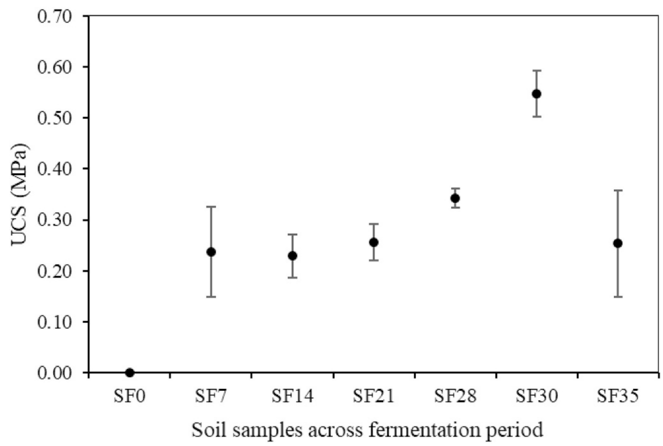

Fig. 9. Effect of fermentation period on soil strength. Error bars represent the standard deviation of triplicate measurements (n = 3).

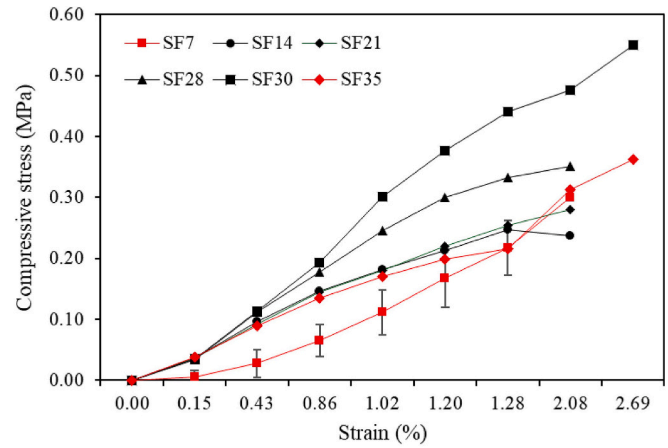

Fig. 10. Stress–strain curves of BVG-treated soil samples obtained from UCS testing. Error bars represent the standard deviation of triplicate measurements (n = 3).

Table 3
Statistical analysis of UCS results.

Analysis	Comparison	Statistical value	p-value
One-way ANOVA	SF7–SF35	F = 12.93	0.0002
t-Test	SF7–SF30	t = −6.782	0.0025

development. A further comparison between the BVG-treated soil for the initial fermentation period (SF7) and the optimum fermentation period (SF30) was performed using a two-sample *t*-test. The analysis showed a statistically significant difference between SF7 and SF30 ($t = -6.782$, $p = 0.0025 < 0.05$), confirming that the increase in fermentation period from 7 to 30 days resulted in a significant improvement in UCS.

The observed optimum performance at 30 days may be attributed to the fact that fermentation is a dynamic process involving the transformation of organic materials and therefore the chemical composition and functional properties of fermented products change over time (Maomao et al., 2023). As discussed previously additional studies investigating the composition of the BVG over time would be needed to identify which characteristics of the BVG at day 30 made this the most effective fermentation period. Prolonged fermentation may further alter the composition or effectiveness of these constituents, resulting in reduced stabilization performance, as reflected by the lower UCS and partial reduction in particle contact observed for SF35.

The stress-strain behaviour of BVG-treated soil samples obtained from UCS testing further illustrates differences in mechanical response. The results show that strain increased progressively until the soil samples reached their peak stress and subsequently failed. As shown in Fig. 10, the SF30 sample sustained the highest compressive stress of approximately 0.55 MPa at a strain of 2.69%, demonstrating enhanced load-bearing capacity and resistance to failure. In contrast, although SF35 endured a comparable loading duration, it exhibited a markedly lower peak stress. This behaviour indicates reduced load transfer efficiency at extended fermentation periods, which is consistent with the observed decline in UCS. Similar behaviour has been reported in soil improvement studies, where increased additive content leads to higher failure strain but not necessarily higher peak compressive strength, indicating a trade-off between strength and deformation characteristics (Chen et al., 2021).

Conventional stabilizers, such as lime, have been widely used for improving the strength of fine-grained soils through cation exchange, flocculation-agglomeration, and pozzolanic reactions. Islam et al. (2019) reported that lime treatment improved the UCS of fine-grained soil, with values ranging from approximately 0.29 to 0.36 MPa depending on the lime content and curing period. Although direct comparison is difficult due to differences in soil characteristics, stabilizer dosage, curing conditions and testing procedures, the UCS values achieved in the present study (0.24–0.55 MPa for BVG-treated soils) are similar to those reported for lime-stabilized soils. This indicates the potential of BVG as a bio-based stabilizer for improving soil strength. However, further comparative studies under identical conditions are required to evaluate the relative performance of BVG and conventional stabilizers.

In our previous study, BVG-treated sandy silt soil with 20% BVG liquid and 10 days of curing reached a maximum compressive stress of 0.06 MPa at a strain of approximately 1.7% (Omar et al., 2018), which is significantly lower than the strength achieved in the present study. This difference may be attributed to variations in soil type, fermentation duration, and BVG maturity, which influence the extent of biocementation and bonding within the soil matrix.

Overall, the strength enhancement observed in BVG-treated soils appears to be associated with changes in soil aggregation and packing characteristics, as supported by FT-IR and SEM–EDX analyses. The optimum performance at 30 days suggest that fermentation period plays a critical role in influencing the physicochemical characteristics of the soil-BVG system.

The characteristic functional groups of the BVG-treated soil were analysed using FT-IR spectroscopy (Fig. 11). Compared to FRS, the treated samples exhibited noticeable variations in band intensity, particularly in the O—H and C—O regions, while no new absorption bands were observed. This result indicates that BVG treatment did not introduce new detectable functional groups but influenced the relative abundance of existing ones within the soil matrix.

Bands observed at 3690.06 cm^{-1} and 3617.38 cm^{-1} are attributed to O—H stretching vibrations associated with adsorbed water molecules in soil (Khalid et al., 2023). The broad band around 3349.01 cm^{-1} corresponds to O—H stretching vibration with possible overlapping N—H stretching modes (Islam et al., 2024; Sharma et al., 2021), which may be associated with moisture content and/or organic functional groups within the treated soil system. The band at 1647.48 cm^{-1} may be associated with aromatic C═C skeleton vibration and C═O stretching of amide groups (Cao et al., 2023; Sharma et al., 2021; Xiaoli et al., 2013). Peaks at 999.86 cm^{-1} and 910.40 cm^{-1} correspond to C—O stretching vibrations of ether and alcohol groups (Mythili et al., 2018). Variations in intensity of these bands across fermentation periods suggest differences in the relative contribution of BVG-derived organic components within the soil matrix and could also reflect the transformation or partial degradation of these compounds during the treatment process. These FT-IR results indicate that BVG treatment affects the distribution and relative abundance of oxygen- and nitrogen-containing functional

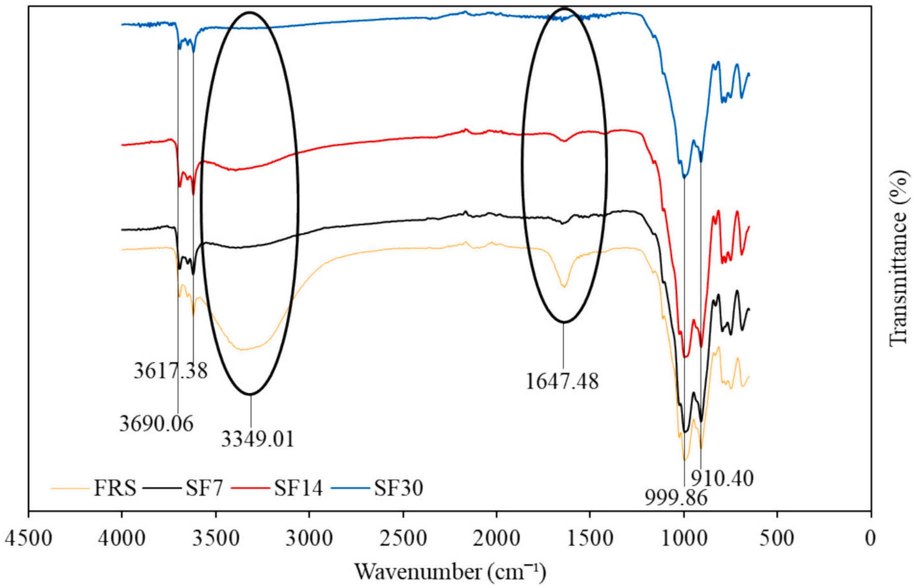

Fig. 11. Identification of potential functional groups in BVG-treated soil using FRS, SF7, SF14 and SF30 samples.

groups in the soil. These changes may contribute to altered interparticle interactions, which are further examined through microstructural analysis using SEM.

The SEM images presented in Fig. 12 illustrate the microstructural evolution of BVG-treated soils across different fermentation periods, with FRS serving as the untreated reference. The FRS sample exhibited a loose and flaky structure characterized by large interparticle spaces and weak particle contacts, indicating limited inherent bonding within the soil matrix. Such a dispersed structure is consistent with its low compressive strength. Following BVG treatment, progressive changes in particle arrangement were observed. At early fermentation (SF7), partial aggregation of soil particles became visible, accompanied by a reduction in interparticle spacing compared to FRS. This indicates an improvement in particle association and packing behaviour. Similar observations have been reported in stabilized soils treated with agricultural waste additives, where enhanced particle association contributed to improve mechanical performance (Gidebo et al., 2023).

At intermediate fermentation periods (SF21–SF28), the microstructure displayed more pronounced aggregation, with particles appearing more closely packed and interconnected. By SF30, the soil matrix exhibited the most compact morphology, characterized by reduced visible spaces and a more continuous particle network. This densified structure corresponds to the highest UCS value recorded at 30 days (0.55 ± 0.05 MPa), indicating enhanced mechanical interlocking and improved load transfer within the soil matrix.

EDX (Oxford X-Max detector, 10–15 kV) analysis (Table 4) showed differences in elemental composition between FRS and BVG-treated soil samples. It should be noted that EDX provides semi-quantitative elemental analysis and is primarily used to observe relative trends rather than absolute concentrations, particularly for light elements such as carbon (C). The results showed that Ca was not detected in most samples, including FRS and BVG-treated soils, although the BVG liquid contained 211 mg/L of Ca. Only a trace amount of Ca (0.13 wt%) was detected in sample SF28, which is within the typical detection limit range of the EDX technique (0.10–0.50 wt%). This indicates that Ca incorporation into the soil matrix was limited, suggesting that Ca-based mineral precipitation was unlikely to be the dominant strengthening mechanism under the present experimental conditions. This observation is consistent with the BVG liquid characteristics, which showed a high TOC concentration (13,800 mg/L) and TKN concentration (1910 mg N/L), indicating the presence of abundant organic constituents derived from vegetable waste fermentation. Compared with conventional mineral-based biocementation systems, where external calcium sources are commonly supplied at high concentrations to provide sufficient Ca^{2+} ions for calcium carbonate precipitation (Abharian and Sadrekarimi, 2026; Lai et al., 2024), the limited Ca availability in BVG may restrict extensive mineral cementation.

In contrast, C content of treated soils increased compared to the FRS sample, suggesting the incorporation of BVG-derived organic constituents into the soil matrix. However, increase in C content did not directly correlate with strength development, as SF30 exhibited the highest compressive strength despite not having the highest C content. This suggests that strength improvement is governed by the composition or concentration of organic constituents that results in enhanced interparticle bonding and soil structure after 30 days of fermentation, whereas excessive organic content, or the composition of BVG may reduce effective particle contact and lead to lower strength. Therefore, the observed strength enhancement is more likely associated with organic-assisted stabilization through physicochemical interactions, and possible pore-filling effects within the soil matrix, as supported by the EDX, FT-IR, pH, conductivity and mechanical test results, rather than dominant mineral cementation such as calcium carbonate precipitation.

Although the present study did not directly quantify the specific mechanisms responsible for soil strengthening, the observed microstructural changes provide insights into possible stabilization processes. The pore filling and aggregation of soil particles observed from SEM analysis are consistent with observations reported in biopolymer-based soil stabilization studies. In those studies, naturally derived organic materials interact with soil particles to improve cohesion, modify pore structures, and enhance mechanical strength (Bagheri et al., 2023; Chen et al., 2019; Costa et al., 2018; Zhang and Liu, 2023). Fermentation-derived materials have been reported to contain organic compounds with potential soil-stabilizing effects, and several biopolymers used in soil stabilization such as xanthan, dextran, and gellan gum which are products of fermentation (Fatehi et al., 2021). Therefore, the organic constituents generated during vegetable waste fermentation in BVG may contribute to soil improvement through organic-soil interactions, including particle aggregation, physicochemical interactions, interparticle bridging and pore-filling effects. Similar strengthening mechanisms have been demonstrated in studies involving biopolymers such as carrageenan, alginate, xanthan gum, guar gam, and chitosan, where organic materials promote cohesive structures within the soil matrix (Azimi et al., 2024; Fatehi et al., 2024). Although the specific chemical nature of BVG-derived organic constituents was not identified in the

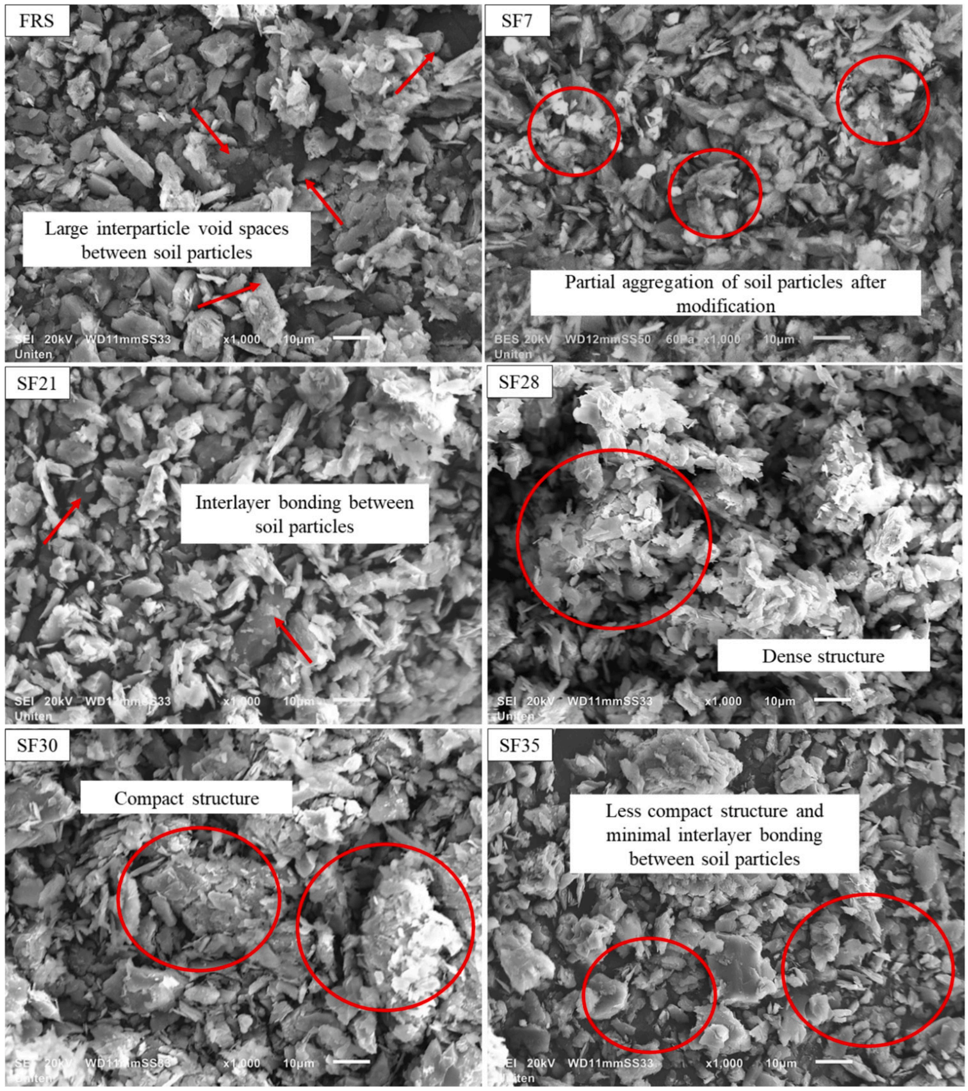

Fig. 12. SEM image analysis of raw and BVG-treated soils after 28 days curing. The red circles indicate representative areas corresponding to the morphological features described in the text boxes for each respective micrograph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Elemental composition of BVG-treated soil samples using EDX.

Sample	Elements (wt%)						
	C	O	Al	Si	K	Fe	Ca
FRS	1.39	44.23	11.49	28.77	3.43	2.18	0.00
SF7	2.15	49.24	15.46	20.98	3.11	4.35	0.00
SF28	4.93	41.04	15.33	23.64	2.13	7.73	0.13
SF30	3.03	42.92	19.24	24.08	4.62	1.50	0.00
SF35	7.68	42.35	13.87	25.57	3.55	2.47	0.00

present study, a mechanism driven by organic molecules is plausible based on the organic rich composition of BVG and previous work that shows the ability of products of fermentation to stabilise soil. Further detailed chemical characterization would be required to confirm the mechanism and identify the specific compounds and interactions responsible for the observed stabilization. At extended fermentation (SF35), the SEM image revealed partial reappearance of interparticle spaces and reduced continuity in particle contacts compared to SF30. This morphological change corresponds to the decline in UCS (0.25 $\pm$ 0.10 MPa), suggesting that prolonged fermentation may decrease the effectiveness of particle association achieved during the optimal fermentation period.

Overall, the combined microstructural, elemental and mechanical results demonstrate that fermentation period significantly influences soil aggregation and packing density. The 30-day fermentation period produced the most compact and mechanically stable microstructure, whereas extended fermentation to 35 days resulted in partial structural loosening and reduced compressive strength.

Although the present study demonstrates that the use of a 30-day BVG fermentation period produced the optimum initial mechanical performance after 28 days of curing, the long-term durability of the BVG-treated soil was not evaluated. For practical engineering applications, durability characteristics such as resistance to wet-dry cycling, repeated loading, and environmental weathering are important for assessing the long-term performance of stabilized soils (Nasiri et al., 2025; Sesay et al., 2025).

3.4. Bacterial communities from BVG and soil samples

16S rRNA gene sequencing revealed distinct shifts in bacterial community at the family level in both the fermented BVG and the treated soils at 7-, 28- and 30-days fermentation stages (Fig. 13). During the early fermentation stage (7 days), the microbial community in the

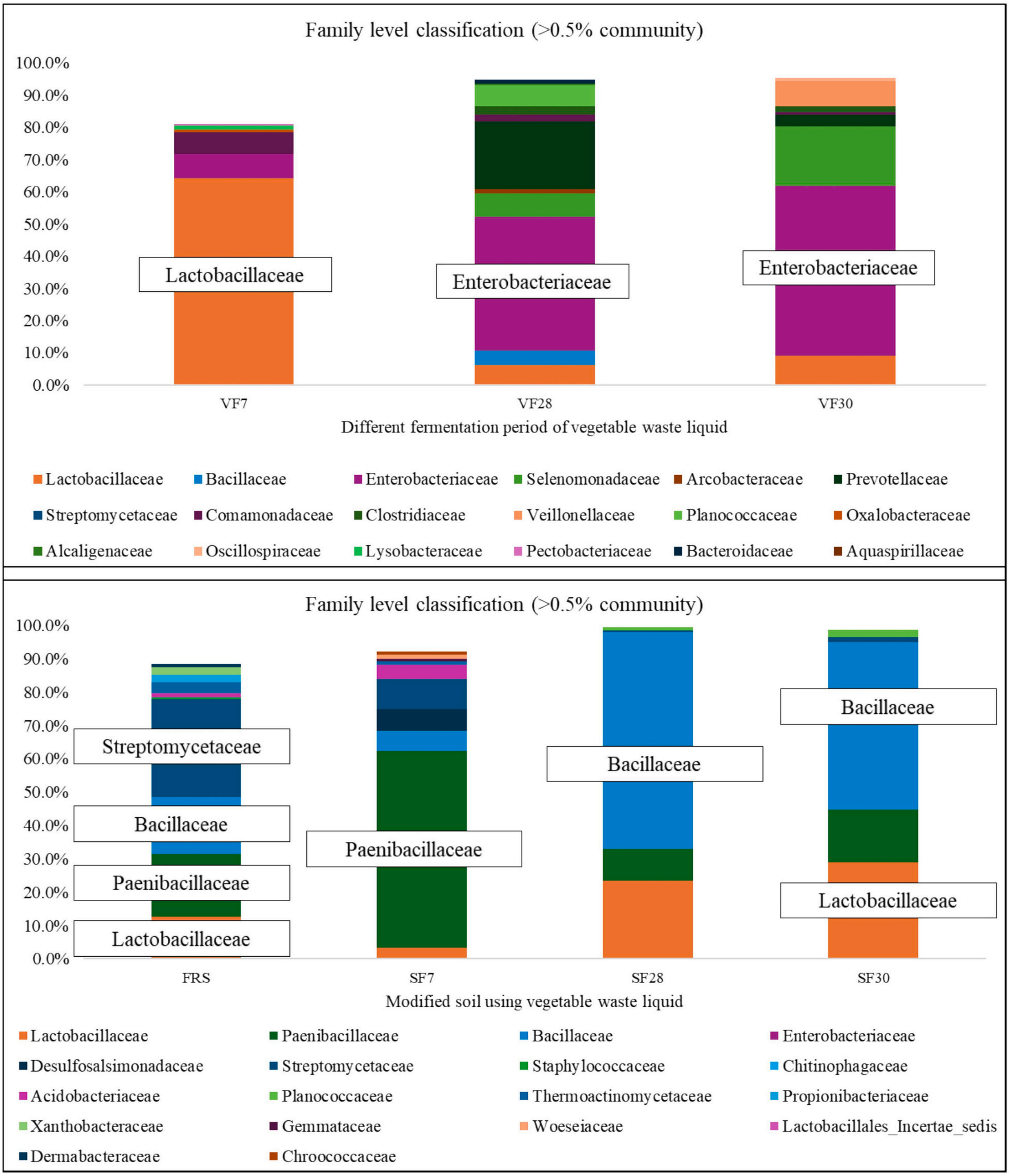

Fig. 13. Bacterial community in BVG liquid (upper panel) and treated soil samples (lower panel). Data is shown at the Family level.

BVG liquid was dominated by Lactobacillaceae, consistent with the proliferation of lactic acid bacteria commonly associated with fermentation of plant-based substrates (Lavelle et al., 2025). Lactic acid bacteria are heterotrophic microorganisms that metabolize carbohydrates into organic acids, which contributes to acidification and transformation of organic substrates during fermentation (Punia Bangar et al., 2022; Zhou et al., 2025). As fermentation progressed to 28 and 30 days, a higher relative abundance of Enterobacteriaceae was observed in the fermented BVG liquid. Members of this family are facultative anaerobic heterotrophs frequently reported in fresh produce and vegetable fermentation systems (Kilonzo-Nthenge et al., 2018; Li et al., 2022). Normally, if these bacteria become abundant during vegetable fermentation it is during the initial stage and has been associated with spoilage processes such as the production of gas and foul odours (e.g. (Medina-Pradas et al., 2017; Ostling and Lindgren, 1993; Pérez-Díaz et al., 2019)). In successful food fermentation their growth is inhibited by the addition of salt to the fermentation and by the pH reducing activity of lactic acid bacteria. Some Enterobacteriaceae can grow at around pH 4 but are more able to outcompete Lactobacillaceae at higher pHs (Li et al., 2026; Zhai et al., 2023). The pH of samples where

Enterobacteriaceae were dominant was pH 4.25 (day 28) and pH 3.81 (day 30). The factors that triggered the switch to dominance of Enterobacteriaceae rather than Lactobacillaceae between day 7 and day 28 are not clear; the increase in pH may be a result or cause of this change.

In BVG-treated soils, differences in bacterial family composition were also seen. All treated soils had lower diversity (as measured by total number of families present at >0.5% relative abundance) than FRS. Soils treated with early stage fermented BVG liquid showed a higher relative abundance of Paenibacillaceae, whereas soils treated with 28- (SF28) and 30-day (SF30) fermented BVG liquids exhibited increased representation of Bacillaceae and Enterobacteriaceae compared to FRS. Bacillaceae is commonly found in soil environments and are associated with various metabolic activities, including organic matter transformation (Dobrzyński et al., 2023). The decrease in Lactobacillaceae in SF7 compared to FRS, and the increase in SF28 and SF30 was unexpected given the relative abundance of this family in the BVG during fermentations. The DNA sequencing approach used is not appropriate for confirming the origin of the bacterial community in the cured soils, especially as there is an overlap with the bacterial families in both the starting BVG and FRS. However, there is an indication that the soil community may the more important contributor as no Bacillaceae was detected in BVG 30-day fermentation but was found in FRS and the corresponding cured soil. Also, Streptomycetaceae is found in all the cured soils and FRS but not in any of the starting BVG liquids. However, the length of fermentation still had an effect on the microbial community in the BVG and that which developed after curing as well as on the chemical and physical properties of the cured soil, suggesting that the concentration or composition of organic constituents in the BVG plays a role. However, further investigation is required to fully understand the role that BVG plays in shaping the bacterial community in treated soils and how this contributes to soil strengthening.

Although changes in the bacterial community during BVG fermentation coincided with improvements in soil strength, the present study did not establish a direct quantitative relationship between the bacterial communities and UCS. The proposed stabilization mechanism is therefore based on the combined physicochemical, microstructural, and mechanical observation rather than direct microbial correlation. Future studies should investigate the durability of the 30-day BVG-treated soil under these conditions and establish relationships between microbial

Table 5
Comparison of the present study with previous BVG, bio-based soil stabilization and microbial-induced carbonate precipitation (MICP) studies.

Study	Stabilizer	Soil type	Fermentation period	Main objective	Mechanical strength	Key finding
A. Previous BVG studies						
Baharuddin et al. (2013)	BVG	Silty gravelly sand	–	Engineering properties	–	Improved liquefied soil
(Omar et al., 2016)	BVG	Sandy silt	–	Strength and permeability	Maximum UCS: 0.06 MPa	Improved micaceous soil strength and permeability
Abdul Azam et al. (2024a)	Combined BVG with polyethylene terephthalate (PET) plastic waste	Silty sand	30 days	Effect of plastic waste on soil strength	Shear strength increased to 84.16% with PET integration	Improved soil stability
Abdul Azam et al. (2024b)	BVG	Peat soil	30 days	Problematic types of soil	Maximum UCS: 0.27 MPa	Improved soil strength
Abdul Azam et al. (2024c)	Combined BVG with polyethylene (PE) plastic waste	Clayey silt	30 days	Effect of plastic waste on soil strength	Maximum shear strength: 220 kPa	Improved soil strength
B. Present study						
Present study	BVG	Clayey silt	7, 14, 21, 28, 30 and 35 days	Effect of fermentation period on soil strength	Maximum UCS: 0.55 ± 0.05 MPa	Identified the optimum fermentation period, characterized bacterial community during BVG fermentation and proposed an organic-assisted stabilization mechanism
C. Bio-based stabilization						
Makhatova et al. (2026)	Bio-based polyelectrolytes (PEs) with sodium lignosulfonate (LS), chitosan (CHI) and their complexes (PECs)	Clay-rich soil and silty sand	–	Establishing correlation between polymer-soil interactions and macroscopic soil performance	UCS range: 0.40–5.30 MPa	Improved soil strength by correlating the molecular binding of polymer chains to soil particles
Ojuri et al. (2022)	Cassava peel powder (CPP) and carboxymethyl cellulose (CMC)	Clay soil	–	Evaluation of agro-wastes for in situ soil stabilization	Highest UCS: 1) CMC-treated clay: 0.90 MPa 2) CPP-treated clay: 1.79 MPa	Improved engineering properties of the regional clay
D. MICP-based stabilization						
Lajmiri et al. (2025)	Purchased bacterial stabilizer: *Sporosarcina pasteurii*	–	–	Comparing different calcium sources for MICP	–	Low-cost alternative calcium sources significantly outperform expensive reagent-grade calcium chloride in MICP applications.
Zhang et al. (2026)	Purchased bacterial stabilizer: *Sporosarcina pasteurii*	Clayey soil	–	Effect of calcium concentration on soil strength	Maximum UCS: 0.12 ± 0.83 MPa	Calcium ion concentration by MICP technology influences improvement effects on soil strength

community composition, fermentation-derived metabolites, and engineering performance through detailed chemical characterization and statistical correlation analyses. Such investigations will provide a more comprehensive assessment of the field applicability of BVG as a sustainable soil stabilizer.

3.5. Comparison with previous bio-based soil stabilization studies

Table 5 compares the findings of the present study with previous BVG, bio-based soil stabilization and microbially induced calcium carbonate precipitation (MICP) studies. Previous BVG studies have consistently demonstrated the potential of fermented vegetable waste as a sustainable soil stabilizer for improving the engineering properties of different soil types (Abdul Azam et al., 2024a,b,c; Baharuddin et al., 2013; Omar et al., 2016). However, the influence of fermentation period on the stabilization performance of BVG has not previously been systematically investigated.

The present study extends the existing BVG research by demonstrating that fermentation period is an important processing parameter governing soil stabilization performance. In this study, the 30-day BVG produced the highest UCS (0.55 $\pm$ 0.05 MPa), which exceeds the compressive strength reported in previous BVG studies conducted on sandy silt (0.06 MPa) and peat soil (0.27 MPa). Although direct comparison should be interpreted with caution due to differences in soil type, specimen preparation and testing conditions, these findings indicate the optimization of the fermentation process can substantially influence the strength of BVG-treated soils.

Comparison with other bio-based stabilization approaches further suggests that the proposed stabilization mechanism in the present study is more closely related to organic-assisted stabilization than to mineral cementation. Similar strengthening mechanisms have been reported for naturally derived stabilizers, including bio-based polyelectrolytes, cassava peel powder, and carboxymethyl cellulose. These improvements in soil strength are attributed to physicochemical interactions, particle aggregation, interparticle bridging and pore filling effects rather than extensive mineral precipitation (Makhatova et al., 2026; Ojuri et al., 2022). These mechanisms are consistent with the SEM observations and FT-IR characteristics obtained in present study.

In contrast, MICP-based stabilization primarily relies on calcium carbonate precipitation, where sufficient calcium availability is essential for effective mineral cementation (Lajmiri et al., 2025; Zhang et al., 2026). In the present study, only trace amounts of calcium were detected in the BVG-treated soils despite the BVG liquid containing 211 mg/L Ca, suggesting that calcium carbonate precipitation was unlikely to be the dominant strengthening mechanism. Instead, the combined EDX, FT-IR, SEM and mechanical test results indicate that the improvement in soil strength was more likely associated with organic-assisted stabilization arising from fermentation-derived organic constituents. This distinction highlights that BVG represents a complementary bio-based stabilization approach that differs from conventional MICP systems while offering a sustainable alternative through the utilization of vegetable waste.

The present study demonstrated significant improvement in the initial mechanical performance of BVG treated soil after 28 days of curing and longer-term performance was not investigated. Sustainable mineral-based additives such as pumice powder have been reported to maintain improvements in soil strength and microstructural stability over extended curing periods (Nasiri et al., 2024) and future studies should include long-term durability assessment to demonstrate the value of BVG treatment for practical engineering applications.

3.6. Preliminary cost estimation and scalability considerations

To provide an initial perspective on the potential scalability and economic feasibility of the BVG system, a preliminary cost estimation was conducted based on pilot-scale preparation and small-scale field deployment assumptions. This estimation was developed during was developed during the early stage of the study to evaluate the approximate resource requirements associated with BVG production and application. The estimation considered the preparation and characterization of BVG liquid, microbial characterization and preliminary field trials. This estimation only represents a research-stage evaluation and does not constitute a comprehensive techno-economic assessment, as factors such as large-scale production efficiency, energy consumption, labour requirements, transportation and long-term operational costs are not included.

The pilot-scale production cost of BVG liquid was estimated based on the use of commercially available vegetables. The BVG formulation consisted of five vegetable types, namely long bean, spinach, cucumber, water spinach and cabbage, mixed at a fresh mass ratio of 2:2:2:2:1 using a 60-L fermentation container, producing approximately 30 L of usable BVG liquid. The utilization of vegetable waste as the primary feedstock reduces raw material costs by converting an agricultural waste steam into a value-added soil improvement material.

The cost associated with microbial analysis and characterization was estimated based on the utilization of existing university laboratory facilities and collaboration with other organisations. The availability of instrumentation, analytical equipment, and technical support can reduce the initial research and development cost associated with microbial evaluation. In contrast to MICP, which commonly requires the maintenance of specific bacterial cultures and external chemical inputs such as calcium sources and urea, BVG relies on a fermented organic matrix containing naturally occurring microbial communities. This characteristic may provide potential economic advantages by reducing dependency on additional microbial cultivation and chemical reagents.

A preliminary field deployment was also considered for a small-scale application involving slope areas of approximately 10 to 20 m^2. The estimated costs associated with BVG preparation, small-scale application and microbial analysis support are summarized in Table 6.

3.7. Conclusion and recommendations for future studies

The present study extends previous BVG-based and other bio-based soil stabilization approaches and identifies the optimum fermentation period for soil strength improvement. It also provides new insights into the microbial succession patterns associated with different fermentation stages. The 30-day fermentation period produced the highest compressive strength, indicating an optimal stage for soil improvement. FT-IR analysis revealed variations in O—H and C—O functional groups, suggesting progressive modification of organic components during fermentation. SEM observations confirmed enhanced soil particle aggregation and reduced spaces between soil particles at longer

Table 6
Preliminary cost estimation per batch for pilot-scale BVG preparation on small-scale field deployment.

Component	Basis of estimation	Estimated cost
BVG liquid preparation	Pilot-scale preparation using five vegetables types (~30 L BVG liquid)	RM528 (~USD 112)
Pilot-scale field deployment	Small-scale application for soil areas of 10–20 m^2	RM420 (~USD 89)
Microbial characterization support	Microbial isolation and screening supported by existing university laboratory facilities and collaboration organisations	Minimal direct cost
Total preliminary estimation	Initial pilot-scale preparation and demonstration of BVG treatment	RM948 (~USD 202)

fermentation periods, while EDX analysis indicated the presence of carbon-rich constituents with only trace calcium detected. High-throughput sequencing showed clear microbial succession across fermentation stages. Therefore, the strength enhancement is more likely associated with organic-assisted stabilization through fermentation-induced physicochemical interactions, and possible pore-filling effects within the soil matrix rather than dominant mineral-based cementation mechanisms.

Although this study demonstrates the potential of BVG as a sustainable bio-based soil stabilizer, several limitations should be acknowledged. First, the specific organic compounds and molecular interactions responsible for soil stabilization were not identified. Second, although the bacterial community analysis provided insight into microbial succession during BVG fermentation, direct relationship between specific microbial community, fermentation-derived metabolites, and soil mechanical performance were not established. Third, the long-term durability under environmental conditions, such as wet-dry cycling, repeated loading and weathering, was beyond the scope of the present study. Finally, the findings are based on a single soil type and laboratory-scale conditions, and the performance of BVG may vary for soils with different mineralogical and geotechnical characteristics.

Future research should therefore focus on (i) detailed chemical characterization of fermentation-derived organic constituents, (ii) investigation of the relationships between microbial community, microbial metabolites and engineering performance, (iii) evaluation of long-term durability under field-relevant conditions, and (iv) validation of the proposed stabilization mechanism using advanced analytical techniques in studies involving different soil types and larger-scale field applications. Combined, these studies would provide further insight into the practical applicability of BVG as a sustainable soil stabilization technology.

CRediT authorship contribution statement

Wan Aisyah Fadilah Wae AbdulKadir: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rohayu Che Omar:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Simon Gregory:** Writing – review & editing, Investigation, Formal analysis. **Farah 'Atiqah Abdul Azam:** Writing – original draft, Investigation, Formal analysis. **Megan Barnett:** Writing – review & editing, Investigation, Formal analysis. **Muhammad Afiq Mohamed Akbar:** Writing – review & editing, Investigation, Formal analysis. **Nur 'Atikah Mahazir:** Writing – review & editing, Investigation, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biteb.2026.102980.

Data availability

Data will be made available on request.

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