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Microbial Screening and Morphological Analysis of the Peat Soil Gebeng, Malaysia

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Abstract. Peatlands are amongst the most critical ecosystems, representing hydrological, biological, and biogeochemical characteristics determined by water storage functions and greenhouse gas exchange. Peat soils have distinct problems of acidity, compressibility, and nutrient imbalances, which limit their agricultural, constructional, and environmental uses. Most current studies have focused on a single component, such as organic content, microbial diversity, and mineral composition, leading to a rather limited understanding. This paper combines microbial community screening with mineral and morphological analysis to evaluate various features and dynamics of peat soils and their uses, and therefore it brings new insights into the physical, chemical, and biological properties that concern its long-term use. The methodology entails collecting soil samples from various locations in Gebeng, Malaysia, and then determining their moisture content and pH. After that, it included the Morphological characterisation using Scanning electron microscope (SEM), Energy dispersive X-ray (EDX), powder X-ray diffractometry (XRD), and Fourier transform infrared spectroscopy (FTIR). Characterisation was then done, followed by DNA extraction and sequencing using the QIAamp PowerFecal Pro DNA Kit. The obtained research results, including SEM, showed that, in general, peat soil particles are poorly fragmented, the shape of which is irregular and heterogeneous with complex angularity rounded and elongated shapes, while the EDX analysis described a significant qualitative contrast. Also, XRD analysis discovered a complex mineralogical composition composed mainly of quartz (SiO_2). Moreover, the tested peat samples showed a wide variety of inorganic salts, minerals, and organic components by FTIR examination. On the other hand, DNA sequencing results revealed richness in bacterial diversity in composition and relative abundances. This study generally has shown that Gebeng peat soil, with high organic matter content and diverse microbial populations, together with a reasonably balanced mineral input, potentially holds promising opportunities for agriculture and other industries such as construction, CO_2 reduction, and environmental management, but problems like acidity of soils, high compressibility, or nutrient imbalances require specified strategies in their management to be effectively exploited.

1. Introduction

Peatlands are probably one of the most widespread ecosystems, driven by biological, hydrological, and biogeochemical processes [1]. These systems play an important role in carbon sequestration [2], biodiversity protection [3], and management of the water cycle [1], all of which are highly relevant to environmental sustainability and climate change control [4].

Peatlands in Malaysia extend over approximately 2.6 million hectares and are predominantly in the coastal/ lowland regions [5]. Of these, the former include local crops, forests, and wildlife [6]. However, several challenges accompany the exploitation of peat lands, including high acidity, raised water table, and degradation of the peat when drained or exploited in other wrong ways [7].

Recent studies have found that peatlands play a significant role in climate regulation, water management, and recreation, preserving ecological conditions. For example, Smith et al. [7] examined how peat soil improves the fertility of the soil and plants' growth, which is indirectly linked to organic matter content. This study's results revealed that high organic content provides key nutrients, enhances structural properties in the soil, and increases water-holding or retention capacity, considered important factors critically relevant to agriculture productivity. Similarly, Too et al. [8] examined microbial variety in peat soils for involvement in nutrient cycling. It was concluded that microbial communities, much more those involved in nitrogen fixation and the decomposition of organic matter, massively contributed to the fertility and health of soils.

Razali et al. [9] proposed lime and cement stabilising peat soils to improve their compressibility and bearing capacity. The methods of proper stabilisation allow extending the use of peat soils in construction by making them suitable for building purposes where problems are usually linked with high organic content and water content. Wang et al. [10] examined the contribution to structural stability from the mineral content of quartz and kaolinite, which is involved in providing structural stability to the peat soil. The results included enhancing the soil's cohesion and stability, raising their suitability for use in construction.

In the study by Harenda et al. [11], an investigation was done on the role of peatlands in climate change mitigation through carbon sequestration. Results indicated that peatlands have a significant capacity to store huge volumes of CO_2. However, the challenge is sustaining organic matter decomposition without leading to overly elevated CO_2 emissions, thus overriding the sequestration process. In this regard, Kowalska et al. [12] examined the need for sustainable management strategies for improving carbon storage within peat soils. Results indicated that peatland conservation and controlled microbial function increase the carbon sequestration in the soil while striving for soil health.

Thiele-Bruhn [13] experimented with peat soils in bioremediation. Results showed that the reactive clay minerals' content, such as kaolinite, and multiple microbial populations enhanced the peat's natural capacity for absorbing and degrading pollutants. Peat soils are a good solution for environmental cleaning operations in polluted areas.

Although several recent studies investigated the peatlands' role in environmental sustainability, knowledge and a better understanding of peat soil's physical, chemical, and biological properties in practical applications are still required, including in agriculture, construction, CO_2 reduction, and environmental management. Previous research concentrated on specific factors, like organic matter concentration, microbial diversity, or mineral composition. These components must be consistently represented in peat soil qualities and their effects on varied applications.

However, there are certain shortcomings in the use of peat soils today, such as high acidity, high moisture content, and the degradation of peat due to improper management, reducing their practical usages in agriculture, construction, and environmental management. Despite the broad recognition of the ecological and functional value of peatlands, most of the earlier studies focused on specific aspects such as organic matter content, microbial diversity, and mineral composition without providing a comprehensive understanding of how these factors interact to support sustainable applications.

Accordingly, this study aims to conduct a Comprehensive microbiological analysis of peat soil from Gebeng, Malaysia, which will be achieved by examining the peat soil mineral and morphological characteristics using SEM and XRD analyses. In addition, the elemental and chemical composition can be determined by EDX and FTIR analyses, and microbial diversity and its potential effects on peat soil applications can be determined by DNA isolation and sequencing. Finally, the study will incorporate the obtained results to explain soil suitability for agriculture, construction, CO_2 reduction, and environmental management.

This work addresses significant gaps in understanding physical, chemical, and biological properties of peat soil from Gebeng, Malaysia, despite its ecological and industrial importance. This research integrates state-of-the-art analytical approaches to provide comprehensive understanding of peat soil qualities and their implications for sustainable uses in environmental management, building, agriculture, and CO_2 reduction.

Gebeng was chosen as the sampling site because it uniquely represents the Malaysian coastal peatlands, considering its various physical, chemical, and biological characteristics. In this area, peat soils are very important in agriculture and industrial activities, but a few research has been conducted on them. The study of Gebeng peat soil provides insights into their potential applications while addressing local environmental challenges.

Consequently, this study's results will contribute to developing efficient peat soil management strategies that can raise their multifunctional potentials while supporting sustainable development goals.

2. Materials and Methodology

2.1 Material

The collection was done from two locations in Gebeng, Kuantan, and Pahang, Malaysia. Two samples were obtained at various depths at the first location, Renikola, Gebeng. The third sample was taken from another location, the Gebeng bypass. Table 1 provides an overview of the specifics of the soil sample sites.

Table 1. Soil sample locations.

Sample	Symbol	Coordinates	Location	Height
Sample 1	S1	4°00'09.5"N 103°21'42.7"E	Renikola, Gebeng, Kuantan, Pahang, Malaysia	5m
Sample 2	S2	4°00'09.5"N 103°21'42.7"E	Renikola, Gebeng, Kuantan, Pahang, Malaysia	3m
Sample 3	S3	Gebeng bypass 26080, Kuantan, Pahang, Malaysia	Gebeng, Kuantan, Pahang, Malaysia	3m

The first test conducted on the collected soil samples was the natural moisture content test. It was done using the oven-drying method outlined by the British Standard EN ISO 17892-1:2014. This test entails placing the soil sample in an oven and letting it dry at a particular temperature until a steady mass is achieved and subsequently finding the mass difference, which offers the free water content of the soil samples. The obtained moisture content results for the used soil samples are provided in Table 2.

Table 2. Moisture content results.

Sample number	Moisture content (%)
S1	313.24
S2	84.69
S3	189.339

Table 2 shows that S1 had the highest moisture content (313.24%), showing an extraordinarily high-water retention capacity, typical of peat soils containing large amounts of organic matter. On the other hand, S2 portrayed a low moisture content of 84.69%, which means it retains slightly water and hence may contain excess minerals or is highly compacted. The last sample was S3, with a middle-range moisture content of 189.34%, reflecting some balance between organic and inorganic components. These differences in moisture content reflect the heterogeneity of peat soils. ASTM D 2976 - Method A also determined the pH for collected soil samples. The pH results obtained for the utilised soil samples are given in Table 3. These low-pH values are typical of peat soils and underline the need for a change in pH when these soils are to be analysed for use in agriculture, among other applications, if optimum crop growth and nutrient availability are to be met.

Table 3. pH results.

Sample	pH
S1	4.83
S2	5.00
S3	4.64

2.2 Experimental Procedures

The experimental programme in this study involves analysing the mineral and morphological characteristics of the three examined soil samples and extracting DNA for microbial screening. SEM and EDX analysis: The obtained Scanning Electron Microscope (SEM) images of the tested soil samples enabled the identification of their surface structure elements, including the soil particles' size, shape, and disposition. The SEM analysis of the samples was done based on the standard procedure mentioned in ASTM E1508 [14]. Further, the elemental analysis of the soil was performed using an Energy-Dispersive X-ray (EDX) analysis. SEM and EDX data also give a general description of the morphological properties of the peat soil. XRD analysis: This study conducted X-ray diffractometry (XRD) according to ASTM D7348 [15] to discover the mineralogical composition of the tested soil samples using X-ray diffraction. This gave thorough information about the tested soil crystalline phases, which helped identify and quantify the involved minerals. FTIR analysis: The Fourier transform infrared spectroscopy (FTIR) analysis was performed following the ASTM E168-06 [16] to study the molecular nature of the soil samples, which needed to be determined using Fourier Transform Infrared Spectroscopy. This analysis type explains the functional groups they are working with and the molecular bonds of the studied soil samples and notes down both the organic and inorganic elements.

DNA isolation: DNA isolation was conducted to identify the kinds of bacteria present in the examined soil samples. DNA was isolated using the QIAamp PowerFecal Pro DNA Kit. The kit enables the production of high-quality DNA from complex soil samples, usually accompanied by pollutants and inhibitors, which often reduce the accuracy of subsequent applications. DNA Quality assessment: Gel electrophoresis was performed to ensure the integrity and absence of any contamination in the DNA extracted from the samples. This process ensures that DNA bands on the gel used to check the integrity and purity of DNA are well visualised. If the bands are clear and distinct, the DNA samples are good for further tests. PCR and DNA sequencing: PCR is used to amplify DNA prior to sequencing it in the susceptible genes identified in the study. In essence, PCR provides adequate amounts of DNA that can be sequenced and maintains greater sensitivity and accuracy. Then, the exact genetic sequences of the amplified DNA were determined, although the above results were the M13-paired sequences between the genes. This sequencing method provides complete information on the bacterial population.

3. Results and Discussions

3.1 Mineral & Morphological Analysis Results

Based on the SEM analysis of the peat soil, the samples showed considerable microstructural variation and shifts in the organic and inorganic matter. Figure 1 (a) showed very porous and fibrous particles, indicating that the soil sample is mainly composited from organic origin with many plant components. Conversely, Figure 1 (b) is very dense and compact, depicting the presence of minerals or microbial activity that hold particles together. Figure 1 (c) shows that the surface is smooth with speckled mineral particles. Therefore, this could be a mixture of organic and inorganic materials, probably due to sedimentation or mineral deposition. These microstructure differences represent the complexity of peat soils and highlight their different physical qualities, which are important for understanding their behaviour and potential for stability. The combination of both organic fibre material and inorganic particles implies that certain stabilisation strategies may be necessary to maximise the engineering. features of these soils[17].

In addition, Table 4 also provides the obtained EDX results of the tested soil samples and lists the included primary elements. According to the results shown in Table 4, a high amount of carbon is contained in S1 (62. 24%), the big oxygen present (36. 54%), and a little silicon (1. 23%). This indicates that S1 is mainly organic, typical for peat soils with some decaying plant matter. In contrast, S2 contains a lot more silicon at 33.55% but also large levels of oxygen at 54.50% and aluminium at 11.96%, thus indicating a major mineral component compared to S1. This proves the greater inorganic impact on the S2 sample, probably because of silt or other mineral deposits. Moreover, S3 showed a more balanced composition and high carbon and oxygen contents of 27.78% and 43.67%, respectively, with detectable silicon at 14.46% and aluminium at 4.46%. These findings are consistent with research such as Ratnayake [18], which emphasizes that tropical peat soils have a high carbon content (over 50%), a characteristic that indicates their organic-rich character. The results of the XRD test conducted on the three-peat soil samples show important mineralogical composition that has far-reaching implications for diverse uses and possible problems. As shown in Figure 2, S1 is mainly made up of quartz low, indicating that the soil is rich in stable, inorganic components.

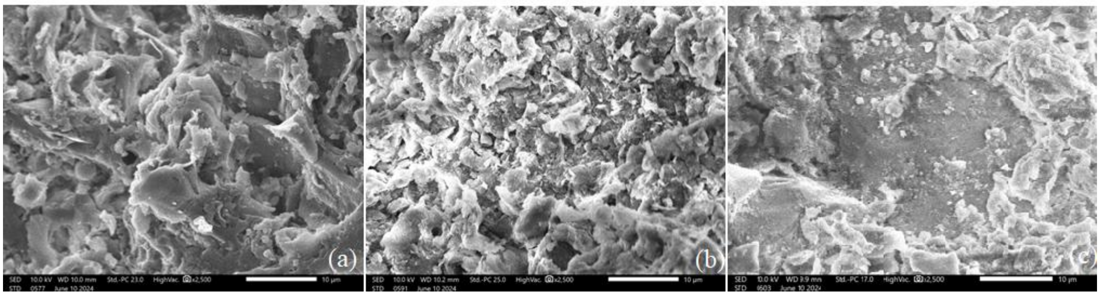

Figure 1. SEM analysis results: (a) S1 SEM results, (b) S2 SEM results, and (c) S3 SEM results.

Table 4. EDX results.

Element	S1 Mass (%)	S2 Mass (%)	S3 Mass (%)
Carbon, C	62.24	-	27.78
Oxygen, O	36.54	54.50	43.67
Silicon, Si	1.23	33.55	14.46

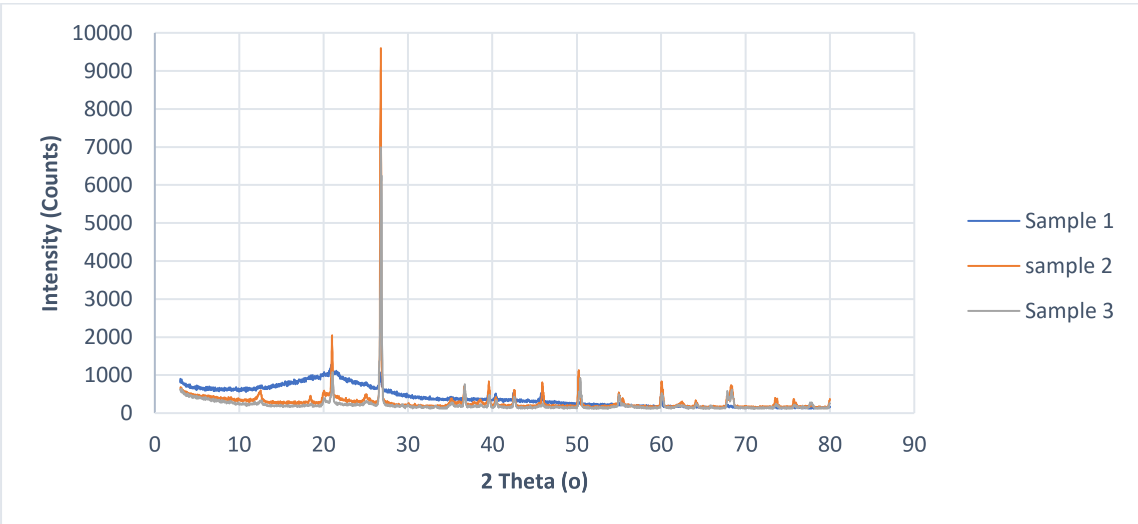

Figure 2. XRD analysis results for S1, S2 and S3.

The high concentration of quartz thus indicates applications requiring durability and resistance to chemical weathering, such as construction and land reclamation operations. However, This can be limited to highly chemical interactive applications since they will need more reactive minerals otherwise [19]. This finding is consistent with research by Dubey et al. [20], which emphasized that soils containing quartz are inert in chemical reactions, which restricts their usage in specific geotechnical applications.

On the other hand, S2, represented in Figure 2, had a low content of quartz and kaolinite, indicating a more composite makeup of its soil type. The presence of kaolinite thereby gives advantages of enhanced flexibility and cation exchange capacity, making the soil more workable for any application requiring soil conditioning or stability, such as in agricultural environments where nutrient retention and workability of soils are essential [21]. This is in line with research by Oyebanjo [22], who highlighted the benefits of kaolinite for agricultural soils' water retention and soil structure. However, the same reactive nature of kaolinite might constitute building problems since its plasticity could result in volumetric changes and probable instability. As shown in Figure 2, S3 is composed of a mixture of quartz and kaolinite; quartz is the major component. This will aid in controlling the ratio between activity and inertia for the appropriate employment of the tested soil [20].

The mixture of quartz and kaolinite can reach environmental engineering, making it more reactive in the sense of the adsorption of contaminants. The advantages possessed of potentially applicable implementations for restoring the environment. [23]. However, stable quartz contributes to the strength needed for structural integrity in applications such as landscaping or erosion prevention [24]. Consideration, however, is necessary for management to minimise potential soil swelling or shrinkage problems when infrastructure is involved with these reactive kaolinite content in S2 and S3.

FTIR analysis of the three-peat soil samples provides insight into their chemical compositions and possible functional groups. As indicated in Figure 3, S1 depicted peaks at 3397 cm^{-1} (O-H stretch), 2920 cm^{-1} (C-H stretch), and 1630 cm^{-1} (C=O stretch), which puts forward the high organic matter content, including humic and fulvic acids. S2 results exhibit peaks at 3337 cm^{-1} (O-H stretch), 1639 cm^{-1} (C=O stretch), and 1033 cm^{-1} (Si-O stretch), indicating organic material and mineral components such as clays. These findings are in agreement with the results obtained by Chen [25], who, while stating that peat soils have a dual organic-mineral composition and are apt for soil stabilization, reported similar FTIR peaks.

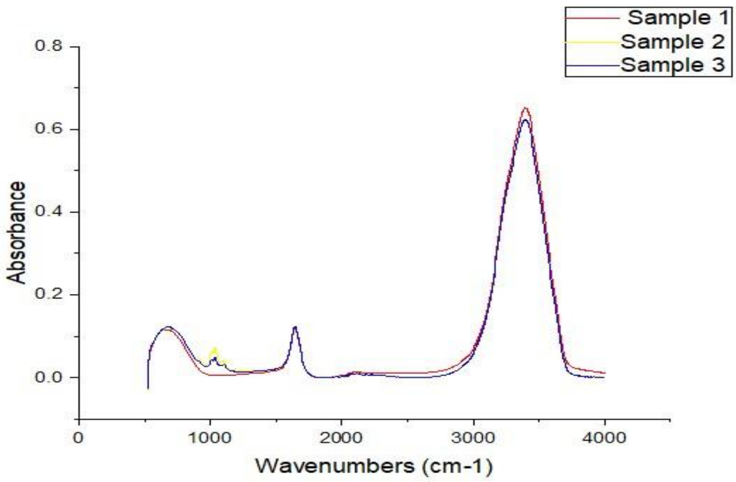

Figure 3. FTIR analysis results for S1, S2 and S3.

Results in Figure 3 of S3 show important peaks at 3433 cm^{-1} (O-H stretch), 2922 cm^{-1} (C-H stretch), and 1644 cm^{-1} (C=O stretch), like Sample 1, but also includes a peak at 1032 cm^{-1} (Si-O stretch), indicating a combination of organic and inorganic elements. Li et al, [26] found comparable FTIR peaks in highly organic soils, highlighting their function in soil fertility and nutrient retention. These findings emphasise the diverse chemical composition of peat soils, including a high organic matter in addition to different levels of mineral presence, which influences their behaviour in environmental and agricultural applications, as well as soil stabilisation and remediation strategies [27].

3.2 DNA Sequencing Results

Figure 4 presents the DNA sequencing results analysis for S1; it has been identified that S1 is a highly diversified microbial community with Proteobacteria as the dominant phylum. Also, results revealed the existence of *Alphaproteobacteria* and *Gammaproteobacteria*, and the dominating orders in these groups *are Rhizobiales, Xanthomonadales,* and *Burkholderiales*. Besides, this sample has large amounts of acidic bacteria and actinobacteria, showing abundant bacteria involved in decomposing organic material and nutrient cycling. It also accommodates organisms like *Pseudomonodaceae* and *Steroidobacteraceae*, which play vital roles in nutrient mobilisation of the soil [28].

This result is consistent with research by Dobrovolskaya et al. [29] who found that Proteobacteria are a significant phylum in peat soils. Furthermore, the types that have been found, such *Rhizobiales* and *Burkholderiales*, align with the findings of Santaren et al. [30], Which pointed to their role in nitrogen fixation and soil health. Besides, the identification of bacterial families such as *Steroidobacteraceae* and *Pseudomonodaceae* agrees with the study by Nanjundappa et al. [31], which highlights the importance of these species for nutrient mobilization and organic matter degradation.

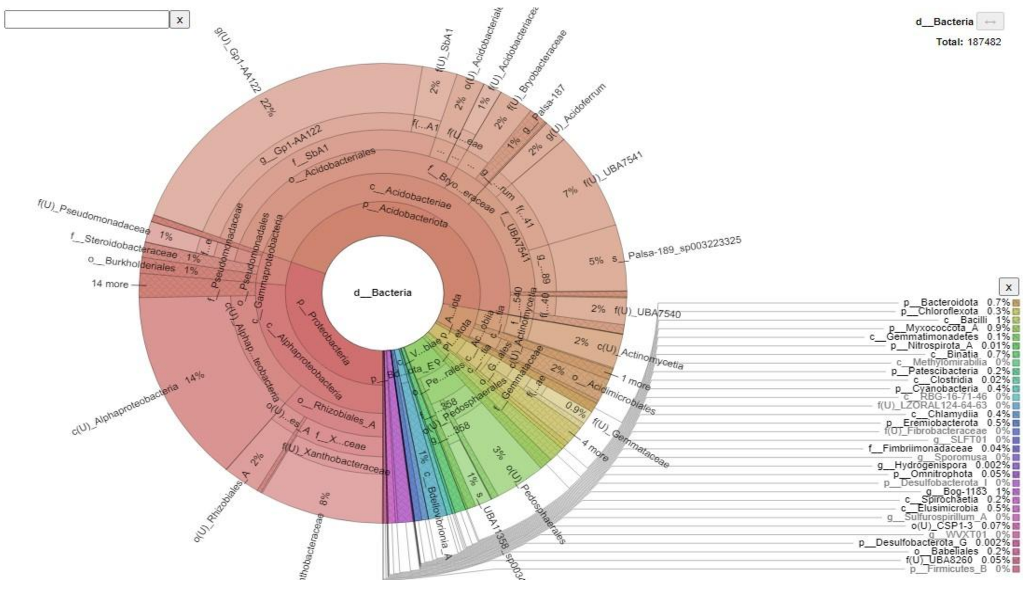

Figure 4. DNA sequencing results for S1.

Proteobacteria are similarly the major phylum in S2, as shown in Figure 5, with Alphaproteobacterial (13%) and Gammaproteobacteria being particularly abundant. Like S1, types like *Rhizobiales* and *Burkholderiales* are common. However, this sample displays a greater relative abundance of *Acidobacteriota*, indicating that the soil is acidic and favours certain bacterial taxa. *Rhodospirillaceae* and *Xanthobacteraceae* indicate vigorous carbon and nitrogen cycling, contributing to soil fertility and structure [32]. The results for S2 are in good agreement with the finding by Liu et al. [33], who observed that *Acidobacteriota* dominates in acidic soils due to its adaptation in low pH conditions and important functions in nutrient cycling, with the dominance of phylum Proteobacteria and higher relative abundance of *Acidobacteriota*. S3, as shown in Figure 6, shows a unique microbial community structure, with Proteobacteria dominating, notably *Burkholderiales* (48%).

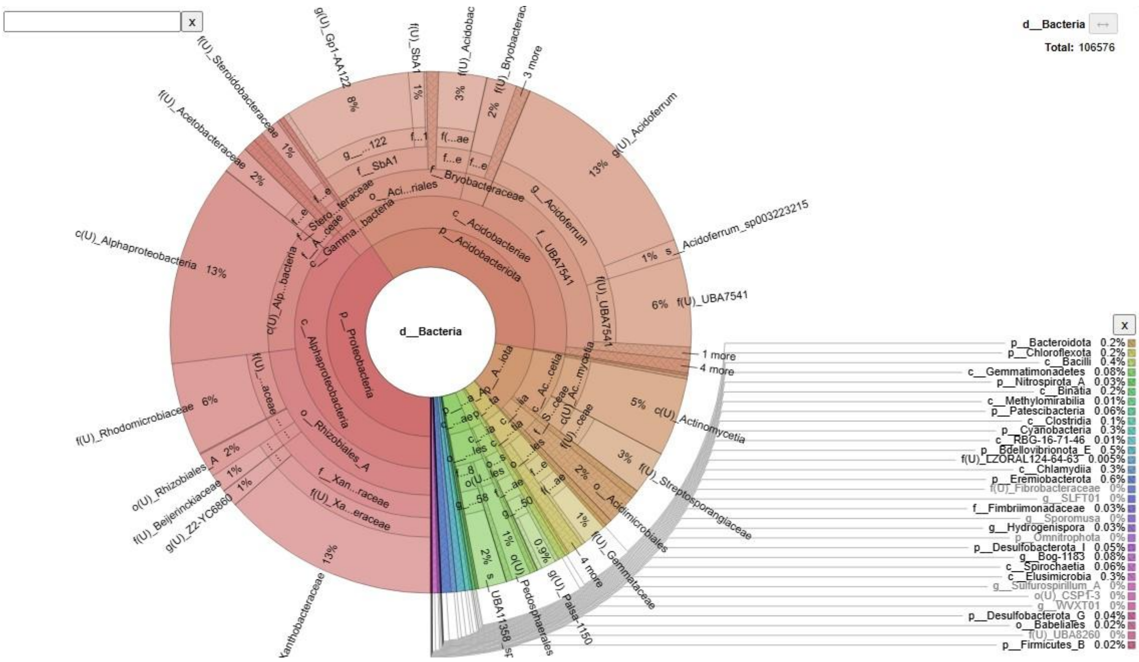

Figure 5. DNA sequencing results for S2.

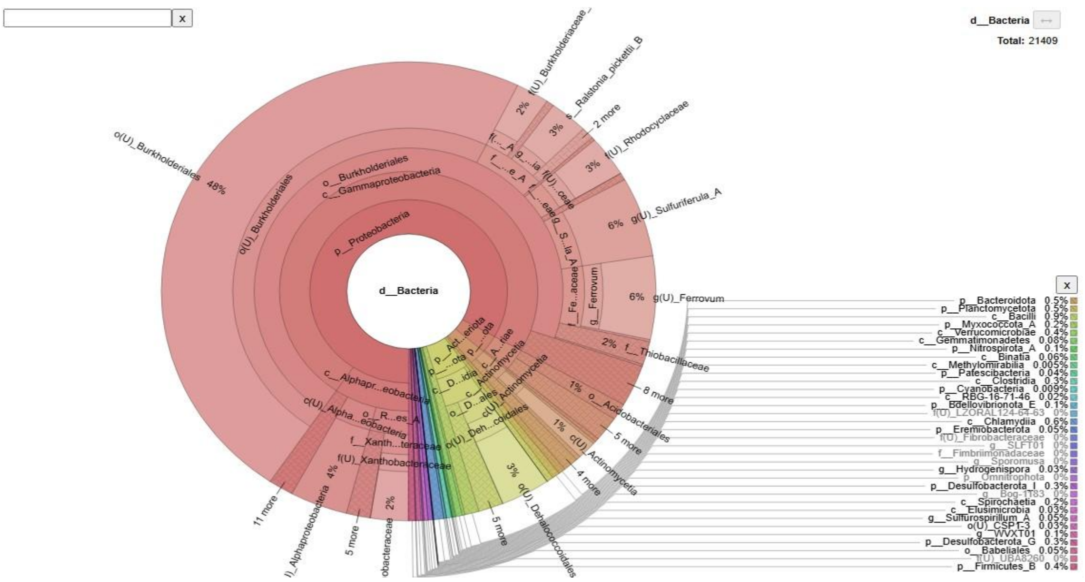

Figure 6. DNA sequencing results for S3.

Taxa such as *Ralstonia* and *Acidovorax* in *Burkholderiales* emphasise their functions in organic matter breakdown and possible plant interactions. Other phyla, including *Acidobacteriota* and *Actinobacteriota*, are present but not dominant, indicating a particular microbial niche in this collection. These results agree with Naylor et al. [34], which emphasizes the presence of Proteobacteria in soils with high microbial activity and their function in organic matter breakdown. DNA sequencing results of all three samples showed a high level of microbial diversity, with Proteobacteria continuously dominating the communities. In this respect, variety and composition in microbial communities of peat soils explain their important ecological roles and possible uses: the presence of microorganisms involved in nutrient cycling and organic matter breakdown depicts that these soils can enrich plant development while maintaining soil health.

3.3 Suitability of Peat Soil from Gebeng, Malaysia for Various Applications

The SEM, EDX, XRD, FTIR, and DNA sequencing results support the peat soil from Gebeng, Malaysia, which has several characteristics that dictate its suitability for agricultural, construction, CO_2 reduction, and other applications. Peat soil in Gebeng Malaysia showed positive indicators of being used for agricultural activities because of the high concentration of organic matter, microbial community, and excellent water-holding capacity. The results of FTIR and EDX show a high content of organic matter that is significant for soil fertility and can provide necessary nutrients to stimulate plants' development [35]. Moreover, DNA sequencing data imply a rather high microbial diversity with the roles of Burkholderiales and Rhizobiales regarding nitrogen fixation and organic matter decomposition [36]. SEM shows that in some samples, the structure has a porosity that suggests that a high water retention capacity is important for crops during dry seasons [37]. However, some limitations, such as soil acidity, imbalance of nutrients, and many others, must be addressed. Moreover, the soil has considerable organic matter, but the fertility aspect, which includes phosphorus and potassium, needs to be managed [38].

Morphological characteristics and microbial communities of peat soil screening have both advantages and disadvantages regarding construction and infrastructure applications. The XRD results showed the presence of quartz and kaolinite, which contribute to the structural stability of the soil [39]. Quartz intrinsically exhibits stability, and kaolinite increases soil cohesiveness, increasing the soil stability required in construction [40] [41]. However, the high organic material in the soil might lead to high compressibility and small bearing capacity that is restricted for construction uses [42]. Stabilising measures include lime or cement, reducing the soil's strength and compressibility[43]. In addition, microbial screening showed that peat soil is host to several potential calcium carbonates ($CaCO_3$) producing bacteria to Medin with the basic Microbially Induced Calcite Precipitation (MICP) stabilisation method [44][45].

The high carbon concentration of peat soil renders it an important carbon sink with great CO_2 reduction potential [46]. By preserving and handling these soils, large amounts of CO_2 can be sequestered, contributing to climate change mitigation [47]. Different microbial communities are involved with the decomposition of organic matter, play an important role in carbon recycling, and can effectively be managed to increase soil carbon storage [48]. The challenges of this type of soil regarding CO_2 reduction include balancing organic matter breakdown and carbon sequestration [49]. Hence, it is necessary to use correct management techniques to obtain optimum carbon sequestration without compromising the stability of the underlying soil.

The studied peat soil can also be used for environmental control and rehabilitation due to its high adsorption of pollutants and microbial degradation. Reactive kaolinite, together with organic matter, increases the soil's ability to adsorb and immobilise contaminants, making it more appropriate for bioremediation purposes [50]. Besides, due to the increased heterogeneity of the microbial community and the presence of species capable of degrading organic pollutants, this soil can be used for environmental remediation [51].

Gebeng peat soil has significant potential for agriculture, building, CO_2 reduction, and environmental management because of its high organic matter, diversified microbial populations, and balanced mineral content. However, difficulties such as soil acidity, high compressibility, and nutrient imbalances must be addressed using specialised management approaches. By capitalising on their strengths and addressing their problems, these peat soils may be efficiently used for sustainable development and environmental protection.

4. Conclusions

Gebeng peat soil is very viable for agriculture usage, construction, reducing CO2 and managing the environment due to the high organic matter content, different involved microbes, and balanced minerals. Nevertheless, this soil is characterised by high acidity, high compressibility, and imbalance of nutrients that require technical management. By effectively leveraging the inherent advantages and addressing the associated challenges, it is possible to achieve efficient and sustainable development while ensuring environmental protection.

This paper discussed and investigated the utilisation of peat soil, specifically the collected from Gebeng, Malaysia, in agricultural usage, structure construction, reduction of CO_2 and environmental control. The adopted methodology included mineral and morphological analysis focusing on SEM, EDX, XRD and FTIR examination and microbial DNA isolation with digital sequencing.

Accordingly, results, including mineral and morphological characteristics such as SEM-EDX, identified a high content of organic matter and structure that is beneficial to the retention of water and nutrient availability in agriculture. XRD showed quartz and kaolinite, the first responsible for stability and cohesiveness in soil characteristics required for building. The FTIR spectroscopy results indicate the presence of functional groups characteristic of abundant organic matter and reactive minerals.

Microbial screening with DNA sequencing revealed a diverse microbial population, including bacteria capable of inducing the formation of calcium carbonate through MICP, particularly about probability outcomes that give sustainable soil-stabilising techniques. On the other hand, there are some factors, including soil acidity and compressibility, that hinder the wider benefits of these peatlands, providing opportunities where the proper stabilising technologies and increased microbial activity may be implemented regarding the fullest use of the soil for several implementations, including the sustainable development and preservation of the environment.

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