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Comprehensive Soil Characterization Using Spectroscopic and Microscopic Techniques

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Abstract: *Various analytical methods have been employed to elucidate the physical and chemical properties of soil.The study employed X-ray diffraction (XRD), Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), and ultraviolet-visible spectroscopy (UV-Vis).Among these, X-ray diffraction (XRD) was chosen for this study because it provides information on the major crystalline minerals (e.g., quartz, feldspar, kaolinite, and montmorillonite), which are the primary factors influencing soil texture, cation exchange capacity, and water retention capacity.FTIR and Raman Spectroscopy revealed organic and clay minerals' molecular structures and functional groups (silicates, -OH, and carbonates).SEM and EDS are used to obtain data on specific spatial and microstructural properties. In addition to this, EDS helped to analyze the elemental composition of soils and many oxides, which are known to be the sources of major soil fertility and structural integrity, including pH, on which soil productivity depends, especiallySiO, AlO, MgO, and CaO. By means of ultraviolet- visible spectroscopy, the connections between the content and quality status of the soils, organic matter, and iron oxides have been determined. The combination of all these complementary analysis methods assisted in the complete description of the I/O properties of the soils. The paper demonstrates the importance of applying both destructive and non-destructive methods (especially those that can be implemented within a short period) to manage soils adaptively.*

Keywords: Soil characterization, Spectroscopic analysis, Microscopic techniques, Mineral composition, Sustainable agriculture

I. INTRODUCTION

The soil is among the most essential natural resources on the planet, as it supports the entire biosphere of the Earth, while also serving as a substrate for agriculture and human development. Soil provides a medium in which plants grow, where primary nutrients are absorbed, stored, and recycled, and a remarkable degree of biodiversity is maintained. Moreover, soil serves as a vital interface between the lithosphere, atmosphere, hydrosphere, and biosphere, and is essential in numerous biogeochemical cycling processes on the planet. Physical and biological constituents of the soil (minerals, organic matter, gases, and water) are dynamic and determine the capacity of the soil to support plant growth, retain carbon, and trap contaminants [1].

Due to the increase in population, industrialization, and the need to produce higher agricultural yields, the soil is being increasingly strained. Inappropriate management practices, such as over-fertilization, land clearing, and urbanization, are also unsustainable practices that typically increase the rate of degradation and decrease soil organic matter. They can also contribute to salinization or heavy metal contamination, affecting water quality and food security through the presence of heavy metals or synthetic inputs. As such, the sustainable use of soil resources has become a global concern and overlaps with various United Nations Sustainable Development Goals (SDGs), including food security, access to clean water, climate action, and conservation of life on land. There should be a priority in providing an integrated and

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systemic definition of the inherent soil properties to understand and control the processes and functions of soil degradation, thereby helping future generations.

The soil characterization process involves the assessment of physical, chemical, mineralogical, and biological characteristics of a soil, which provides an understanding of the behavior of soils and their different characteristics. Through observation, evaluation, and characterization of soil properties, soil scientists, agronomists, and engineers are in a position to gauge soil fertility, establish contamination, and advise about the use of soils, be it agricultural, environmental, or geotechnical use. Characterization of soil and identification of its properties are done through the use of traditional methods, which comprise physical and wet chemical measurements. Nevertheless, they are restricted in pointing out what happens in the mineralogical and molecular scales. The past couple of years have seen the availability of new spatial and time resolutions of soil samples utilizing the analytical methods that integrate spectroscopy and microscopy data, which has provided soil scientists with an opportunity to study the physical and chemical characteristics of soil in addition to providing a more detailed characterization of mineral composition, organic matter, mineral associations, and how the organic matter is organized. Consequently, the introduction of methods of analyzing soil samples has transformed the soil science discipline because the traditional methods of soil characterization, which used wet chemistry and quantitative characterization by using analytical spectra and image spectrophotometry, have been abolished [3].

Accurate soil characterization is necessary for a successful outcome and is at the heart of the entire system.Thus, farmers canmanage nutrients effectively, create crop plans, and utilize soil for other purposes. Plants differ significantly in terms of the kind of soil, its density, and even its pH value. As a result of soil characterization and analysis, farmers can determine the types of food they can cultivate, the optimal nutrient dosage, and the most effective methods for minimizing nutrient loss.In addition, soil can be considered a living system because it contains organic matter and clay minerals that help soil particles unite, hold water, and participate in microbial processes, which are essential components of soil health, sustainability, and agriculture [4].

Soil characterization remains the central point of any research aimed at preventing contamination and remediation of contaminated areas.Knowing soil chemistry and sorption capacity, or the fate of pollutants in the soil, is of utmost importance because soils are the main natural attenuation agents for the remediation of contaminants.Therefore, it is imperative that industrial waste, heavy metals, and pesticides, among other pollutants, be precisely identified in terms of mobility, bioavailability, and specific adsorption.In addition, soil chemistry plays a vital role in changes in the environment, protection of water sources, return of land to nature, and revival of land.Moreover, geotechnical and civil engineering, to which the key issues are the soil framework, stability aspects, and safety factors, are also susceptible to soil aspects. The type of soil may vary depending on the size of the grains, level of compaction, and mineralogy, which may further influence the permeability, bearing capacity, shrinkage, and swelling potential. It is due to these properties that soil can be used to provide building foundations, embankments, and construction [5].

Different soil types can be so complicated and detailed that much work is required to explain them, even if they are assumed to be of the same kind.Conventional techniques, including chemical digestion, mechanical sieving, and pH measurement, are employed to collect data for soil characterization.However, these methods are typically slow, inaccurate, and hazardous.In addition, traditional soil characterization methods often result in the reporting of bulk or average values for different locations; thus, changes in the microstructure or mineralogy of the soil cannot be accurately tracked.Additionally, classical methods do not separate the combined effects of crystalline and amorphous phases, nor do they consider the specific organic compounds that influence reactivity and soil fertility.Spectroscopic and microscopic methods are gaining ground because they provide faster, more accurate, and environmentally friendly analytical alternatives for soil characterization [6].

With the resolution parameter set high and the experiments being non-destructive, multispectral studies of soil have become possible due to recent advances in microscopy and spectroscopy. A large number of techniques from the realm of soil science have been introduced: X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, Scanning Electron Microscopy (SEM), Energy-dispersive X-ray spectroscopy (EDS), and ultraviolet-visible (UV-Vis) spectrometry, which, when used together, can comprehensively evaluate soil properties and furnish the information that is missing in each other. To determine the mineral phases in the soil, X-ray Diffraction

(XRD) was used to analyze the diffraction pattern produced when X-rays were shot through the molecular crystalline lattice of the mineral.These characteristics are complemented by soil minerals, whose signature diffractogram can be identified as quartz, feldspar, kaolinite, and montmorillonite, enabling the identification of the mineral phases present in the soil. Fourier Transform Infrared Spectroscopy (FTIR) can also identify the same characteristics because it identifies the functional groups and molecular vibrational features of soil components, including silicates, carbonates, and hydroxyl groups, and soil additives in the organic matter or minerals, organic context, and groups, not similar to soil fertility monitoring, soil microbial activity facilitation, and encouragement [7, 8].

Because it unveils molecular details based on the principles of inelastic light scattering, Raman Spectroscopy is coupled with FTIR measurements. Raman spectroscopy enables the identification of organic and inorganic compounds, as well as their specific applications in characterizing soil organic carbon, silicate bonding, and carbonate. The main advantage of Raman spectroscopy is its ability to detect subtle molecular changes in a soil sample subjected to weathering or contamination cycles.Scanning Electron Microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDS) provided high-magnification images of the soil microstructure and surface morphology.The SEM features of the soil particle shape, porosity, and aggregation were identified.In conjunction with SEM, EDS readings are indications of the spatial elemental compositional information of the preconditions; hence, Si can be the most appropriate reactivity (in a chemical and fertility sense) agent in a spatially representative saprolite if the Al, Ca, and Fe sequences are considered [9, 10].

When used in conjunction, these methods connect traditional macroscopic studies with more recent nano- or micro-scale research to build an integrated understanding of soil behavior in specific environmental contexts.These methods can also be applied to assess how organic and inorganic matter may interact and to confirm the presence of a contamination footprint, while linking soil structure, composition, and function [11].

Several tests employ destructive techniques, which render some or all of the samples unusable for further use in follow-up measurements/analyses or assessments. Two types of destructive techniques include acid digestion and combustion analysis. In both processes, chemical calculations are the most accurate; however, the samples are destroyed and no longer available for analytical or interpretive measurements.Nondestructive techniques provide a measure without affecting or changing the internal composition of the sample.Examples of standard nondestructive techniques would include X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and UV-vis spectroscopy.This enabled further measurements of the intended results using the same sample.Non-destructive techniques enable in situ evaluations, comparisons, and long-term soil measurements. Non-destructive techniques allow small amounts of soil to be wasted. In addition, soil can be measured under natural conditions several times at different intervals [12].

Soil characterization provides even more information about soil properties.This forms the basis of green and eco-friendly agricultural practices.Understanding soil features, including organic matter, nutrients, and mineral concentrations, makes site-specific agriculture a feasible option.Characterizing soil may also help mitigate climate change by quantifying soil organic carbon and understanding the interactions between clay and minerals that determine soil carbon sequestration capacity. These parameters and characteristics can provide insight into environmental perspectives when land managers or policymakers are provided with information to develop remediation actions for soil restoration, erosion management, or pollution tolerance [13].

The motivation for this study was to develop a comprehensive analysis framework that integrates the advantages of different available spectroscopic and microscopic methods. Many of the previous studies mentioned earlier have been based only on single methods and offer only a limited understanding of soil behavior. However, the applied multi-methods allow the synergy of mineralogical, chemical, and morphological properties of soils; therefore, a comprehensive characterization of soil samples using five different analytical techniques: X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), Raman Spectroscopy, scanning electron microscopy with energy dispersive spectrometer analysis (SEM-EDS), and ultraviolet visible spectroscopy (UV-V). The interchangeable application of these techniques brings to the fore the complementary nature of various methods used. XRD is used to determine crystalline phases, whereas FTIR and Raman spectroscopy determine the molecular and elemental composition. SEM-EDS gives data on the surface morphology and the composition of the elements, and UV-V

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spectroscopy shows the oxidation state of the soil. Thus, we obtained at least the multidimensional assessment of soil structure and fertility.

Three main objectives were fulfilled in this research: (1) to implement a rather big set of contemporary analytical methods to characterize a mixture of mineralogical and chemical structure of any given sample of soil, (2) to take into consideration the influence of each chemical test and its limitations, and (3) to compare the benefits and drawbacks of the use of the destructive method of soil sampling, and the non-destructive one. Besides, one of the objectives of spectroscopic indicators of soil and soil fertility outputs was to explain potential relationships that could be used in agricultural and environmental decision-making processes concerning soil fertility. Besides, because spectroscopic and microscopic analyses offer a broader scope of operation on which to sample soils, it may be a core initial step in enhancing sustainable soil management systems to determine long-term ecological health.

Five varied methods were used to study the soil samples, including electron microscopy (SEM and EDS), X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, synthesis (amalgamation) techniques, and Raman spectroscopy. When the individual methods were applied separately, they showed different soil characteristics depending on the organic matter content, topography, the molecular interaction, and the structure of the crystal lattice. Therefore, an agglomeration study results in one more and more detailed soil analysis, which offers the most favourable terms to agricultural, environmental, and geotechnical effects. The instruments all represent the soil through analysis. We also concomitantly executed and tested the performance of both methods in reading, assessing, and drawing inferences of data and type-value comparisons. To solve this problem, we attempted to offer a wide range of approaches to characterizing the soil through an overall meta-analysis. This means that there could have been more sustainable land management.

Although conventional methods for studying soil physical, chemical, and biological aspects have been reliable, emerging spectroscopy and microscopy techniques have gradually presented enhanced efficiency, accuracy, and range in their evaluations.A novel, holistic, noninvasive, and eco-friendly approach for soil characterization using XRD, FTIR, Raman spectroscopy, SEM, EDS, and UV-Vis spectroscopy is provided in this review.The present investigation into soil fertility, agricultural management, and eco-friendly practices aims to preserve Earth's valuable resources for future generations.

II. NEED FOR SOIL CHARACTERIZATION

Soil characterization is essentially the basis of the current knowledge of the different agricultural practices, environmental management, geotechnical engineering,and an understanding of the properties of soil resources necessary for plant production, ecological stability, and construction support.Soil is a complicated, ever-changing system with heterogeneous physical, chemical, biological, and mineral properties.Soil characteristics influence the behavior and function of the soil.Soil characteristics can vary significantly in other places, even on small spatial scales, and remain important in determining soil fertility, plant-available water storage, pollutant movement, and soil loading stability. The precise, convenient, and in-depth soil property information is vital in the decision-making process concerning agricultural management, environmental protection,and proper planning of land use [14]. The characterization of soils is compulsory to identify whether the soil can sustain the growth of plants.Each plant species requires soil with a specific texture, adequate nutrient availability, sufficient moisture potential, and a suitable pH level.Based on the knowledge of soil properties, farmers and agronomists can decide more accurately whether these properties are nutrient-deficient or nutrient-rich in terms of nitrogen, phosphorus, potassium, calcium, and magnesium.

Determining soil properties is a powerful tool to rationalize fertilizers and irrigation to improve plant productivity. Additionally, soil characterization is necessary to reveal ways to mitigate or reduce pollutants leached through soil characterization when soil properties concerning the nutrient limits are measured or sampled [15].

For instance, soil properties are fundamental in determining the level of soil organic matter, that is, soil organic matter (SOM), as well as microbial activity, as these are components of the soil structure, nutrient cycling processes of soil systems, and soil water holding capacity. The physical channels for soil aggregation, aeration, and cation exchange capacity (CEC), which promote plant production in the soil and provide a living space for microorganisms, thereby increasing general ecosystem diversity and function, are some ways soil organic matter can improve soil. Consequently,

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soil characterization can be used to determine whether any soil has the potential to lose nutrients.In this case, treatments such as lime, gypsum, or organic compost neutralize acidity, salinity, and nutrient loss, which is only apparent.In short, understanding soil characteristics will greatly help farmers and agronomists use best management practices to ensure the continuation of soil fertility and prevent soil degradation [16].

The role of soil in the environment needs to be precisely determined through soil characterization so that environmental monitoring and management can be effective. The soil can store and filter pollutants.Thus, it can determine how many contaminants will be retained and degraded, as well as whether they are transported into groundwater or surface water systems.Once the chemical properties and adsorption potential are characterized, the soil can indicate its capacity to absorb or release contaminants such as heavy metals, pesticides, hydrocarbons, and industrial by-products [17].

Soil characterized by a higher quantity of clay and organic matter can generally absorb pollutants, thus limiting their spread and risks to ecosystems and human health in the vicinity of or areas influenced by contaminants. On the other hand, sandy soils, which typically have a lower organic matter content, may possess properties that enable contaminants to move deeper into the soil profile more quickly, thereby becoming a source of pollution that leads to groundwater contamination. Environmental scientists perform soil characterization, which can be used to create maps of pollutant movement, locate sources of contaminants, and formulate remediation plans for cleaning up contaminated soils, such as phytoremediation, soil washing, and stabilization. Additionally, soil description may determine the influence of land use or the area's historyby gathering baseline data and evaluating soil genetic changes.It is necessary to comprehend the impact of global warming and the ongoing human pressure to determine how the chemical and physical aspects of the resilience of soil systems will stipulate management interventions to reduce environmental quality [18].

Soil characterization is necessary for civil and geotechnical engineers because it is the main condition for structural stability, safety, and pleasing appearance.The load-bearing capacity, compressibility, permeability, and soil cohesion parameters refer to soil evaluation, which aims to identify the most suitable soils for construction projects, such as buildings, bridges, roads, and dams.Soil characterization data can help geologists and geotechnical engineers design foundations that can resist changing loads over time and lower the risk of soil subsidence, landslides, and erosion caused by soil [19].

It is essential to identify the mineral makeup of soils, especially clay minerals that can expand (e.g., montmorillonite), so that the behavior of soil as a construction material can be predicted in the case of changing moisture conditions.The problem with swelling soils is that they expand when absorbing water and shrink when water is released; therefore, they have the potential to cause structural damage.Thus, engineers and designers will be more helpful in conducting X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) tests to determine the mineral and moisture content, which is crucial for risk assessment and design.The physical characterization of soils also defines the factors that influence the geotechnical properties of soil, including soil particle size, porosity, and permeability.The information obtained from them will be sufficient for engineers to develop drainage plans, thereby lessening the chances or eliminating the risk of collapse of weak structures.Soil data are extremely valuable documents in first-class engineering work due to the increased risk, additional costs of future repairs, liability for future maintenance, risk of building collapse, and environmental impacts resulting from unstable structures [20, 21].

Soil characterization supports the long-term goal of soil conservation and land restoration, rather than focusing solely on immediate concerns. Many parts of the world have lost productive topsoil due to degradation related to erosion, deforestation, intensive agriculture, and urbanization. Physical characteristics, such as texture and aggregate stability, and chemical indicators, including nutrient status and salinity, can help scientists identify land that is more prone to soil erosion and devise ways to protect it. Soil characterization can verify that a property is suitable for reforestation, erosion control, and/or organic amendment to restore productivity. Because soil characterization establishes the weaknesses in a land that systemically lead to restoration efforts, it acknowledges restoration efforts in the future to monitor changes over time (such as organic carbon, nutrient balance, and microbial activity). In the case of arid and semi-arid lands, characterizing the moisture retention and infiltration behavior of soil is crucial for developing an effective irrigation system and enhancing irrigation water efficiency. Thus, characterization is critical for sustainable land management because it provides a framework to ensure these resources remain available and are used well with environmental accountability[22].

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Modern soil characterization methods highly depend on the latest developments in spectroscopic, microscopic, and computational technologies. To a large extent, these methods are quicker, simpler, and more precise.Spectroscopic methods, such as Fourier Transform Infrared (FTIR) Spectroscopy, Raman Spectroscopy, and UV-Visspectroscopy, can locate and monitor the soil's total organic carbon (TOC) in a very short, portable, and non-destructive manner.X-ray diffraction (XRD) is applicable in the study of soil minerals to characterize the crystalline structure of minerals, and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) can be used to characterize the mineral structure on a micro- and nanoscale [23]. Each of these hydrochemical and mineralogical characterization techniques could help the researcher to answer questions that would not be possible without the overall knowledge of organic and inorganic soil components, with specific applications in the field of nutrient cycling, mineral weathering, and identification of potential sources of contamination. The high rate of instrumentation, especially when compared to traditional wet chemistry analyses, allows for reducing the sample size and analysis time to provide a quicker reaction to the scientific community, thus challenging the possibility of maintaining the same level of sample integrity when preparing samples to undergo further analyses. The key aspects of the long-term soil monitoring are sample integrity and the possibility of repetitive analysis (in-situ analysis), in particular, when the distribution of physical characteristics and composition of the soil is expected to be variable.

The decision on the destructive and non-destructive analytical procedures also has an impact on the soil characterization. Destructive processes (e.g., chemical digestion or thermal breakdown) completely modify and /or damage the sample. Nevertheless, they are common when the measurements of elements in the sample are to be done in a single analysis. This is an advantage of repeat analysis and constant monitoring of the environment, since the sample can be studied further using non-destructive methods. A growing trend in non-destructive spectroscopy involving a sample modification (e.g., X-ray diffraction (XRD), Fourier transform infrared (FTIR), Raman, and UV-visible spectroscopy) is finding growing popularity because of its many benefits, such as speed, minimal alteration of the sample, and its capability to estimate multiple values of the samples. Constructive role in the structure of attaining the sustainability of global materials can also be non-destructive assays, in that they are environmentally friendly and do not interfere with the advancements that are being made in the field of green chemistry. The popularity of sustainable management of resources has increased in our society [24].

Digital soil mapping and precision agriculture require soil characterization to enhance the process. Precision agriculture involves the application of geospatial technology and sensor-based technologies in order to determine the spatial variation of soil responses in order to improve input management, e.g., water and fertilizer management. The characterization of soil levels is the building block of predictive models, which provide management prescriptions for precision agriculture. Similarly, through digital soil mapping, which combines the results of remote sensing and farm-level analytical data, vivid information is displayed regarding the spatial differentiation of soils in the context of sustainable land utilization, conservation, and agricultural mapping [25].

The world is aware that soil characterization is the first and most crucial action in the process of understanding, management, and conservation of the numerous and priceless resources. That is where the account of soil plays a vital role because the relations and interactions between minerals, organic matter, water, living organisms, and all processes leading to the agricultural production, environmental care, and development of infrastructure are pretty complex. The growing ecological requirements of people and the impact of global warming on the soil systems are the reasons that the system should be studied in a multidisciplinary and comprehensive manner. As such, the idea of soil characterization has taken the scientifically viable concepts and application of spectroscopes and microscopic techniques, whereby soil can be handled sustainably and conserved to be used in the future.

III. METHODOLOGY

The discipline necessitates alternative techniques of quantifying soil characteristics in order to have a holistic picture of the soil. There is also the use of microscopic and spectroscopic methods. All the other techniques gave more details regarding the characteristics of soils. As an example, they will be able to identify the existence of crystalline minerals, functional groups, molecular vibrating modes, surface morphology, and composition of elements of the soil system. It is a study on the progress of characterization techniques. These comprise five different methods of analysing soil samples using X-ray Diffraction (XRD), Fourier Transform Infrared (FTIR) Spectroscopy, Raman Spectroscopy, Scanning Electron Microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and ultraviolet-visible (UV-Vis) spectroscopy. However, when combined, they are an overall complex of multidimensional studies of soil structure on mineralogical, molecular, and chemical levels. The experiment involved four significant phases that comprised earth sample collection and preparation, equipment setup, data collection, and data analysis. The soils of the studies were sieved and air-dried to keep some consistency and comparability in the results of the different devices. The conditions of all the techniques are as follows:

3.1 X-ray Diffraction (XRD) Analysis

An essential tool that has to be understood is X-ray Diffraction (XRD), which identifies the nature of the crystalline features of a soil and mineralogy. It can determine the type of minerals or the percentage proportions of the minerals, which, simply put, are the main determinants governing soil texture, swelling, and retention of nutrients. Quartz, feldspar, and two clay minerals (kaolinite and montmorillonite) make up virtually all the minerals in the soil. The XRD is a non-destructive method used to analyse the mineral structure that gives a significant change to the physical and chemical characteristics of the soil.

- **Principle:**One of the more widespread techniques of analysis applied to determine the mineral crystal structure and phase composition of soil is X-ray diffraction (XRD). In any crystalline sample, the beam of X-rays striking the sample will be scattered off by the sample at some angle in obedience to the law of Bragg:

$$n\lambda = 2d\sin\,\theta \qquad (1)$$

  where n is the total number of diffraction orders. where λ is the wavelength of the X-rays, d is the distance between the atomic planes, and θ is the diffraction angle. The diffraction pattern produced was analogous to a fingerprint, which made it possible to identify the crystalline minerals.
- XRD analysis was performed using an X-ray diffractometer with a Cu Kα source (λ = 1.5406 Å) at 40 kV and 30 mA.Standard Si was used to adjust the XRD instrument to the peak positions.The scan range was from 5° to 80° 2θ with a step size of 0.02° and a counting time of 1s.
- Procedure: The powdered soil material was compacted in a sample holder in a uniform and even fashion. The data on diffraction were noted at room temperature. X'Pert High Score or JADE software was used to identify the peaks in the reference libraries in their diffraction pattern (ICDD PDF-4+). To have reasonable estimates of the proportions of the relative abundances of the phases, each mineral identified by the refinement of Rietveld was determined.
- Interpretation: The XRD patterns reveal that the primary minerals were quartz, feldspar, and calcite, and the clay minerals were found to be kaolinite, montmorillonite, and illite. The acuity and intensity of the minerals identified in the measured peaks were related to the crystallinity levels of the minerals. Additionally, the shrink-swelling property of the soil in relation to water content has also been demonstrated using montmorillonite minerals. On the contrary, kaolinite and quartz possess relatively constant mineral structures and moderate cation exchange capabilities.

3.2 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

The infrared (FTIR) spectroscopy was utilized to determine the functional groups and the molecular bonds in the soil using Fourier-transform infrared (FTIR) spectroscopy. The FTIR spectroscopy technique is applied to give information about organic and inorganic substances based on their typical infrared absorption peaks. FTIR is a method that aims at the primary components of the soil, i.e., the determinants of its fertility, and chemical reactivity, such as silicates, hydroxyl groups, carbonates, and organic matter. FTIR non-destructive analysis assists in developing an improved insight into the relationship between the mineral and organic components of a soil sample, especially where one of the constituents overlies another.

- Principle: Fourier transform infrared (FTIR) Spectroscopy is a technique of identifying the functional groups as well as the motions of the molecules in different components of soil by way of the absorption of infrared radiation. The infrared radiation that was absorbed is a measure of particular spectral regions, which are vibration modes that can be quantified in specific molecules. FTIR spectroscopy can also be applied in semi-qualitative and semi-quantitative identification of organic and inorganic soil components by scientists. FTIR spectroscopy is a conventional technique of tracking the presence of silicates, carbonates, hydroxyls, and organic matter in soil profiles.

- Instrumentation: FTIR was done using a Bruker Tensor II FTIR spectrometer using an Attenuated Total Reflectance (ATR) accessory. The spectral range was 4000 to 400 cm-1 with a resolution of 4cm-1. The process of averaging scans took 64 scans per sample to enhance the signal-to-noise ratio. Additionally, background spectra were taken after all samples were measured to enable the correction of atmospheric interference (CO2 and H2O).
- Procedure: First, a small amount of powdered soil was placed on the ATR crystal surface and rubbed into it to ensure that the contact was more efficient. The spectra were recorded at room temperature, and a baseline correction was performed. The identification of the peaks was done relative to their common frequencies of absorption.
- Interpretation: FTIR spectra show that the most powerful absorption bands are found at approximately 10001100 cm -1 (SiO silicate), 14001500 cm -1 (normal carbonate vibrations), and 36003700 cm -1 (OH stretching of hydroxyl groups). They used their fingerprints to ascribe the significant proportions of minerals to silicates and clay minerals. The presence of organic matter (C=O and CH vibrations respectively) is supported by the presence of the peaks near 1650 cm and 2920, 2850 cm respectively. These are real concomitant mineral and organic ratios in the soil, indicating functional soil chemistry and fertility.

3.3 Raman Spectroscopy

Raman spectroscopy enhances FTIR analysis by scattering light, rather than absorbing it, and provides additional information about the concentration of the molecules being analyzed. Raman Spectroscopy is used to detect crystalline and amorphous materials, minerals, and to identify organic carbon structures in soils. Raman Spectroscopy identifies silicates, carbonates, and organic materials, bridging the relationship between molecular composition, soil fertility, and organic matter content. Raman Spectroscopy provides evidence for mineral-organic interactions and serves as corroboration and supplementary evidence for FTIR and XRD findings.

- Principle: Raman spectroscopy was used along with FTIR to obtain vibrational information from the inelastic scattering of a monochromatic light source (Raman effect).Most incident photons scatter elastically, thereby preserving the energy. However, when a photon interacts with a molecular bond, elastic scattering events occur, and a small fraction of the incident photons scatter at an energy shift related to the transition of vibrational energy of the molecule. Therefore, the Raman spectra represent the "molecular fingerprints" of organic and inorganic components.
- Instrumentation: A Horiba LabRAM HR Evolution Raman spectrometer with a CCD detector and a 532 nm excitation laser was used for the measurements. The laser power was maintained at a maximum of 10 mW to prevent heating or sample degradation. The spectrometer gathered spectra from 100 to 3500 cm−1, with a spectral resolution of 1 cm−1.
- Procedure: To analyze soil samples, the samples were ground into a powder and placed onto glass slides. A laser beam excites the samples, and a 50× objective lens was used to collect the measurement spectra. Multiple spectra were collected from different locations owing to the heterogeneity of the samples. All the spectra were calibrated from a silicon wafer to the 520 cm^{-1} line.
- Interpretation: Distinct silicate bands associated with Si-O-Si stretching (~465 cm ^{1}) and carbonate vibrations (CO_3^{2-}, ~1085 cm ^{1}) were observed in the Raman spectra, along with quartz peaks within the ~800 cm ^{1} range. Weak bands (~1350 cm ^{1} and ~1580 cm ^{1}) suggest that some mineral components might reflect humic and fulvic-type organic carbon structures. Overall, the Raman data only solidified the FTIR data, and both

provided complementary information regarding the interactions between the mineral and organic matter phases at the molecular scale.

3.4 Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS)

Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX) is a suitable method for determining the soil composition.SEM provides a detailed picture of the soil surface and the spread of the particles. EDX indicates the amounts of silicon, aluminum, iron, calcium, and magnesium. If you do both, you can see how the soil feels, holes, and chemicals are tied together. The pictures and readings also help you understand what is happening with the soil, such as how it might react with the substances and how nutrients move around.

- Principle: Scanning electron microscopy (SEM) enables high-resolution imaging of the soil surface by scanning a sample placed under the effects of a focused electron beam. Secondary and backscattered electrons were produced as the beam interacted with the sample. These electrons can subsequently accumulate to provide topographical images. When combined with SEM, EDS enables the simultaneous examination of elemental composition and morphology by detecting X-ray emissions resulting from the interaction of the electron beam with the sample. Therefore, it is possible to make connections between chemistry and morphology.
- Instrumentation: A field-emission scanning electron microscope (FESEM; JEOL JSM-7610F) equipped with an Oxford Instruments EDS system was used for imaging and elemental analysis. The imaging parameters were as follows: acceleration voltage, 15 kV; working distance, 10 mm; and beam current, 1 nA. Images were captured at magnifications ranging from 500× to 10,000×.
- Procedure: Soil bonding was carried out with the conductive carbon adhesive tape by bonding soil to an aluminum stub to enhance the conduction at the surface. Samples were dried under air and a thin layer of gold was deposited through sputtering. The samples were put in a vacuum and scanned in high-vacuum in the SEM. Scanning was also done to determine the elements which were denoted by the spectral peaks of EDS spectra.
- Interpretation: The FESEM pictures covered the micro-textural characteristics of the soil material, which meant that the material was not uniform on its surface, was porous in form, and even had varying particle sizes, suggesting that they were other sources of the soil materials that constituted them. As the analysis of the EDS showed that the primary elements of the soil were Si, Al, Fe, Mg, and Ca, it was possible to state that oxides and silicate minerals were present. SiO2 and Al2O3 were used as mineralogical anchors of the soil. Some iron oxides and carbonate minerals were also present in the soil such as iron (Fe) and calcium (Ca). The SEM pictures and EDS analysis have indicated the variability of the soil morphology and composition, variability of the microstructural conditions, reactivity and fertility.

3.5 Ultraviolet-Visible (UV-Vis) Spectroscopy

UV spectroscopy was used to study the optical properties of soil organic matter and iron oxide using Vis spectrometry. The latter includes both UV- and visible-light-absorbing substances (UV-Vis), such as humic materials and ferric compounds, which all influence the fertility, color, and photochemical behavior of soils as a function of their long-term exposure to UV radiation.Therefore, it can be used as an effective, comparatively nondestructive, low-cost method for analyzing soil organic content and other health indicators.

- Principle: UV-Vis spectroscopy is used to understand a sample's absorption and reflection of ultraviolet and visible light and to determine its optical and electronic characteristics. It is one of the most indicative measures for chromophores (i.e., organic matter, humic substances, and iron oxides or minerals) because most of these compounds confer color to soils, influence productivity, and affect soil fertility.
- Instrumentation: In continuation of the analysis, samples were measured on a Shimadzu UV-2600 spectrophotometer using a slit width of 1 nm and recording wavelengths over the 200–800 nm range. All the samples were measured in quartz cuvettes to obtain a transparent optical window in the UV range.

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- Procedure: For the analysis, 1 g of soil was added to 50 mL of distilled water and stirred for 30 min.The resultant mixture was centrifuged, and the supernatant was filtered through a 0.45-μm membrane. The absorbance spectra of the filtered solution were then measured at room temperature. Distilled water was used as a blank.
- Interpretation: UV-Visspectra showed that there are two absorption peaks between 250-300 nm and 400-450 nm that are commonly associated with organic aromatic compounds and iron oxides, respectively. The fact that various values of absorption were present meant that there was more organic matter and Fe3 iron oxides, which would not only influence the color of the soil but also its fertility. These findings indicate that UV-Vis spectroscopy can be used in the rapid and non-invasive measurement of soil OMA and Fe concentration**.**

Each of the five methods applied was rather supplemental in nature and they provided different pieces of information that would improve the explanation of the source of the soil better. Phase identification and determination of the degree of crystallinity was performed through the XRD method and the chemical properties and functional groups were examined with the FTIR and Raman spectroscopy. To give one example, SEM-EDS is an efficient device to determine the surface features of a specimen and its elemental structure. The UV-VIS spectroscopy time domain on the other hand, was used to show the organic and optical characteristics of the soil material. Each of the 5 non-destructive methods led to complete description of the soil material, including mineralogical, chemical and structural characteristics. XRD and SEM-EDS were used to identify inorganic and mineral constituents, whereas the organic matter and molecular interactions were studied with the help of FTIR, Raman, and UV-VIS spectroscopy. Nevertheless, all the five methods did not alter the material properties of the soil. Precise samples of soil that were at the same point were collected on several occasions. These techniques are a perfect substitute to the conventional laboratory standard techniques, encompassing wet chemistry and complicated spectrometry, e.g., Raman and UV-VIS spectroscopy.

IV. RESULTS AND DISCUSSION

XRD, FTIR, Raman spectroscopy, SEM-EDS and UV-Vis spectroscopy have been under exploration to find soil physicochemical parameters, minerals as well as organic matter. To certain extent, both techniques present a variety of data and knowledge; they make up a full picture of the complete soil material, its chemical and molecular structure. The results helped to understand the nature of the soil system, mineral progression, functional group, the distribution of elements, and the existence of organic matter. All the analytical methods will be summarized and synthesized now in the subsections given below giving useful data on fertility of soil and soil stability and their uses in sustainable land use.

4.1 X-ray Diffraction (XRD) Analysis

The diffraction patterns are a measure that suggests variation in the mineral composition, expressed in the variation of the peak locations. Montmorillonite allows soils to either increase or decrease in volume as a result of the presence of secondary feldspar and clay.

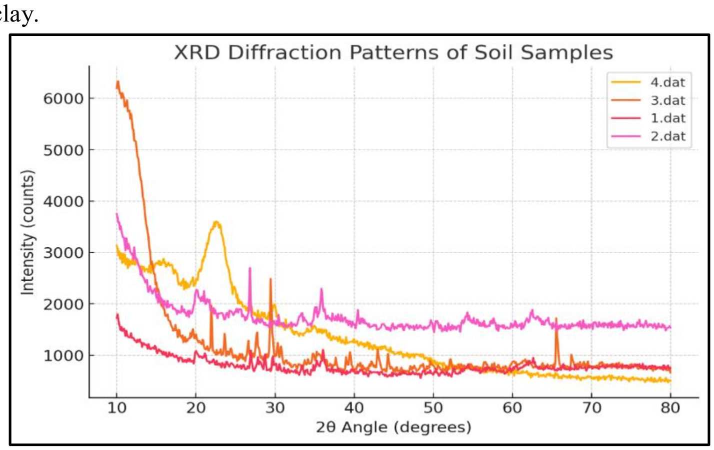

Fig.1 XRD Diffusion pattern of the soil sample

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The X-ray diffraction (XRD) spectrum obtained from the soil sample, as shown in Fig. 1, reveals a few sharp and clear-cut peaks which point to the availability of crystalline and non-crystalline minerals. The quartz (SiO2) was observed at the 20.9, 26.6, 36.5, 39.5, 50.1, and 59.9 degrees, which are the diffraction angles (2nd).The sharply defined and narrow-range overall peaks for quartz indicate a high degree of mineral crystallinity and stability characteristic of soils with intense weathering from granitic parent material.

The other peaks between 27.8° and 31.4° 2θ likely indicate the presence of feldspar ($KAlSi_3O_8$), suggesting that aluminosilicates may provide cation exchange capacity (CEC) and nutrient retention in the soil. The lower peaks at 12.4°, 24.8°, and 35.0° 2θ suggest the presence of kaolinite ($Al_2Si_2O_5(OH)_4$) and montmorillonite [$(Na, Ca)_{0\cdot3}(Al, Mg)_2Si_4O_{10}(OH)_2\cdot nH_2O$], which are clay minerals known to improve soil plasticity and moisture retention. The broad peak near 29.4° 2θ likely indicates the presence of calcite ($CaCO_3$), a characteristic of carbonate minerals, which is a sign of soil alkalinity and buffering capacity.

The soil texture was indicated by the relative intensities of the peaks for both quartz and clay minerals, thus revealing a sandy–clay texture that is probably a result of better aeration and medium nutrient-holding capacity.The reverse relationship between kaolinite and montmorillonite suggests that the soil is moderately weathered and has excellent ion-exchange capacity.The absence of an amorphous hump indicates that low-amorphous silica (or potentially ill-defined oxides) is either present or shaped via consolidation (i.e., bulk mostly crystalline matter shaped via geological processes).The XRD results summarized the mineral components, which included quartz and feldspar, providing mechanical strength.At the same time, kaolinite and montmorillonite represent the transport and exchange of water and nutrients, which help sustain their ecosystem fertility potential and potential for sustainable agriculture.

4.2 Fourier Transform Infrared (FTIR) Spectroscopy

The relevant absorption peaks in the FTIR spectrum showed silicate at 1000–1100 cm^{-1}, while carbonate compounds were merely inferred from peaks at 1400–1500 cm^{-1}. Peaks associated with OH stretching corresponded to hydrated clay minerals. FTIR data were used to identify soil functional groups by identifying and plotting the infrared spectra.

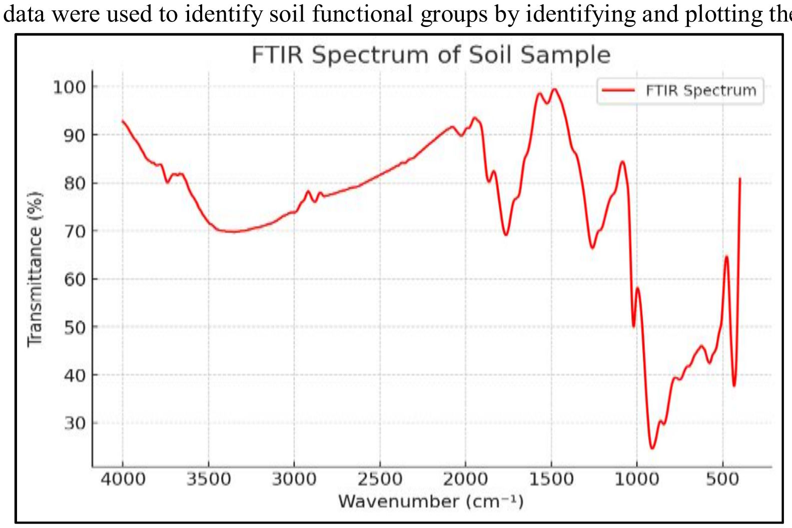

Fig.2 FTIR Spectrum of the soil sample

The FTIR spectrum (see Fig. 2) exhibits an intricate pattern of absorption peaks in the 4000 to 400 cm^{-1} region, corresponding to naturally distinct molecular vibrations that will assist in characterizing the soil's mineral and organic components. The sharp and broad absorption band in or around 3620–3700 cm < sup>< le ¹ represents the O–H stretching vibrations of the kaolinite and montmorillonite hydroxyl groups, indicating the structure and adsorbed water in the soil sample. This addition supports the conclusion that the soil contained hydrated clay minerals (i.e., montmorillonite and kaolinite) that could swell and retain water in response to fluctuations in the moisture levels of its environment. Additionally, the medium-intensity band observed in the FTIR spectrum at ~3400 cm^{-1} is consistent with that of the –OH group. This is likely due to the hydrogen bonds associated with adsorbed water and/or organic matter. The peaks observed at approximately 2920 and 2850 cm <> ls ^{1} are also evidence of C–H stretching vibrations associated with CnH2n organic matter (e.g., aliphatic hydrocarbons) as a result of organic soil amendments (i.e., humic or fulvic fractions), which are known to increase microbial activity and nutrient exchange capacity in amended soils.

The clear presence of a doublet between 1400 cm^{-1} and 1500 cm^{-1} signifies strong asymmetric stretching vibrations of the carbonate (CO_3^{2-}) ion, which supports the presence of carbonates shown in X-ray diffraction (XRD) studies. Carbonate indicates preparation for moderate alkalinity and can resist acidification from the surrounding environment. Another prominent and noteworthy peak in the 1030–1100 cm < B-> ^{1} region indicates silicate minerals' Si–O stretching vibrations (quartz and feldspar).The better definition/shape of these peaks suggests that silica underwent some degree of crystallization. Additionally, minor peaks were observed at around 800 cm^{-1} (Si–O–Al bending) and nearly 470 cm^{-1} (Si–O deformation), indicating the presence of other frameworks in aluminosilicate clay minerals. Also, the existence of more peak activities means that there are silicate, carbonate, hydroxyl, and organic bands in the soil. All these are molecular signs of mineral-organic interactions of the soil. Other bands show broad peaks and one in the area of 3400 cm -1 that co-exists with the signal of organic matter and clay hydration layers. It is the interactions that cause nutrient uptake and aggregate stability, which influence soil fertility and stability.

4.3 Raman Spectroscopy

The XRD and FTIR were validated with the Raman spectra, which provided extra evidence in an attempt to prove the presence of transparent silicates and carbonates. The organic matter was explained using the organic signatures. Each figure depicts a Raman spectrum, which indicates the molecular vibrations common to the molecules in the soil.

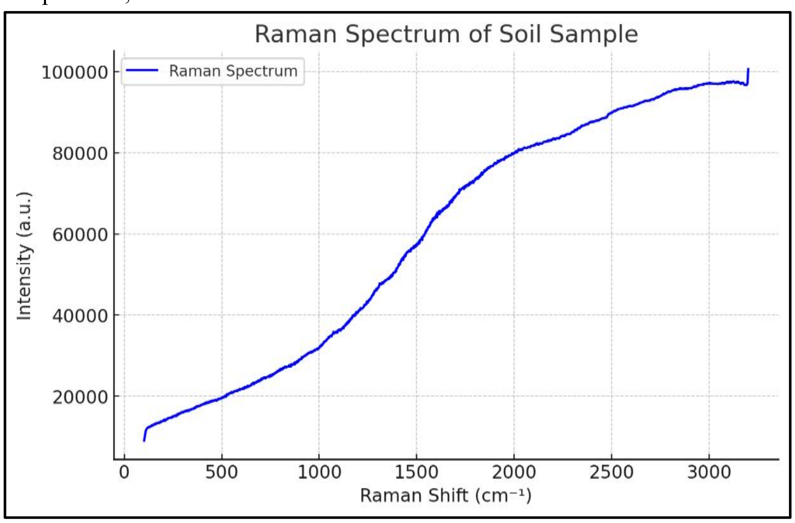

Fig.3Raman Spectrum of the soil sample

As Fig. 3 indicates, the Raman spectrum obtained validates and clarifies the descriptive data of the molecules in Section 3.1 (FTIR). The Raman spectrum exhibits a high peak of around 465 cm -1, which is due to the symmetric stretch vibration of quartz (Si-O-Si), indicating that quartz is the primary mineral phase. Two other peaks were also seen at 0.798 and 1086 cm-1, which can be related to the Si-O stretching of the Al in feldspar and carbonates.The two lower-intensity bands, centered at ~approximately 1350 cm-1 (D-band) and 1580 cm-1 (G-band), are attributed to disordered and graphitic carbon structures, suggesting that organic carbonaceous materials are present in the soil.The bands were attributed to the C=C stretching modes of humic substances and lignin. Therelatively low intensity of the organic carbonaceous content in the soils suggests that organic structures may still be present.Organic carbonaceous structures may be a potential source of fertility and carbon sequestration.

The small peak in the 360–380 cm^{-1} range probably indicates Al–O and Mg–O vibrations in montmorillonite and illite, reinforcing the clay mineral contribution and supporting the XRD results.The Raman data also have slightly broad features at approximately 980–990 cm <ts> ^{1}, consistent with Si–O stretching in amorphous silica or secondary silicate phases present in the soil, providing further evidence for some minor weathering effects.The intensities in the Raman spectrum further reinforce the presence of silicate, carbonate, and organic functional groups in the soil, fitting the soil into an amphibious definition that incorporates both mineral and organic aspects.Thus, a soil incorporating crystalline quartz and feldspar, along with clay minerals and organic matter, should be a functional system for both plant establishment and growth performance, as well asproviding mechanical resistance to support growth.Additionally, the Raman spectroscopic method was shown to be sensitive for detecting organic (and inorganic) fractions of soil, as only a minimal amount of pre-sample preparation was required.

4.4 Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS)

The SEM images indicate a heterogeneous mixture of minerals that differed in size.The primary soil constituents were confirmed by EDS analysis, which showed high levels of silicon and aluminum, confirming the presence of silicate minerals. The structural and reactive attributes of the soil minerals were influenced by the relatively large abundance of SiO_2-, AlO-, MgO-, and Ca-based minerals found in the elemental composition analysis.

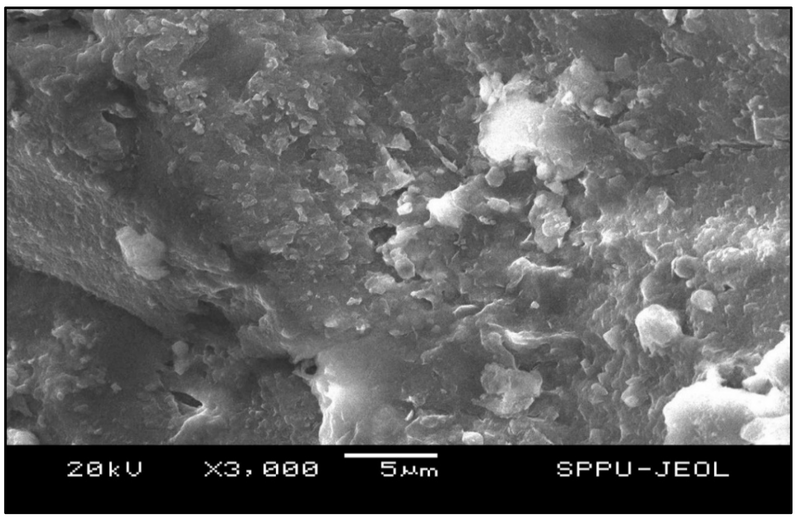

Fig.4 SEM-EDS analysis of the soil sample

Micrographs made with the help of SEM (Fig. 4) represent the morphology, texture, and structure of the soil on a high level. According to the micrographs, it is possible to note that the particles are irregular in nature, as they have uneven edges, coarser surface texture, and are micro-porous. Good grading of this band of soil was exhibited by the large variety of particle sizes which it contained, the finest particle being clay platelets and the coarser particles being silts and sands. The separation of the various sizes of particles facilitated good soil aeration and deeper infiltration compared to the band, plant rooting, and movement of soil microbes. The presence of the micropores and flocculated aggregates depicts that the two soil bands are rich in clay and they are stable in their structures. The overall structure was presumably the result of the attachment of organic matter and Fe-oxides to the clay particles to contribute to the gravimetric and /or volumetric frictional forces that hold the soil particles, as denoted by the FTIR and UV- Vis spectroscopic findings. Moreover, the roughness of each particle offered more adsorbent surface on which soil nutrients and/or contaminants could be adsorbed, meaning that this soil band would be a desirable candidate for cycling nutrients and potentially for immobilizing pollutants in the soil matrix.

The elements were analyzed through the analysis of the soil samples. The aluminosilicates were the dominating minerals, since the silicon (Si) and aluminum (Al) peaks were high in the EDS spectra, which were consistent with the XRD and FTIR analysis. The red color of the soil is mainly contributed by the iron (Fe) and is characteristic of the iron oxides or hydroxides, and is associated with the redox reactions. The reason behind this is that the peak of calcium (Ca) and magnesium (Mg) indicates that there are carbonates and dolomite, respectively, that determine the pH of the soil

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and buffering capacity. In addition to this, potassium (K) and sodium (Na) were the most insignificant elements that were closely related to feldspar and clay exchange sites. Quantitative EDS had come up with a general oxide formula SiO 2: 48-52, Al 2O 3: 18-20, Fe 2O 3: 8-10, CaO: 6-8, and MgO: 3-4, and K 2O and Na 2O were estimated to be less than 2%. These estimates indicate that the soil is silicate and has a moderate amount of basic oxides, which is chemically good both in nutrient retention and rigidity.

When used in combination with elemental mapping, the topography of the sample is correlated with the chemistry of the sample. The porous framework provides and diffuses nutrients, and the metal oxides are very reactive and include hydroxyl groups, which elevate their cation exchange and adsorption qualities. The principal characteristics of complex and well-balanced soils are differences in their morphology and composition.

4.5 Ultraviolet–Visible (UV–Vis) Spectroscopy

UV-Vis an absorption spectrum that indicates relationships involving iron oxides and organic materials that affect soil color and fertility.

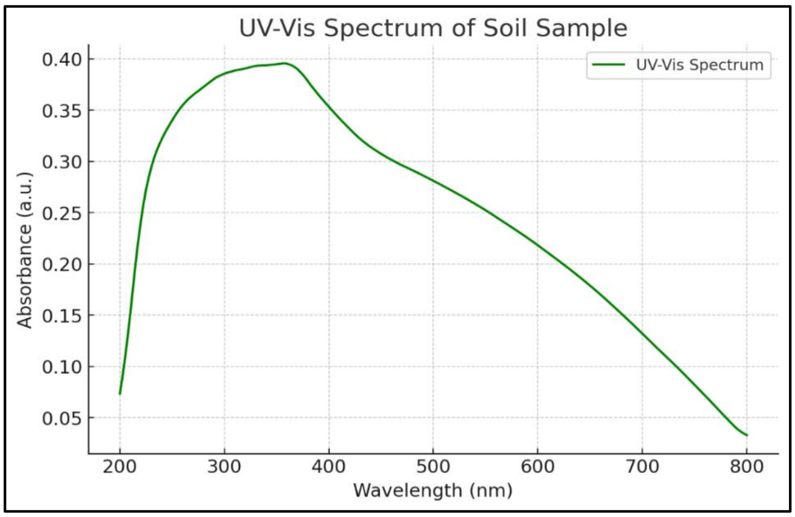

Fig.5 UV-Vis Spectrum of the soil sample

The ultraviolet-visible absorption spectrum (Fig. 5) exhibits numerous broad absorption features in both the ultraviolet and visible regions, associated with both organic and inorganic chromophores.The relatively strong absorption band, ranging from 250 to 300 nm, is most likely a result of $\pi \rightarrow \pi^*$ transitions commonly observed in aromatic and conjugated double-bond structures associated with humic and fulvic acids, which could indicate the presence of organic material that could improve soil fertility and color.The secondary absorption band at approximately 400-450 nm suggests charge-transfer transitions of Fe^{3}+ ions associated with iron oxides (i.e., Fe_2O_3, FeOOH).The intensity of this band is directly proportional to the iron oxide concentration in the soil and helps explain the reddish-brown hues of the soil.Iron oxides are believed to have a significant impact on soil color, nutrient adsorption processes, and electron transfer during soil redox reactions.

Those transitions which may be included in the lower wavelength (less than 250 nm) absorption intensity may be a $\sigma \rightarrow \sigma^*$ transitions in either the oxygen or hydroxyl groups on the minerals, indicating the input of silicate and hydroxide minerals. The shape of the spectrum in general was relatively smooth (there were no sharp peaks), which implied that the absorption was a combination of overlapping organic and inorganic constituents; therefore, the most likely source of the soil was the heterogeneous one. The absorbance ratio (E2/E4 ratio) of humic substances at 280 and 400 nm was used to measure aromaticity and molecular weight. UV-Vis spectroscopy was used to analyze the soil samples, and the results indicated that the samples had large proportions of organic substances and ferric oxides. All these factors make them fertile and stable. FTIR, Raman spectroscopy, and SEM-EDS were used to identify the optical properties of the sample and were supportive of this finding.

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V. DISCUSSION

Different techniques of analysis were used to have a detailed view of how the soil works and what its structure is. CRX analysis was used to describe the crystal structure of the soil, and it is primarily composed of minerals (quartz, feldspar, kaolinite, and montmorillonite). The FTIR and Raman spectroscopy were used to identify the minerals.The study was conducted on the functional groups (Si-O, OH, CO3(2-), and C-H), which indicate silicate, carbonate, and organic phases already revealed by spectroscopic methods.SEM-EDS revealed the microstructure and compositional background by characterizing a heterogeneous texture and the abundance and composition of aluminosilicates, iron oxides, and carbonates. UV-Vis detected the organic matter and ferric oxides and provided some chemistry with color and fertility indicators.Together, these findings suggest that a relatively balanced mineral–organic matrix is biologically sustainable for agricultural production.Quartz and feldspar make the soil physically stable; clay minerals and organic matter make the soil nutrient and water retention capable; iron oxides make the soil trace metal-rich and reduce its redox buffering capacity, whereas carbonate acts as a buffer for pH and acidification that naturally occurs over time, even with agricultural usage.

Using a combination of spectroscopic and microscopic approaches, the authors suggest that the problems raised by the individual use of either type of analysis can be overcome.For example, X-ray diffraction (XRD) can identify minerals much better than other methods; however, it does not provide figures for amorphous phases.FTIR and Raman methods can provide details on molecular interactions, while also helping to overcome the limitations of XRD.Contextual information derived from scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), which provides both spatial and elemental information, is beneficial when combined with relatively rapidestimates of organic matter obtained using UV-Vis spectroscopy.

The nondestructive, multiscale, and multi-technique approach described in our paper for collecting chemical and physical information is relevant to soil research and monitoring soil health.The obtained data on mineral and organic compositions can be considered the basis for the agronomic and environmental consequences of soil health.Sandy or silty soils are usually rich in quartz and feldspar.They are firm and provide good ventilation to the plant roots.Some clay minerals, such as montmorillonite, improve soil nutrient retention and cation exchange capacity (CEC).This technology is also eco-friendly and, at the same time, enhances production. It is a turning point in which the study of soil using the organic farming method will result in a better future. It may play a significant role in the evaluation of pollutants, including metals or synthetic pesticides, that ultimately cause the deterioration of the organic quality. Therefore, it assists farmers to guarantee and certify the quality of their land, as custodians of nature and creators of healthy food.

The organic matter plays a significant role in soil fertility as it determines soil structure, water storage capacity, and microbial diversity, as found in FTIR, Raman, and UV-Vis studies. Supposing that the principles of conservation farming govern the soils, then the long-term productivity of the soils in the future can be determined by verifying the organic and mineral phases of the soil. The non-destructive analysis can be conducted multiple times with minimal damage to the samples; therefore, it is possible to assess the soil health more often. This study will mainly contribute the following:

- Crystalline minerals such as quartz, feldspar, kaolinite, montmorillonite, and calcite were also found in the samples of soils under analysis in relatively high concentrations. These were reactive as well as stable minerals.
- FTIR and Raman spectroscopy were used to determine the presence of silicate, carbonate, hydroxyl, and organic functional groups. These results imply that minerals and organic matter correlate in a complex way, which means the possibility of nutrient retention and better soil production.
- Different types of microporosity were observed by SEM-EDS examination.Si, Al, Fe, Ca, and Mg represent fertility, equilibrium, and geochemistry, respectively, and were incorporated into the elemental composition.
- UV-Vis spectroscopy has been used to identify ferric oxide aggregates and many organic materials.This finding supports the findings of earlier methods and those using nutrient-rich, pigmented soils.

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- The combination here is a comprehensive and non-destructive method for evaluating soil quality processes that help make agricultural decisions.

A summary of the results is presented in Table I.

Table I: Summary of the results

Technique	Key Observations	Major Components Identified	Significance
XRD	Sharp peaks for quartz, feldspar, kaolinite, montmorillonite, and calcite	Silicates, clays, carbonates	Defines crystalline structure and texture
FTIR	Si–O, OH, CO_3^{2-}, C–H, and C=O bands	Silicates, hydroxyls, organics	Identifies functional groups and bonding
Raman	Peaks at 465, 800, 1085, 1350, 1580 cm^{-1}	Quartz, carbonates, and organic carbon	Confirms molecular composition
SEM-EDS	Irregular, porous morphology; Si, Al, Fe, Ca peaks	Aluminosilicates, oxides, carbonates	Reveals microstructure and elemental content
UV–Vis	Absorption at 250–300 nm and 400–450 nm	Humic matter, Fe^{3+} oxides	Evaluates organic matter and color index

Extensive spectroscopic and microscopic studies have revealed that the Earthcomprises a well-balanced mix of crystalline silicates, hydrated clay minerals, carbonates, iron oxides, and small amounts of organic matter.These components improve fertility potential, chemical reactivity, and soil structure.Detailed studies have revealed that the use and necessity of a combination of non-destructive methods in soil science are unquestionable.Soil quality is used for farming, environmental, or land management purposes.

VI. CONCLUSION

In-depth characterization of soil samples using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Raman Spectroscopy, scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), and UV-Vis spectroscopy has shown that a fully multi-technique approach eventually results in a comprehensive evaluation of soil mineralogy, molecular extent, and elemental or material composition. XRD was instrumental in identifying minerals such as quartz, feldspar, and clay minerals (kaolinite and montmorillonite), which are the main minerals that form the physical characteristics of the soil, e.g., water retention and cation exchange capacity. The functional groups tightly bound in silicates, hydroxyls, carbonates, and organic materials were identified by FTIR and Raman spectroscopy, as indicated, providing the first clue to mineral-organic attachments and, therefore, suggesting both soil fertility and stability. In addition, the SEM-EDS data represent the change in the shape of the microstructure and the particles, and, therefore, the modifications in the elements Si, Al, Fe, Ca, and Mg indicate the mineral-oxide-carbonate composition and the localized soils. The UV-Vis is also helpful in verifying the regulated amount of humus and ferric oxides that constitute the primary source of soil productiveness, hue, and redox mobility. The findings suggest that more spectroscopic, microscopic, and sophisticated techniques should be used to provide a more in-depth and complex view of soil systems as opposed to the conventional destructive testing techniques.

The study findings also showed that non-destructive and quick techniques are critical and valuable in the investigations and measurements of soil health, which are based on environmental and climatic factors, and land-use adjustments, at different intervals. The finer evaluation plan may also be taken as a tool to come up with a better soil simulation to make sustainable decisions about crops, nutrient cycling, and resource control. This attitude can also help in the general sustainable management of agri-systems, such as the management of soil. It is a universal evaluation instrument that can be used in soils and other places. Simultaneously, it can set scientific research standards through advanced soil research and also introduce sustainable policies and practices on soils throughout the world.

Any new soil study is suitable for implementing machine learning or a data-driven model along with near-, mid-, or far-infrared spectroscopic and microscopic data to create predictive modeling of soil properties.Automation can conduct rapid assessments of soil health and fertility using libraries of spectra or repositories of mineral–organic signatures. Using hyperspectral imaging and portable spectrometers on the ground can be an excellent method for real-time soil assessment. Therefore, the need for laboratories can be reduced, and at the same time, samples can be evaluated and kept intact. In addition, the use of these methods in conjunction with a geospatial toolkit, such as GIS or remote sensing, will enable the creation of guidelines and the precise application of digital soil maps in precision agriculture, taking into account landscape recovery and restoration, as well as environmental monitoring, at both regional and global scales.

It would also help deepen our knowledge of soil chemical and nanoscale processes if more non-destructive methods were used in general when introducing new techniques such as X-ray photoelectron spectroscopy (XPS), near-infrared (NIR) spectroscopy, and synchrotron-based microanalysis. If these methods are non-destructive, the soil-plant-microbe interactions, as observed through long-term studies, could eventually provide a new source of knowledge regarding soil microstructure changes and their impact on ecosystem function. Scientists can investigate the mineralogical components of the soil to better understand the influence of mineralogical composition on various aspects of environmental fate, carbon sequestration, and climate change resilience. Interdisciplinary research combining advanced analytical sciences with sustainable agricultural land and crop management practices may be a way forward for agricultural innovation, land and environmental conservation, and utilizing soil resources to support sustainability benefits.

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