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Comparison of MIR Spectral Signatures of Soils from Acacia, Eucalyptus, and Cassava Plantations in the Tropical Region of the Batéké Plateau (Republic of Congo)

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Abstract

This study examines the effects of Acacia, Eucalyptus, and Cassava plantations on soil chemical composition in the Batéké Plateau, a tropical savanna region in Congo-Brazzaville. Using mid-infrared (MIR) spectroscopy, the research reveals distinct spectral signatures for each type of plantation, highlighting notable variations in soil chemical properties. Soils under Acacia exhibit increased organic nitrogen content, enhancing fertility through atmospheric nitrogen fixation. In contrast, soils under eucalyptus contain lignified organic matter, which is less biodegradable and limits immediate nutrient access but may contribute to long-term carbon storage. Cassava soils show high levels of silicates and labile components, indicating a risk of rapid nutrient depletion without proper management. The results underscore the importance of carefully selecting plant species to achieve sustainable soil management objectives and suggest that a combined MIR and NIR spectroscopy approach could enrich analyses by providing a more comprehensive view of soil variations based on vegetation cover.

Keywords

MIR Spectroscopy, Acacia, Eucalyptus, Cassava, Soil Fertility

1. Introduction

Soils in tropical regions, particularly those in savannah areas like the Batéké Plateaux in the Republic of Congo, play a crucial role in ecosystem management and the sustainability of agricultural resources [1] [2]. These soils, beyond supporting biodiversity, are essential for agriculture and forestry—two pillars of the local economy [3] [4]. However, due to their low organic matter content and natural fertility, these soils require adapted management practices that consider the interactions between vegetation cover type and soil properties [5]-[7].

Among the vegetation used for soil improvement, acacia, eucalyptus, and cassava plantations are widespread [1] [6]. Each species has a unique impact on the soil due to its biological characteristics and specific nutritional needs [4] [8]. Acacia, a nitrogen-fixing legume, is often utilized to restore the fertility of depleted soils thanks to its ability to enrich them with nitrogen [9] [10]. In contrast, eucalyptus, known for its rapid growth and resilience, can have more complex impacts on soil dynamics, such as depleting water resources and altering soil structure due to its high nutrient extraction capacity [11] [12]. Finally, cassava, an essential food crop, affects soils through its deep rooting and nutrient requirements, necessitating careful management to prevent soil depletion [4] [8]. **Common amendments applied in cassava plantations include organic compost, crop residues, and occasionally lime to improve the fertility of acidic soils [13] [14].**

In this context, characterizing and understanding the modifications brought by each type of plantation to the soil becomes essential. Mid-infrared spectroscopy (MIR) is an increasingly popular method in pedology for analyzing soil spectral signatures. This technique enables non-destructive analysis of soil chemical composition and provides valuable information on variations in organic and mineral components [2] [15] [16]. By measuring the specific absorption bands of soils, MIR spectroscopy allows for precise comparisons of soils from different types of plantations and identification of the chemical elements influenced by each plant species [17].

The use of spectroscopy to characterize soils based on their plant cover has proven effective in various contexts, particularly for predicting soil organic matter fractions [18]. Moreover, studies have highlighted the importance of particulate organic matter in soil structuring and carbon sequestration, emphasizing the relevance of examining the specific effects of tropical plantations on the chemical and biological composition of soils [19]. **MIR spectroscopy is a valuable tool for detecting these variations, especially in complex environments like the Batéké Plateaux, which are characterized by sandy soils, sparse vegetation, and dynamic soil-vegetation interactions influenced by varying climatic and topographical conditions [20] [21].**

Finally, soil samples were collected at a depth of 30 cm, a standard approach to capture the root zone directly influenced by plantation activities and amendments [22] [23]. This depth also allows for standardized comparative analyses between different types of vegetation cover and highlights the effects of plantations on soil properties [23].

This study aims to compare the MIR spectral signatures of soils under acacia, eucalyptus, and cassava plantations in the Batéké Plateaux. By identifying and analyzing the characteristic spectral bands of each soil type, this research seeks to provide valuable insights for sustainable soil management in tropical regions and to determine how each type of plantation influences the chemical and physical properties of soils.

2. Materials and Method

2.1. Study Area

The Batéké plateaus, located in the southeast of the Republic of Congo, are characterized by a savannah landscape with sandy soils low in organic matter. This region is known for its acidic, low-fertility soils, which are suitable for grasslands and open forests but vulnerable to degradation. The climate is tropical, with an extended dry season that affects soil formation processes and limits natural plant biodiversity [1] [6]. Average annual temperatures range between 24˚C and 28˚C, while annual precipitation varies from 1200 to 1500 mm, with irregular distribution. The soils of the Batéké plateaus, primarily composed of Quaternary sands, have low organic matter and essential nutrient levels, necessitating specific agricultural management practices to maintain productivity [7].

2.2. Plantations Studied

Three types of plantations were examined: acacia, eucalyptus, and cassava. The plots, selected from 58 within the Bambou-Mingali state reserve, include acacia plantations aged 2, 4, 5, and 6 years; eucalyptus plantations aged 4, 5, 6, and 7 years; and cassava plantations aged 5 to 15 months. These plots were chosen based on criteria such as age, current condition, planting history, and specific species [7].

2.3. Sampling Methodology and Sample Preparation

In each plot, soil was collected from three points at two different locations to create a composite sample. At least two composite samples were taken per plot, resulting in a total of 28 samples for MIR spectroscopy analysis across all plantations. Soil samples were collected at a depth of 0 to 30 cm, air-dried, and sieved at 2 mm to homogenize the samples and minimize variations due to particle size and residual moisture [17].

2.4. Spectroscopic Methodology

Analyses were conducted using mid-infrared (MIR) spectroscopy with a BRUKER Vertex70 FTIR spectrometer, equipped with an MCT detector, in diffuse reflection mode. Each spectrum represents the average of 32 scans, with a spectral resolution of 4 cm^{-1}, allowing for the non-destructive analysis of soil chemical composition. As noted by [8], **this method is effective for soil analysis, and additional studies, such as [24], have demonstrated its utility in predicting soil fertility indices.**

2.5. Preprocessing of Spectral Data

The raw spectral data were improved through several preprocessing methods: absorbance correction, normalization to reduce variations in sample quantity, and application of derivatives to accentuate spectral variations and reduce noise [16] [18]). The preprocessing and spectral processing methodology aligns with FAO MIR analysis recommendations, particularly for managing the effects of particle size and residual moisture in soil spectral data [25].

2.6. Statistical Analysis

Statistical analysis of the spectral data was conducted using Principal Component Analysis (PCA), a dimensionality reduction technique that simplifies the data and extracts the primary sources of variation between soil samples [26]. PCA aids in distinguishing chemical profiles by grouping samples according to their spectral characteristics, which is particularly useful for analyzing soils under different types of plant cover, such as acacia and eucalyptus plantations [10] [12]. This statistical approach enables the capture and interpretation of structural and chemical variations present in the MIR spectra of the soils studied [8].

3. Results

3.1. Distinctive Spectral Signatures of Soils under Different Plantations

The MIR spectra of soils reveal distinctive spectral signatures for each plantation type studied (**Figure 1**). Soils under acacia plantations exhibit specific peaks associated with organic nitrogen absorption bands in the region of 1510 - 1650 cm^{-1} (**Figure 1(a)**). For soils under eucalyptus plantations, the spectra display characteristic absorption bands of lignin and phenolic compounds around 1320 - 1400 cm^{-1} and 1600 - 1700 cm^{-1} (**Figure 1(b)**). In contrast, the MIR spectra of soils under cassava plantations show bands in the region of 1000 - 1200 cm^{-1} (**Figure 1(c)**), indicative of a high content of silicates and other labile mineral components. These spectral values reveal the distinctive effects of each plantation type on the soil's chemical composition and quality, underscoring the relevance of MIR spectroscopy for rapid, non-destructive assessment of soil properties based on plant cover.

3.2. Comparison of the Impacts of Species on the Chemical Properties of Soils

The results (**Figure 2**) indicate that each plantation type influences the soil's chemical properties uniquely, with varied impacts depending on the plant species. Soils under acacia exhibit spectral signatures rich in organic nitrogen, with peaks in the 1510 - 1650 cm^{-1} region. Soils under eucalyptus display absorption bands in the 1320 - 1400 cm^{-1} and 1600 - 1700 cm^{-1} regions, characteristic of lignin and phenolic compounds. Lastly, soils under cassava show spectral signatures in the 1000 - 1200 cm^{-1} region, associated with silicates and other labile minerals.

3.3. Differentiation of Soil Samples According to Plantations by PCA

The factorial map of individuals (**Figure 3**) presents the projection of soil samples from acacia, eucalyptus, and cassava plantations in the space defined by the main dimensions, Dim1 and Dim3, explaining 52.7% and 12.9% of the total variance, respectively. The ellipses indicate groupings for each plantation type, with soils under cassava distinctly positioned along Dim1 with predominantly negative values. This suggests a unique spectral signature and chemical composition, characterized by a high content of silicates and other labile minerals, indicative of an extractive profile. Soils under acacia and eucalyptus are closer to the center of the factor space, with some overlap and relatively similar characteristics compared to cassava, though their impacts on soil chemical composition remain distinct. Soils under acacia and eucalyptus are primarily located in the positive zone of Dim1, showing less variability. The differentiation of soil samples is further enhanced by Dim3, capturing an additional 12.9% of variance and allowing further isolation of vegetation groups, with centroids indicating proximity between acacia and eucalyptus, while cassava remains more distant.

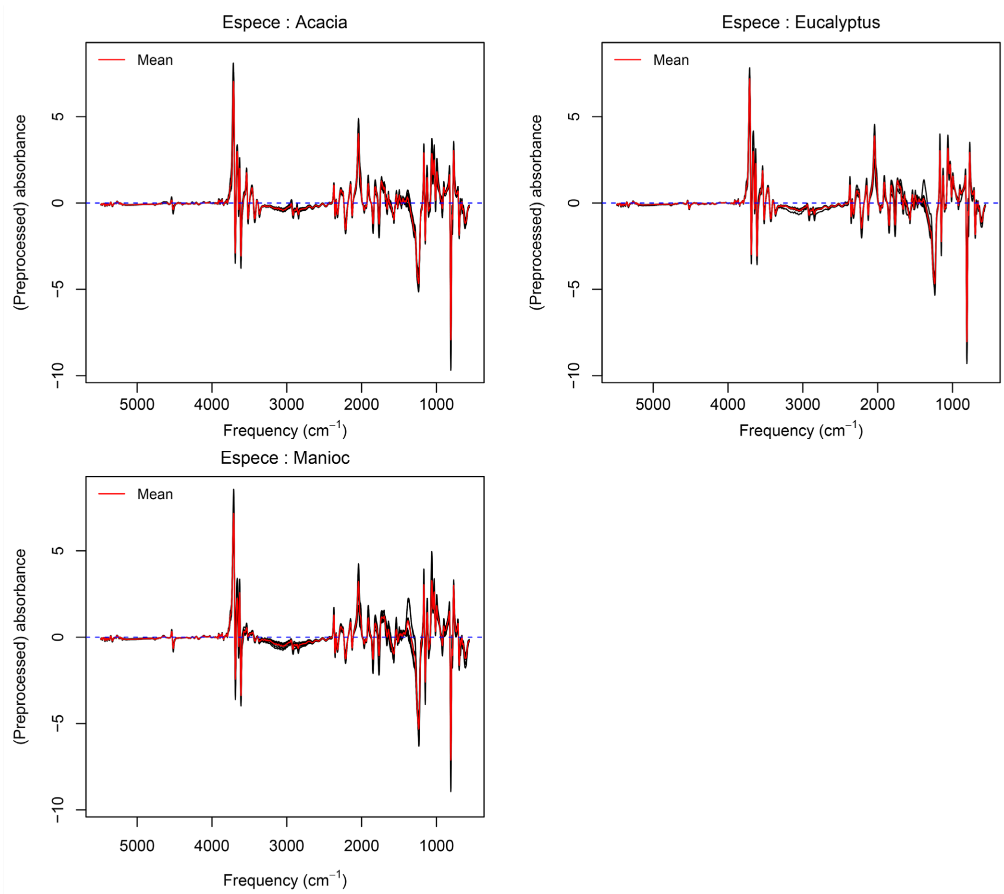

Figure 1. Average MIR spectra of soils under plantations of (a) acacia, (b) eucalyptus, and (c) cassava. (a) displays the MIR spectrum of soils under acacia, highlighting nitrogen absorption peaks. (b) shows the spectrum of soils under eucalyptus, with dominant lignified bands. (c) illustrates the spectrum of soils under cassava, with peaks associated with silicates.

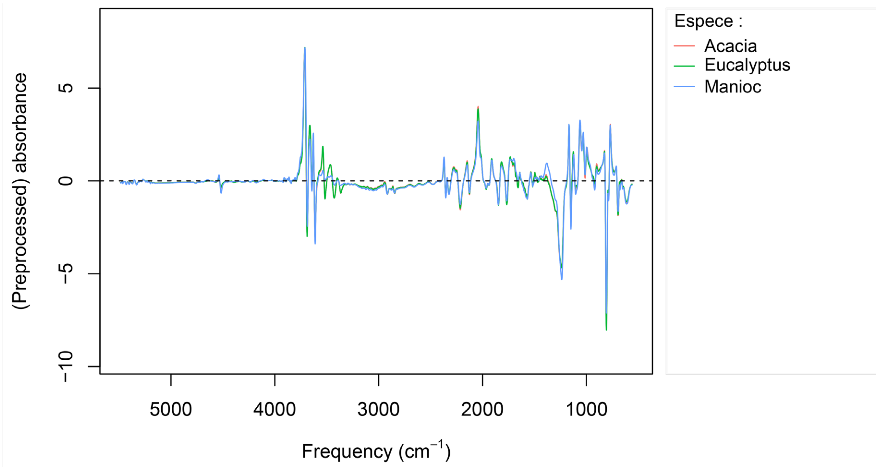

Figure 2. Comparison of average MIR spectra of soils under acacia, eucalyptus, and cassava plantations.

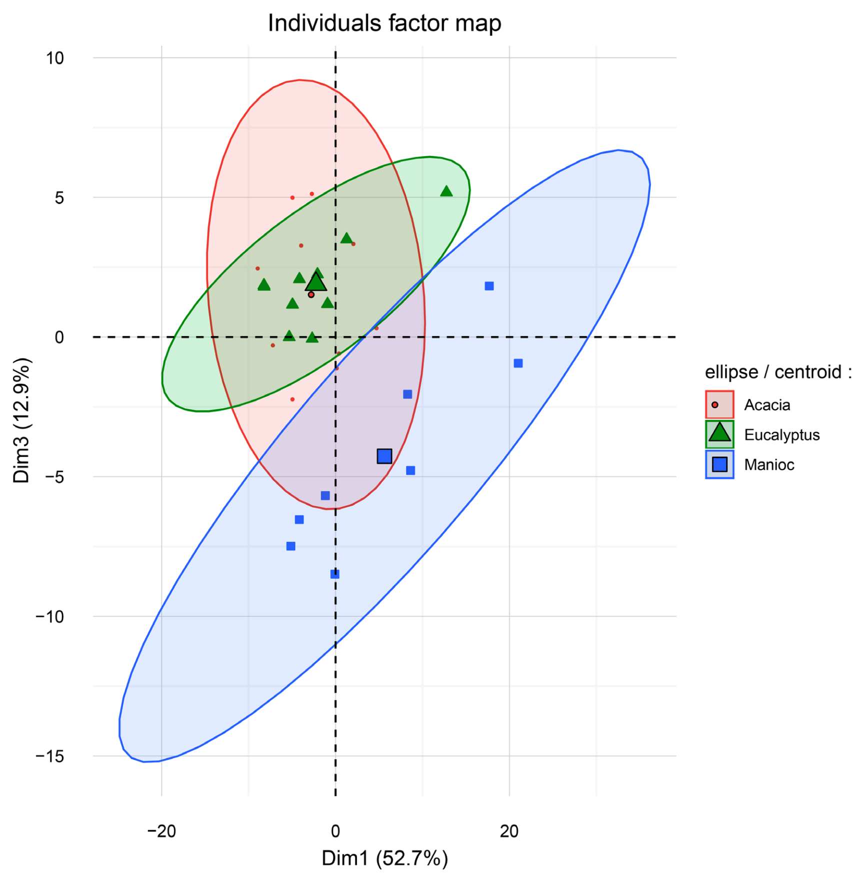

Figure 3. PCA projection of soil samples from acacia, eucalyptus, and cassava plantations.

4. Discussion

4.1. Influence of Plantations on Soil Chemical Composition

The results of this study indicate that each plantation type specifically influences the chemical composition of soils in the Batéké plateaus. Soils under acacia plantations show a notable increase in organic nitrogen, with absorption bands in the 1510 - 1650 cm^{-1} region, illustrating this legume's ability to fix atmospheric nitrogen through root symbioses [9] [10]. This nitrogen enrichment enhances soil fertility, which is particularly beneficial in this nutrient-poor region. Acacia also contributes to an increase in labile organic matter, improving soil structure and water retention—two key factors for long-term productivity [6].

In contrast, soils under eucalyptus show absorption bands associated with lignin and phenolic compounds in the 1320 - 1400 cm^{-1} and 1600 - 1700 cm^{-1} regions, indicating stabilized organic matter that is less biodegradable [8] [12]. Although this composition limits rapid nutrient availability, it promotes carbon storage, contributing to long-term carbon sequestration but necessitating compensatory practices to maintain soil fertility [3]. Finally, soils under cassava are characterized by a spectral signature in the 1000 - 1200 cm^{-1} region, revealing a high content of silicates and other labile minerals. This is attributed to cassava's deep root system, which mobilizes nutrients from lower soil layers [4].

However, cassava's high nutritional requirements can lead to rapid depletion of surface nutrients without sustainable management practices, such as crop rotation or the addition of amendments [1] [6]. These observations underscore the distinct influence of each plantation type on soil chemical properties, emphasizing the importance of selecting species based on sustainable soil management objectives—whether to enrich fertility, conserve nutrients, or store carbon.

4.2. Potential of MIR Spectroscopy for Tropical Soil Management

Mid-infrared (MIR) spectroscopy has proven to be a powerful tool for tropical soil management due to its ability to provide precise, non-destructive information on soil chemical composition. In this study, MIR spectroscopy identified distinctive spectral signatures associated with acacia, eucalyptus, and cassava plantations, underscoring the specific impact of each vegetation cover on soil properties. By measuring specific absorption bands—particularly in the regions of 1510 - 1650 cm^{-1} for organic nitrogen, 1320 - 1400 cm^{-1} and 1600 - 1700 cm^{-1} for lignified compounds, and 1000 - 1200 cm^{-1} for silicates—this technique enables rapid characterization of the effects of various plantations on soil [8] [15].

The use of MIR spectroscopy for tropical soil management offers several advantages. It facilitates rapid assessment of soil fertility, carbon storage potential, and chemical structure—essential parameters for adapting agricultural and forestry practices in vulnerable ecosystems. Additionally, it provides a method for long-term soil quality monitoring without requiring destructive sampling or complex laboratory analyses, which is particularly beneficial in tropical regions where logistical resources may be limited [2]. In previous studies, [24] demonstrated the effectiveness of near-infrared (NIR) spectroscopy for predicting site indices in sandy soils under eucalyptus plantations in the Republic of Congo, suggesting that combined MIR and NIR approaches could further enhance soil characterization in similar tropical environments.

In conclusion, MIR spectroscopy holds significant potential for optimizing tropical soil management by enabling monitoring and anticipation of the effects of planting practices on soil chemical properties. It is thus a valuable tool for sustainable management strategies, promoting productivity and preservation of tropical soils, and providing a robust database for informed decision-making in agriculture and forestry

5. Conclusion

This study aimed to compare the MIR spectral signatures of soils under acacia, eucalyptus, and cassava plantations in the Batéké plateaus to evaluate their influence on soil chemical properties. The results indicate that each plantation has a distinct effect: acacia enriches the soil with organic nitrogen, enhancing fertility; eucalyptus promotes carbon storage through stabilized organic matter; and cassava, by drawing on mineral reserves, poses a risk of rapid nutrient depletion. MIR spectroscopy proved to be an effective tool for this analysis, offering promising prospects for sustainable and tailored management of tropical soils. These findings underscore the importance of selecting planting species based on ecological objectives, whether to improve fertility, conserve nutrients, or support carbon storage.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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