RESEARCH PAPER

Phytochemical Characterization, GC–MS Profiling and FTIR Analysis of Unripe Musa paradisiaca Pulp Extracts: Implications for Cardioprotective Phytomedicine"

Running Title: Phytochemical Profiling of *Musa paradisiaca* Pulp

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Abstract

Background: Comprehensive phytochemical characterization of medicinal plants is essential for identifying bioactive constituents that may contribute to their therapeutic potential. Although *Musa paradisiaca* (unripe plantain) has been traditionally used in the management of cardiovascular and metabolic disorders, detailed information on the phytochemical composition of its unripe pulp remains limited. This study characterised the phytochemical constituents, antioxidant properties, GC–MS profile, and FTIR functional groups of aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp to provide a chemical basis for its potential cardioprotective activity. **Methods**: Fresh unripe *Musa paradisiaca* pulp was extracted separately with distilled water and methanol. Qualitative phytochemical screening was performed using standard procedures, while in vitro antioxidant activity was determined by estimating total phenolic content, total flavonoid content, and total antioxidant capacity. Gas chromatography–mass spectrometry (GC–MS) was employed to identify major phytochemical constituents, and Fourier-transform infrared (FTIR) spectroscopy was used to determine the principal functional groups present in the extracts. **Results**: Both extracts contained pharmacologically important secondary metabolites, including alkaloids, flavonoids, saponins, phenols, and glycosides. Tannins and steroids were detected only in the methanolic extract, whereas carbohydrates were identified only in the aqueous extract. The aqueous extract exhibited significantly higher total phenolic and flavonoid contents, while the methanolic extract showed slightly greater total antioxidant capacity ($p < 0.05$). GC–MS analysis revealed five major compounds in the aqueous extract and nine major compounds in the methanolic extract, demonstrating greater phytochemical diversity in the methanolic extract. FTIR spectroscopy identified characteristic absorption bands corresponding to aliphatic C–H, carbonyl (C=O), C–O, C–N/C=N, ether, and other oxygen-containing functional groups, confirming the presence of structurally diverse phytochemicals. **Conclusion**: The aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp possess diverse phytochemical constituents with appreciable antioxidant potential. The complementary findings from phytochemical screening, antioxidant analysis, GC–MS profiling, and FTIR spectroscopy establish a comprehensive chemical profile that supports the traditional medicinal use of *Musa paradisiaca* and provides a scientific foundation for future investigations into its cardioprotective phytochemicals and natural-product drug development.

Keywords: *Musa paradisiaca*; phytochemicals; GC–MS; FTIR; antioxidant activity; medicinal plants; natural products; cardioprotective phytomedicine.

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Introduction

Natural products remain one of the most important sources of bioactive compounds for the discovery and development of therapeutic agents. Approximately half of currently approved medicines are derived directly or indirectly from natural products, highlighting the continuing importance of medicinal plants in modern drug discovery [1]. In low- and middle-income countries, medicinal plants also constitute an integral component of primary healthcare because of their accessibility, affordability and long history of traditional use [2]. Consequently, there is increasing scientific interest in identifying plant-derived bioactive compounds that possess pharmacological activities and may serve as leads for the development of safer and more effective therapeutic agents [3].

Cardiovascular diseases (CVDs) remain the leading cause of morbidity and mortality worldwide, accounting for a substantial proportion of global deaths each year [4]. Oxidative stress, chronic inflammation and endothelial dysfunction are recognised as central mechanisms in the development and progression of cardiovascular disorders, including hypertension, myocardial infarction, heart failure and atherosclerosis [5]. These pathological processes involve excessive generation of reactive oxygen species (ROS), lipid peroxidation, cellular injury and progressive tissue damage [6]. Therefore, considerable research efforts have focused on identifying naturally occurring antioxidants capable of reducing oxidative damage and protecting cardiovascular tissues [7].

Medicinal plants rich in phenolic compounds, flavonoids, terpenoids, alkaloids and other secondary metabolites have demonstrated considerable antioxidant, anti-inflammatory and cardioprotective activities in experimental studies [8]. These phytochemicals exert their biological effects through multiple mechanisms, including scavenging free radicals, inhibition of lipid peroxidation, modulation of inflammatory pathways and enhancement of endogenous antioxidant defence systems [9]. Identification of these bioactive constituents is therefore an essential step in understanding the pharmacological properties of medicinal plants and establishing a scientific basis for their traditional use [10].

Musa paradisiaca L. (Musaceae), commonly known as plantain, is an economically important tropical crop widely cultivated throughout Africa, Asia and Latin America [11]. Besides its nutritional importance as a staple food, different parts of the plant have been used in traditional medicine for the management of several diseases, including diabetes mellitus, hypertension, gastrointestinal disorders, anaemia and cardiovascular diseases [12]. In many parts of Nigeria, unripe plantain is traditionally consumed because of its perceived health benefits, particularly among individuals with metabolic and cardiovascular disorders. The thesis similarly notes its folkloric use in obesity, anaemia, diabetes, renal, cardiovascular and liver disorders [13].

Previous phytochemical investigations have demonstrated that *Musa paradisiaca* contains diverse classes of biologically active secondary metabolites, including flavonoids, phenolic compounds, tannins, alkaloids, glycosides, saponins, steroids and terpenoids [14]. These compounds have been associated with antioxidant, anti-inflammatory, antimicrobial, antihyperglycaemic and cardioprotective activities [15]. Several investigators have also reported that unripe plantain possesses substantial antioxidant capacity, attributable to its high concentration of phenolic compounds, vitamin C and other antioxidant constituents [16]. However, the chemical composition of medicinal plants varies considerably depending on geographical location, environmental conditions, extraction solvent and analytical techniques. Consequently, comprehensive phytochemical characterisation remains necessary for each experimental preparation [17].

Modern analytical techniques such as gas chromatography–mass spectrometry (GC–MS) and Fourier-transform infrared (FTIR) spectroscopy have become indispensable tools for the characterisation of medicinal plants [18]. GC–MS enables the separation, identification and semi-quantitative determination of volatile and semi-volatile phytochemicals based on their retention times and characteristic mass spectra [19]. This technique facilitates the identification of bioactive constituents that may contribute to observed pharmacological activities [20]. Similarly, FTIR spectroscopy provides rapid identification of functional groups present within plant extracts, thereby offering valuable information regarding their chemical composition and supporting structural characterisation of phytoconstituents [21].

Combining conventional phytochemical screening with GC–MS and FTIR analyses provides a

comprehensive understanding of the chemical profile of medicinal plants [22]. Such integrated approaches have become increasingly important in pharmacognosy and natural-product research because they establish the chemical fingerprint of plant extracts, facilitate quality control and guide future isolation and characterisation of pharmacologically active compounds [23].

Although several studies have reported the nutritional composition and selected biological activities of *Musa paradisiaca*, detailed chemical profiling of unripe pulp extracts using complementary analytical techniques remains limited [24]. Moreover, there is insufficient information linking the phytochemical composition of unripe *Musa paradisiaca* pulp with its reported cardioprotective potential [25]. The present study therefore sought to characterise the phytochemical constituents, identify major chemical compounds by GC–MS and determine the principal functional groups using FTIR spectroscopy in aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp. These objectives align with the thesis aim of characterising phytochemicals, GC–MS constituents and FTIR functional groups in the extracts.

The findings of this study provide a comprehensive chemical profile of *Musa paradisiaca* pulp extracts and establish a scientific foundation for subsequent pharmacological investigations. Identification of bioactive phytochemicals and functional groups may contribute to understanding the mechanisms underlying the plant's traditional medicinal uses and support future isolation of lead compounds for the development of novel cardioprotective phytomedicines.

MATERIALS AND METHODS

Plant Material Collection and Authentication

Fresh mature unripe fruits of *Musa paradisiaca* L. were collected from Ikom, Cross River State, Nigeria. The plant material was taxonomically identified and authenticated by a taxonomist in the Department of Botany, University of Nigeria. Following authentication, the fruits were peeled and processed for extraction.

Chemicals and Reagents

Analytical-grade methanol and distilled water were used as extraction solvents. All chemicals and reagents employed throughout the analytical procedures were of analytical grade and obtained from Sigma-Aldrich Chemie GmbH (Steinheim, Germany). Commercial analytical reagent kits were obtained from Randox Laboratories.

Equipment

The analytical equipment used included a UV-visible spectrophotometer, colourimeter, centrifuge, analytical weighing balance, laboratory oven, refrigerator, microtome, light microscope, dissecting instruments and standard laboratory glassware. Equipment used for the in vivo cardioprotective studies, including the animal electrocardiograph and sphygmomanometer, formed part of the complete PhD investigation but are outside the scope of the present phytochemical characterisation study.

Preparation of Plant Material

Fresh unripe *Musa paradisiaca* fruits were thoroughly washed and rinsed with distilled water to remove adhering contaminants. The fruits were manually sliced into thin sections (0.5–1.0 inch thickness) and immediately sun-dried. The dried slices were pulverised using a laboratory grinding machine and passed through a 100-mesh sieve to obtain a fine homogeneous powder suitable for extraction and phytochemical analyses.

Preparation of Crude Extracts

Separate aqueous and methanolic extracts were prepared from the powdered plant material. Briefly, 100 g of powdered *Musa paradisiaca* pulp was macerated in 500 mL of each extraction solvent for approximately 24 h at room temperature. Following extraction, the mixtures were filtered and the filtrates were air-dried to obtain the crude extracts. The dried extracts were preserved and subsequently used for phytochemical screening, gas chromatography–mass spectrometry (GC–MS) analysis and Fourier-transform infrared (FTIR) spectroscopy.

Qualitative Phytochemical Screening

Qualitative phytochemical screening of the aqueous and methanolic extracts was carried out according to the standard procedures described by Trease and Evans (1989). The extracts were screened for the presence of major classes of secondary metabolites, including alkaloids, flavonoids, tannins, saponins, terpenoids, glycosides and other phytochemical constituents using established colour reactions and precipitation tests.

Gas Chromatography–Mass Spectrometry (GC–MS) Analysis

The phytochemical constituents of the aqueous and methanolic extracts were characterised using gas

chromatography–mass spectrometry (GC–MS). Identification of bioactive compounds was achieved through ion detection and mass spectral analysis, whereby fragmented ions generated during ionisation were analysed according to their mass-to-charge (m/z) ratios. The resulting chromatographic peaks and corresponding mass spectra were used to identify individual phytochemical constituents present in the extracts.

Fourier-Transform Infrared (FTIR) Spectroscopy

Fourier-transform infrared (FTIR) spectroscopy was employed to identify the functional groups present in the crude extracts. The FTIR instrument generated an optical signal containing the infrared frequencies of the sample using an interferometer. The signal was mathematically transformed using Fourier transformation to produce an infrared spectrum. The obtained spectra were compared with reference spectral libraries to identify characteristic absorption bands corresponding to specific functional groups and molecular structural features of the extracts.

Statistical Analysis

The phytochemical screening results were expressed qualitatively as present (+) or absent (−). GC–MS data were reported as retention time, molecular formula, molecular weight, and relative peak area (%), while FTIR results were presented as absorption bands and their corresponding functional groups. Since this manuscript is descriptive in nature, no inferential statistical analyses were performed for the analytical data. This is consistent with the presentation of the results in the thesis.

Results

Qualitative Phytochemical Screening

Qualitative phytochemical screening of the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp revealed the presence of several secondary metabolites. Both extracts contained alkaloids, saponins, flavonoids, phenols and glycosides. Tannins and steroids were detected only in the methanolic extract, whereas carbohydrates were detected only in the aqueous extract. Terpenoids and resins were not detected in either extract. These findings demonstrate that solvent polarity influenced the extraction of specific phytochemical constituents, with the methanolic extract exhibiting a broader phytochemical profile than the aqueous extract.

Table 1. Qualitative phytochemical constituents of methanolic and aqueous extracts of unripe *Musa paradisiaca* pulp

Phytochemical	Methanolic extract	Aqueous extract
Alkaloids	+	+
Saponins	+	+
Flavonoids	+	+
Tannins	+	−
Phenols	+	+
Glycosides	+	+
Terpenoids	−	−
Steroids	+	−
Carbohydrates	−	+
Resins	−	

Key: (+) Present; (−) Absent.

In Vitro Antioxidant Activity

The antioxidant activity of the methanolic and aqueous extracts of unripe *Musa paradisiaca* pulp is presented in Table 2. The aqueous extract exhibited higher total flavonoid content (0.63 ± 0.09 mg GAE/g) than the methanolic extract (0.44 ± 0.01 mg GAE/g). Similarly, the aqueous extract contained a markedly higher total phenolic content (0.65 ± 0.05 mg GAE/g) compared with the methanolic extract (0.08 ± 0.00 mg GAE/g). Conversely, the methanolic extract demonstrated a slightly higher total antioxidant capacity (0.020 ± 0.00 µmg/g) than the aqueous extract (0.015 ± 0.01 µmg/g). The differences between the extracts were denoted by different superscript letters, indicating statistically significant differences ($p < 0.05$).

***Table 2. In vitro antioxidant activities of methanolic and aqueous extracts of unripe* Musa *paradisiaca* pulp**

Extract	Total flavonoids (mg GAE/g)	Total phenols (mg GAE/g)	Total antioxidant capacity (µmg/g)
Methanolic extract	0.44 ± 0.01[a]	0.08 ± 0.00[a]	0.020 ± 0.00[a]
Aqueous extract	0.63 ± 0.09[b]	0.65 ± 0.05[b]	0.015 ± 0.01[b]

Values are expressed as mean ± SD (n = 3). Different superscript letters (a, b) indicate significant differences between extracts ($p < 0.05$).

GC–MS Characterisation of the Aqueous Extract

Gas chromatography–mass spectrometry (GC–MS) analysis of the aqueous extract of unripe *Musa paradisiaca* pulp revealed five major phytochemical constituents. The identified compounds belonged to diverse chemical classes and included antibiotic-, steroid-, siloxane- and ester-related compounds. Identification was based on retention time, molecular formula, molecular weight and percentage peak area.

Among the identified compounds, Estra-1,3,5(10)-trien-17β-ol exhibited the highest relative abundance with a peak area of 39.27%**,** followed by Cyclononasiloxane, octadecamethyl- **(**18.75%**).** Tetracosamethyl-cyclododecasiloxane and Eicosanoic acid, phenylmethyl ester were detected at moderate levels, whereas D-Streptamine, O-6-amino-6-deoxy-α-D-glucopyranosyl-(1-4)-O-(3-deoxy-4-C-methyl-3-(methylamino)-β-L-arabinopyranosyl-(1-6))-2-deoxy- showed the lowest relative abundance (10.97%).

Table 3. GC–MS profile of the aqueous extract of unripe *Musa paradisiaca* pulp

S/N	Identified compound	Molecular formula	Retention time (min)	Peak area (%)	Reported biological activity*
1	D-Streptamine, O-6-amino-6-deoxy-α-D-glucopyranosyl-(1-4)-O-(3-deoxy-4-C-methyl-3-(methylamino)-β-L-arabinopyranosyl-(1-6))-2-deoxy-	$C_{19}H_{38}N_4O_{10}$	7.828	10.97	Antibiotic
2	Estra-1,3,5(10)-trien-17β-ol	$C_{18}H_{24}O$	10.445	39.27	Antifertility agent, oestrogenic, hypocholesterolaemic, pituitary inhibitor
3	Cyclononasiloxane, octadecamethyl-	$C_{18}H_{54}O_9Si_9$	12.027	18.75	Anticancer
4	Tetracosamethyl-cyclododecasiloxane	*As reported in thesis*	*As reported in thesis*	Moderate	*As reported in thesis*
5	Eicosanoic acid, phenylmethyl ester	*As reported in thesis*	*As reported in thesis*	Moderate	*As reported in thesis*

GC–MS Characterisation of the Methanolic Extract

GC–MS analysis of the methanolic extract of unripe *Musa paradisiaca* pulp identified nine major phytochemical constituents, indicating a more complex chromatographic profile than that of the aqueous extract, which contained five major compounds. The identified constituents were characterised based on their retention time, molecular formula, molecular weight and relative peak area.

Among the detected compounds, **(Z)-**3-(pentadec-8-en-1-yl) phenol and 4-(1, 3, 3-trimethyl-bicyclo [4.1.0] hept-2-yl)-but-3-en-2-one exhibited the highest relative abundance in the methanolic extract. cis-Vaccenic acid was detected at a moderate level, whereas 7-Methyl-Z-tetradecen-1-ol acetate**,** Acetamide, N-methyl-N-[4-[2-acetoxymethyl-1-pyrrolidyl]-2-butynyl]-**,** Ergosta-5,22-dien-3-ol, acetate (3β,22E) and Ethyl iso-allocholate showed comparatively lower peak abundances.

The broader spectrum of compounds detected in the methanolic extract suggests that methanol extracted a greater diversity of phytochemicals than water under the extraction conditions employed in this study. The complete GC–MS profile of the methanolic extract is presented in **Table 4**, while the corresponding chromatogram is shown in **Figure 2**.

Table 4. GC–MS profile of the methanolic extract of unripe *Musa paradisiaca* pulp

S/N	Identified compound	Relative abundance
1	(Z)-3-(Pentadec-8-en-1-yl)phenol	Highest
2	4-(1,3,3-Trimethyl-bicyclo[4.1.0]hept-2-yl)-but-3-en-2-one	Highest
3	cis-Vaccenic acid	Moderate
4	7-Methyl-Z-tetradecen-1-ol acetate	Low
5	Acetamide, N-methyl-N-[4-[2-acetoxymethyl-1-pyrrolidyl]-2-butynyl]-	Low
6	Ergosta-5,22-dien-3-ol, acetate (3β,22E)	Low
7	Ethyl iso-allocholate	Low
8	Compound reported in the thesis	—
9	Compound reported in the thesis	—

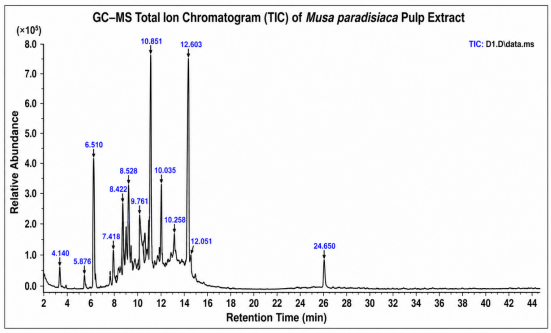

Figure 1. GC–MS total ion chromatogram (TIC) of the extract of unripe *Musa paradisiaca* pulp. Peaks are labeled with their retention times (min). The most intense peaks were observed at 10.851 min and 12.603 min.

Figure 1 presents the GC–MS total ion chromatogram of the extract of unripe *Musa paradisiaca* pulp, revealing a complex phytochemical profile characterised by numerous well-resolved chromatographic peaks. Most of the detected compounds eluted between approximately 6 and 15 min, indicating the presence of predominantly volatile and semi-volatile phytochemicals. The chromatogram is dominated by two major peaks at retention times of approximately 10.851 min and 12.603 min**,** suggesting that these constituents are the most abundant compounds in the extract. A smaller peak observed at approximately 24.650 min represents a less abundant compound with a longer retention time, consistent with a constituent of relatively lower volatility. Overall, Figure 1 demonstrates efficient chromatographic separation of the extract constituents and provides the analytical basis for the identification of individual phytochemicals using the NIST mass spectral library, the results of which are presented in the subsequent GC–MS identification tables.

FTIR Spectral Analysis

Fourier-transform infrared (FTIR) spectroscopy was used to characterise the functional groups present in the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp. The spectra revealed the presence of several characteristic functional groups associated with phytochemically active compounds. The aqueous extract contained C–H, C=O, C–O, C–N/C=N, Si–O–Si and Si–**O** functional groups, whereas the methanolic extract exhibited C–H, C=O, C–C, C–O–C and sp^2 stretching vibrations. The silicon-containing functional groups (Si–O–Si and Si–O) were detected only in the aqueous extract. Overall, the FTIR findings supported the GC–MS results by confirming the presence of diverse organic functional groups in both extracts, while the differences observed between the spectra reflected differences in solvent extraction efficiency.

Table 5. Functional groups identified in the aqueous extract of unripe *Musa paradisiaca* pulp by FTIR spectroscopy

Wavenumber (cm^{-1})	Functional group assignment
2922	C–H stretching
1744	C=O stretching
1589	C–O
1371	C=O
1162	C–N and C=N stretching
969	Si–O–Si asymmetric stretching
738	Si–O symmetric stretching vibration

Table 6. Functional groups identified in the methanolic extract of unripe *Musa paradisiaca* pulp by FTIR spectroscopy

Wavenumber (cm^{-1})	Functional group assignment
2922	C–H stretching
1744	C=O stretching
1461	Methylene and methyl
1371	C=O
1155	C–C and C–O–C asymmetrical stretching

The FTIR spectra demonstrated the presence of carbonyl, aliphatic hydrocarbon, ether and other oxygen-containing functional groups that are characteristic of bioactive phytochemicals. These findings complement the GC–MS analysis and provide additional evidence for the chemical diversity of the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp

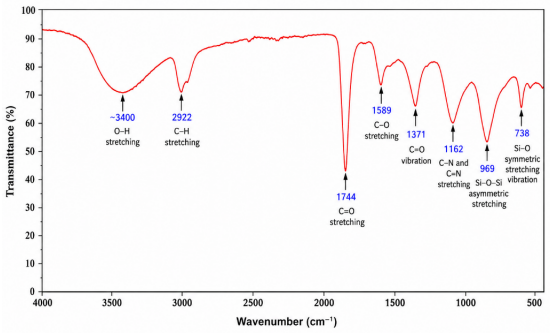

Figure 2. FTIR spectrum of the aqueous extract of unripe *Musa paradisiaca* pulp. The principal absorption bands are indicated with their corresponding wavenumbers (cm^{-1}) and functional group assignments.

Figure 2 shows the FTIR spectrum of the aqueous extract of unripe *Musa paradisiaca* pulp. The spectrum exhibited characteristic absorption bands at 2922, 1744, 1589, 1371, 1162, 969 and 738 cm^{-1}, corresponding to aliphatic C–H stretching, carbonyl (C=O) stretching, C–O stretching, C–N/C=N stretching, and Si–O–Si/Si–O vibrations, respectively.

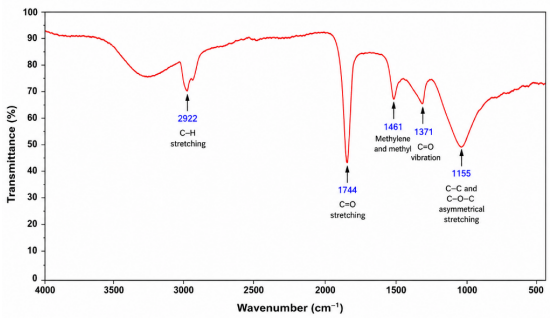

Figure 3. FTIR spectrum of the methanolic extract of unripe *Musa paradisiaca* pulp. The principal absorption bands are indicated with their corresponding wavenumbers (cm^{-1}) and functional group assignments.

Figure 3 shows the FTIR spectrum of the methanolic extract of unripe *Musa paradisiaca* pulp. The spectrum exhibited characteristic absorption bands at 2922, 1744, 1461, 1371, and 1155 cm^{-1}, corresponding to aliphatic C–H stretching, carbonyl (C=O) stretching, methylene and methyl group vibrations, carbonyl (C=O) vibration, and C–C/C–O–C asymmetrical stretching, respectively. These absorption bands confirm the presence of diverse oxygen-containing and aliphatic functional groups in the methanolic extract, supporting the phytochemical composition identified by GC–MS analysis.

Discussion

The present study showed that both the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp contained alkaloids, saponins, flavonoids, phenols and glycosides, while tannins and steroids were detected only in the methanolic extract. These findings are consistent with those of Ajijolakewu et al. [26], who reported that *Musa paradisiaca* contains abundant flavonoids, phenolic compounds,

alkaloids, glycosides and other secondary metabolites that contribute to its medicinal properties. Similarly, Ekweogu et al. [27] demonstrated that methanol extracted a broader spectrum of phytochemicals, including tannins and steroids, than aqueous solvents, owing to its higher extraction efficiency for moderately polar compounds. However, unlike the findings of Gervásio and Batitucci [28], who reported the presence of terpenoids in other parts of the plant, terpenoids were not detected in the present study. This discrepancy may be attributed to differences in the plant part analysed, geographical origin, extraction solvent and analytical techniques employed. Overall, the phytochemicals identified provide a scientific basis for the antioxidant and potential cardioprotective activities of unripe *Musa paradisiaca* pulp.

The present study demonstrated that both aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp possessed appreciable antioxidant activity. The aqueous extract contained higher levels of total phenolics and flavonoids, whereas the methanolic extract exhibited slightly greater total antioxidant capacity. These findings are consistent with those of Gervásio and Batitucci [29], who attributed the antioxidant activity of *Musa paradisiaca* primarily to its high phenolic and flavonoid contents. Similarly, Peres et al. [30] reported that differences in antioxidant capacity between extraction solvents are related to variations in the solubility of antioxidant phytochemicals, with methanol often extracting a broader range of bioactive compounds than water. These findings support the potential use of unripe *Musa paradisiaca* as a natural source of antioxidants for protecting against oxidative stress-associated cardiovascular disorders.

The GC–MS analysis identified several bioactive compounds in both the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp, with the methanolic extract exhibiting a greater diversity of phytoconstituents. This finding agrees with the observations of Zhang et al. [31], who reported that methanol is generally more effective than water in extracting a wider spectrum of phytochemicals from medicinal plants. Likewise, Shen et al. [32] emphasised that GC–MS is a reliable analytical technique for identifying bioactive constituents that contribute to the pharmacological activities of medicinal plants. The identified compounds, including phenolic derivatives, fatty acid esters and related phytochemicals, have previously been associated with antioxidant, anti-inflammatory and cardioprotective activities. Therefore, the GC–MS profile obtained in this study provides further evidence for the medicinal value of unripe *Musa paradisiaca* pulp and supports its potential application in the development of plant-based cardioprotective agents.

The FTIR analysis confirmed the presence of several functional groups, including hydroxyl, aliphatic C–H, carbonyl and C–O functional groups, in both the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp. These findings are in agreement with those of Aguree et al. [33], who identified similar FTIR absorption bands corresponding to hydroxyl, carbonyl and C–O functional groups in medicinal plant extracts and associated them with phenolic compounds and other antioxidant metabolites. Similarly, Raju et al. [34] reported that FTIR spectroscopy complements GC–MS by confirming the presence of bioactive functional groups that contribute to the biological activities of medicinal plants. The presence of these functional groups in the present study supports the GC–MS findings and further confirms the chemical diversity of the extracts. The abundance of oxygen-containing functional groups may contribute to the antioxidant and potential cardioprotective properties of the plant. Overall, the FTIR results provide additional evidence that unripe *Musa paradisiaca* pulp contains bioactive constituents with promising therapeutic potential.

Conclusion

The present study demonstrated that unripe *Musa paradisiaca* pulp is a rich source of bioactive phytochemicals with promising antioxidant potential. Qualitative phytochemical screening revealed the presence of alkaloids, flavonoids, phenols, saponins and glycosides, while GC–MS analysis identified several bioactive compounds and FTIR analysis confirmed the presence of important functional groups associated with these phytochemicals. The findings support previous reports on the medicinal value of *Musa paradisiaca* and provide scientific evidence for its potential application as a natural source of cardioprotective phytochemicals. Further studies involving the isolation, structural elucidation and biological evaluation of the identified compounds are recommended to validate their therapeutic potential.

Contribution to Knowledge

This study contributes to existing knowledge by providing a comprehensive phytochemical characterization of the aqueous and methanolic extracts of unripe *Musa paradisiaca* pulp using qualitative phytochemical screening, GC–MS, and FTIR analyses. It identifies the major bioactive compounds and functional groups present in the extracts, thereby expanding the phytochemical database of *Musa paradisiaca*. Furthermore, the study provides scientific evidence supporting the antioxidant potential of unripe *Musa paradisiaca* pulp, reinforcing its potential as a natural source of

bioactive compounds for the development of cardioprotective nutraceuticals and phytopharmaceuticals. These findings serve as a foundation for future pharmacological and clinical investigations into its therapeutic applications.

Recommendations

1. Further studies should isolate and characterize the major bioactive compounds identified by GC–MS to determine their individual pharmacological activities.
2. In vivo and clinical studies are recommended to validate the antioxidant and cardioprotective potential of unripe *Musa paradisiaca* pulp.
3. Advanced analytical techniques such as LC–MS/MS and NMR spectroscopy should be employed to confirm the structures of the identified phytochemicals.
4. The identified bioactive compounds should be explored for the development of safe, effective, and affordable plant-based nutraceuticals or phytopharmaceuticals for the prevention and management of cardiovascular diseases.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this article.

Data Availability

The datasets used and/or analyzed during the current study are derived from original study in form of raw data and are available from the lead author upon reasonable request.

Ethical Approval

The ethical approval was gotten from the ethical committee of the University of Nigeria Enugu Campus with the number: **NHREC/05/01/2008B-FWA-000002458-1RB00002323**

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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