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Phytochemical Profiling and Characterization of Bioactive Compounds from Mambila Highland Tea Leaf Fibres

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ABSTRACT

This study evaluated the efficiency of three extraction methods, Soxhlet, maceration, and infusion for obtaining an extract from tea leaf fibers, followed by comprehensive phytochemical and chemical characterization. Soxhlet extraction was the most efficient method, achieving the highest yield (26.42%), significantly surpassing maceration (21.92%) and infusion (12.75%). Phytochemical screening of the resulting extract confirmed a rich profile, revealing the presence of saponins, alkaloids, glycosides, flavonoids, phenolic acids, steroids, tannins, coumarins, phlobatannins, and quinones, while terpenoids were notably absent. UV-Visible (UV-Vis) spectroscopy determined a high dry matter content (66.6%) and spectral characteristics, exhibiting a maximum absorbance (λmax) of 4.707 at 270 nm. This spectral data led to a calculated total color value of 70.67, which is higher than values typically reported for fermented black tea. Further chemical characterization using Fourier-transform infrared (FTIR) spectroscopy identified key functional groups, notably hydroxyl (−OH) and carbonyl (C=O) groups. Gas Chromatography-Mass Spectrometry (GC-MS) identified five major compounds: benzoic acid (28.62%), caffeine (22.09%), dimethyl phthalate, hexadecanoic acid methyl ester, and methyl oleate (Z−9-octadecenoic acid, methyl ester). The high yields and the identification of benzoic acid and caffeine suggest the tea leaf fiber extract holds promise as a natural source of preservatives and stimulants for industrial applications.

Keywords: *Phytochemicals, Gas chromatography, Fourier Transform Infra-red Spectroscopy, Tea leaf Fibre.*

1. Introduction

Tea, derived from the leaves of *Camellia sinensis*, is one of the most widely consumed beverages globally and is commonly known by names like *Chaye* and *Cha*. The plant yields three main commercial varieties: oolong, green, and black, with their differentiation arising primarily from varying levels of fermentation. Beyond its use as a beverage, tea is a rich source of naturally occurring phytochemicals, including polyphenols (10-13%), caffeine (1-4%), flavonoids, phenolic acids, and amino acids. These compounds are critically important due to their proven antioxidant properties, which offer significant health advantages, including protection against cardiovascular diseases, cancer, and neurodegenerative conditions [4].

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Despite this high intrinsic value, the residue generated from tea processing, often referred to as spent tea leaf (STL) or tea chaff, is a substantial source of agricultural waste. Countries like Nigeria, which benefit from a humid climate for tea production, generate vast quantities of this residue. Currently, this waste is typically either discarded or incinerated. This indiscriminate dumping and burning results in a considerable loss of a potentially valuable resource, generating significant environmental pollution and imposing an unnecessary economic burden for disposal [14]. This material, particularly the fibrous components, still contains residual, high-value compounds that are structurally protected, making their full potential currently unrealized.

To transform this environmental liability into an economic asset, focused research is required to valorize the specific components of the waste stream, such as the tea leaf fibre (TLF). While the general composition of tea is well-established, there is a distinct gap in the literature regarding the optimized, targeted extraction and comprehensive characterization of phytochemicals sequestered within the structure of the spent, fibrous residue. Therefore, the study aims to develop an optimized extraction methodology for the efficient recovery of bioactive phytochemicals from Tea Leaf Fibre (TLF). Furthermore, this research will involve the detailed characterization of the extracted compounds to confirm their composition and potential application as a high-value, sustainable raw material for the nutraceutical and functional ingredient industries.

2. Materials and Methods

2.1 Sample Collection and Treatment

Tea leaf fibre from Mambila was obtained after the Mambila Beverages Production Company, located in Kakara, Taraba State, Nigeria. The collected Mambila tea leaf fibre samples underwent oven drying at a temperature of 60 ^{0}C overnight to decrease moisture levels. The dried fibre was subsequently ground into a fine powder was sieved with a mesh of 20 µm.

2.2 Determination of Moisture Content

A moisture content assessment was performed on the powdered tea Fibres. 5 g of the sample were weighed, dried in the oven for 30 minutes at 150 ^{0}C, allowed to cool in a desiccator, and weighed multiple times until consistent weights were attained. The ground samples were then stored in labeled brown envelopes for later use in the extraction of colorants.

$$\% \text{ Moisture content} = \frac{\text{Intial weight weight} - \text{weight of oven sample}}{\text{Initial weight of sample}} \times 100$$

2.3 Extraction Techniques for Colorants from Tea Leaf Fibre

2.3.1 Soxhlet Method

A sample of 120 grams of the finely ground tea leaf Fibres was placed in a thimble within a Soxhlet extractor. In this process, methanol solvent was vaporized, condensed, and cycled back into the sample chamber, facilitating the extraction of the desired compounds [3]. Following extraction, it was filtered through muslin cloth and the extract was then evaporation using a water bath at 40 °C, which was then utilized for phytochemical analysis.

2.3.2 Maceration Method

To extract the fine powder of tea leaf fibre, the maceration technique was used. This involved adding 120 grams of fine powdered tea leaf fibre into a 1000 mL beaker and covering it with water as the menstruum. The container was sealed and left for a minimum of three days, during which it was stirred occasionally to ensure thorough extraction [2]. After three days, it was filtered through muslin cloth and the extract was then evaporation using a water bath. The yield of the extract was subsequently measured and noted.

2.3.3 Infusion Method

The extraction of the fine powdered tea leaf Fibres was carried out using the infusion method. In this process, 120 grams of the fine powder was steeped in 260 mL of hot boiling water within a 1000 ml beaker. The mixture stood in hot water for about five minutes before being filtered through muslin cloth and then Whatman No. 1 filter paper collected in a 250 mL conical flask. The clear filtrate was then concentrated using a water bath set at 60 °C. The yield of the extract was subsequently measured and noted [12].

2.4 Purification of the Extracts

Soxhlet, Maceration and Infusion methods were employed to extract the desired compounds from the TLF. The soxhlet, Maceration, and Infusion extracts were filtered through a muslin cloth, and then, the extracts were filtered through a Whatman No. 1 filter paper to remove particulate matter and impurities.

2.5 Preliminary Phytochemical Screening of Tea Leaf Fibres

2.5.1 Saponins (Foam test): In a test tube, 0. 5 g of extract was combined with 5 mL of distilled water and shaken vigorously. Olive oil was then added in small amounts. The appearance of stable foam suggested the presence of saponins, or the extract was shaken with distilled water forcefully. The presence of a lasting foam indicated that saponins were present [5].

2.5.2 Glycosides (Precipitation test): To the extract, a few drops of mercuric chloride were introduced. The formation of a precipitate showed that glycosides were present [5].

2.5.3 Alkaloids (Mayer's test): The extract received some drops of Mayer's reagent (potassium mercuric iodide). A cream or pale-yellow precipitate appeared, indicating the presence of alkaloids [5].

2.5.4 Test for Tannins: A sample weighing 0. 5 g was boiled in 20 milliliters of distilled water in a test tube and subsequently filtered. To the resulting filtered solution, 0. 1% Ferric chloride was added, which was observed for brownish green or blue, indicating the presence of tannins [5].

2.5.5 Test for flavonoids (Alkaline Reagent Test): To the extract, a few drops of sodium hydroxide (NaOH) were added. The solution turned yellow, signifying the presence of flavonoids. This yellow tint faded after standing for a while [5].

2.5.6 Phenol (Ferric Chloride Test): A few drops of ferric chloride were added to the extract. A green or blue color showed that phenolic compounds were present [5].

2.5.7 Test for phlobatannins (HCl): The extract was boiled together with a 2% aqueous solution of HCl. A red precipitate was formed, it indicated the presence of phlobatannins [5].

2.5.8 Test for quinones (NaOH): 1 mL of the extract had dilute NaOH added to it. The emergence of blue-green or red coloration suggested the presence of quinones [5].

2.5.9 Test for coumarin (10% NaOH Test): The extract received 10% NaOH, followed by chloroform, a yellow color was formed, which indicated the presence of Coumarin [5].

2.5.10 Steroids (Libermann-Buchard Test): To 0. 5 mL of the extract, 2 mL of acetic anhydride and 2 milliliters of H_2SO_4 were added. A color change from violet to blue or green in the samples indicated the presence of steroids. [5].

2.5.11 Test for terpenoids (Salkowski Test): 5 mL of the extract was mixed with 2 mL of acetic anhydride, and then 3 mL of concentrated H_2SO_4 was carefully layered. The development of a reddish-brown color at the interface confirmed the presence of terpenoids [5].

2.6 Characterization of Extracted Colorants

2.6.1 Ultra-Violet-Visible spectrophotometer (UV-Vis)

UV-Vis spectroscopy was employed to analyze absorbance and determine the concentration of colorants according to the Beer-Lambert law. The absorbance of the solution was measured at 270 nm (A270) against a blank of distilled water. The total color was calculated as follows:

Total color = A270 nm × 10

2.6.2 Measurement of Dry Matter

The procedure described by Obi *et al.*, [14] was used, which involved weighing 15 g of the concentrated extracted Tea Leaf

Fibre sample to the closest 0. 001 g. This was put in a weighing bottle and then heated in an oven at 60 °C for no less than 16 hours until a stable weight was reached. The dry matter percentage (DM) in the sample was then determined:

$$\frac{Dry\ weight\ of\ sample}{Wet\ weight\ of\ sample} \times 100\%$$

2.6.3 Determination of the Total Color of the Extracted Colorants

To determine the total color of the extracted colorants, the method used was according to Obi *et al*., [14]. In this procedure, 5 mL of the extracted tea fibres were pipetted into 45 mL of distilled water inside a 100 mL conical flask. The mixture was shaken properly to mix thoroughly. The absorbance of this solution was measured at 270 nm (A_{270}) using a distilled water blank. The total color was calculated as follows:

$$Total\ colour = \frac{A_{270nm} \times 10}{DM/100}$$

Where:
A_{270nm} = Absorbance at maximum wavelength (4.707).
DM = Percentage dry matter of extract (66.6%)

2.6.4 Fourier Transform Infrared Spectroscopy

A small drop of the liquid tea leaf fibre extract was placed directly between two clean, polished potassium bromide. The plates were then gently pressed together to spread the liquid into a uniform, thin film [20].

A background scan of the empty, clean salt plates was performed to measure the ambient atmospheric conditions (like water vapor and carbon dioxide) and the instrument's environment. This background spectrum was crucial and was automatically subtracted from the sample's spectrum to ensure a clean result [20].

The prepared sample (the salt plates with the thin film) was placed in the FTIR spectrometer's sample holder. An infrared beam was passed through the sample. The sample's molecules absorb specific frequencies of the IR radiation, causing them to vibrate. The instrument measured the amount of light transmitted through the sample at each frequency, generating a spectrum of absorbance versus wavenumber (cm^{-1}) [20].

The resulting spectrum was analyzed by identifying the positions of the absorption peaks. Each peak corresponded to a specific molecular vibration, which was correlated to a specific functional group [20].

2.6.5 GC-MS Analysis

The solution of the Tea Leaf Fibre extract was injected into the apparatus, allowing for the separation and identification of the individual components [16; 18].

3. Results and Discussion

3.1 Results

Table 1: Comparison of Yields from Different Extraction Techniques

Extraction Technique: Infusion Method	Maceration Method	Soxhlet Extraction Method
Weight of Samples(g)	120	120	120
Loss of Weight (g)	15.3	26.3	31.7
Extraction yields %	12.75	21.92	26.42

Table 2: Shows the Preliminary Phytochemical Screening of Tea Leaf Fibres Extract

S/N	Phytochemical Compositions	Status
1	Saponin	+
2	Alkaloid	+
3	Glycoside	+
4	Flavonoid	+
5	Phenolic acids	+
6	Steriods	+
7	Tannins	+
8	Coumarins	+
9	Phlobatannin	+
10	Quinones	+
11	Terpenoids	-

Note: "-" = Absent, "+" = Present

Table 3: The GC-MS Analysis of the Tea Leaf Fibre Five Principal Compounds

S/N	Retention time (min)	Peak Area (%)	Compound Detected	Quality Score
1	6.284	28.62	Benzoic acid	95
2	14. 831	22. 09.	Caffeine	47
3	10. 184	10. 48.	Dimethyl Phthalate	93
4	17.876	2.93	9-Octadecenoic acid (Z)-, methyl ester	99
5	15. 627	1. 64	Hexadecanoic acid, methyl ester	97

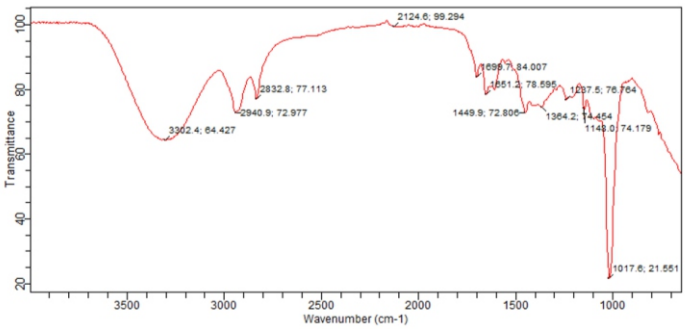

Figure 1: FT-IR Spectra of Tea Leaf Fibres Extract

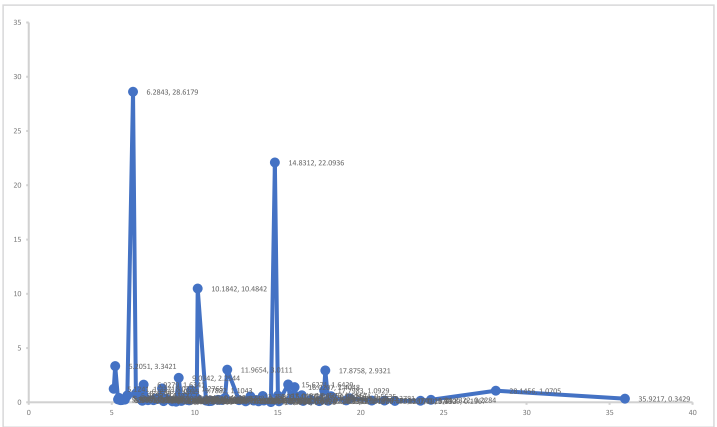

Figure 2: GC-MS Chromatogram of Tea Leaf Fibre Extract

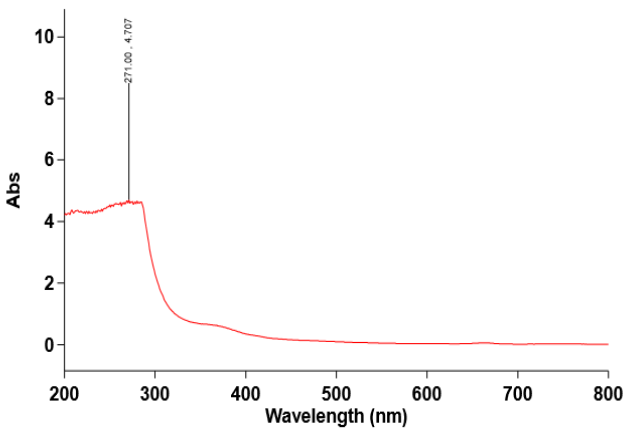

Figure 3: UV-VIS Spectral Curve for Tea Leaf Fibre Extract

3.2 Discussion

Generally, Table 1 shows that the Soxhlet extraction method produces a higher yield percentage when compared to the Maceration and Infusion methods of extraction. This is mainly due to the fact that Soxhlet extraction is a more automated and efficient method, allowing continuous cycling of solvents that aids in extracting more compounds from finely ground Tea Leaf Fibres.

In contrast, Maceration and Infusion depend on slower and milder extraction methods, which might lead to lower yields. Nevertheless, these techniques can still work well for extracting specific compounds, especially those that are sensitive to heat or strong solvents.

The extract from tea leaf Fibres appeared dark brown to black. This coloration could result from the oxidation process that black tea experiences during its production, giving it its typical dark hue. The extract maintains this deep color, leading to a rich, brown-black appearance. This was in agreement with the report from the related Extraction studies of crude Curcumin from Tumeric using Soxhlet apparatus and ethyl alcohol as a solvent was found to be 10.23% [7].

The preliminary phytochemical screening of tea Leaf fibres extract in Table 2: Shows it is widely recognized that a majority of products labeled as herbal or traditional plant medicines are based on their antioxidant properties or phytochemical compounds [15]. The extracts from Tea Leaf Fibres were found to have saponins, alkaloids, glycosides, flavonoids, phenolic acid, steroids, tannins, coumarin, phlobatannin, and quinones, while terpenoids were absent. The methanol extracts displayed a diverse array of secondary metabolites. Conversely, the medicinal value of plants comes from certain chemical compounds that fulfill specific physiological roles in the human body. Various phytochemicals have been identified to possess a variety of medicinal characteristics, which may aid in defending against numerous diseases. For instance, flavonoids represent a class of polyphenolic compounds that are advantageous in the human diet due to their roles as antioxidants, scavengers of free radicals, and in reducing inflammation [9]. Saponins are known for their protective effects against tumors and microbial activities. Tannins exhibit properties that contribute to both antimicrobial and antioxidant effects [17]. Therefore, the findings of this study underscore the significance of incorporating these extracts into human food or local drinks because they contain natural bioactive compounds that offer medicinal benefits.

The Tea Leaf Fibre Extract sample showed several significant peak wavelengths: 3302. 4, 2940. 9, 2832. 8, 2124. 6, 1449. 9, 1699. 7, 1851. 2, 1364. 2, 1237. 5, 1148. 0, and 1017. 6 cm^{-1}.

At 3302. 4 cm^{-1}, the peak suggests vibrations related to N-H or O-H stretching, commonly found in alcohols or amines, indicating single bond hydrogen absorption [13, 19, 10]. Kalu *et al.,* [8] found similar peaks in their alcohol analysis, verifying the existence of hydroxyl groups. The broad O-H stretch of alcohol was seen at 3454. 21 cm^{-1}, which could be linked to an interbond between the extracted Sesamum indicum seed oil (SISO) and glycerol.

The peaks at 2940. 9 cm^{-1} and 2832. 8 cm^{-1} corresponds to vibrations from C-H stretching, analogous to those identified by Mamand *et al.*, [10] in the range of 2916–2851 cm^{-1}, typical of organic compounds [13]. A similar peak at 2933. 51 cm^{-1} was noted by Kalu *et al*., [8] in their SISO study, indicating alkane functionalities.

The peak at 2124. 6 cm^{-1} might suggest C≡C stretching vibrations, which are typical for alkynes. Nnorom and Onuegbu, [13] observed analogous peaks in their study of unsaturated hydrocarbons, indicating triple bonds at 2094. 8 cm^{-1}.

At 1699. 7 cm^{-1}, the peak is related to C=O stretching vibrations, often found in carbonyl compounds such as ketones or aldehydes. Strong absorptions near this area were reported by Nnorom and Onuegbu, [13] in their ketone research, confirming carbonyl functionalities at 1718. 3 cm^{-1}, suggesting the presence of ketones in their aqueous extracts. However, Thummajitsakul *et al*., [19] found C=O stretches between 1734. 5 - 1740. 54 cm^{-1} in carbonyl groups from lipids studied, while Samanidou, [16] detected bands from 1680 – 1750 cm^{-1} attributed to C=O stretching related to aromatic structures.

The peak at 1851. 2 cm^{-1} may also indicate C=O stretching, especially in cyclic compounds or conjugated systems. Kalu *et al*., [8] noted a similar peak for SISO at 1743. 83 cm^{-1}, linked to C=O stretching as evidenced in their unsaturated fatty acid study, which suggested the presence of double bonds.

The peak at 1449. 9 cm^{-1} is often related to C-H bending vibrations typically found in aliphatic compounds. Kalu *et al*., [8] recorded a peak at 1454. 59 cm^{-1} for SISO. The peak at 1364. 2 cm^{-1} may indicate C-H bending vibrations, particularly in methyl groups [8]. Nnorom and Onuegbu, [13] identified these peaks in their analysis, indicating potential phenolic compounds or tannins. The peaks at 1237. 5 cm^{-1} and 1148. 0 cm^{-1} typically relate to C-O stretching vibrations commonly seen in ethers and esters [6]. At 1017. 6 cm^{-1}, the peak may represent C-N stretching vibrations, indicative of amines or amides. Zhang *et al.*, [23] noted such peaks in nitrogenous compounds during their research, proposing the presence of amine functionalities.

The evaluation of the GC/MS findings shown in Table 3 and Figure_2 demonstrated multiple notable peaks, with Benzoic acid being the most significant one. It displays a retention time of 6.284 minutes and holds an area percentage of 28.62, indicating it is the most prevalent substance in the sample. The quality score of 95 indicates a very strong alignment with the reference library, confirming its presence with a high level of certainty. This substance is well-known for being a preservative in food and drinks because of its ability to fight microbes. Its detection suggests possible uses in food safety and preservation [6].

Following Benzoic acid, Caffeine ranks as the second most important peak, with a retention time of 14. 831 minutes and an area percentage of 22. 09. Its quality score, however, is lower at 47 but still reflects a decent identification level, implying that caffeine is also a significant element of the sample. Caffeine, which is known for its energizing effects, is commonly present in coffee, tea, and energy drinks [23; 22]. Its identification points to the possibility that the sample may be linked to products containing caffeine or similar energizers.

Dimethyl Phthalate is the third key peak, showing a retention time of 10. 184 minutes and an area percentage of 10. 48. The quality score of 93 indicates a strong correlation, making it an important compound in this analysis. Typically, this substance is utilized as a plasticizer in many consumer goods, such as cosmetics and personal care products. Its identification raised concerns about the sample's potential exposure to phthalates, which are known for their extensive application in industries [20].

Another significant peak was found at 15. 627 minutes, where Hexadecanoic acid, methyl ester was detected with an area percentage of 1. 64% and a quality score of 97. This fatty acid methyl ester is frequently used in producing biodiesel and serves as a surfactant in various industrial uses [1].

The presence of 9-Octadecenoic acid (Z)-, methyl ester was noted at 17.876 minutes, with an area percentage of 2.93 and a quality score of 99. *Methyl 9-octadecenoate is a fatty acid methyl ester*. Methyl 9-octadecenoate has been reported in Antrodiacinnamomea, erythrophloia, and it is significant in lipid chemistry. It is employed in the production of biodiesel and as a solvent in various chemical processes [11].

The peak at m/z 55 was indicated to possibly result from further fragmentation of larger fragments, potentially corresponding to a $C_3H_3N^+$ or $C_4H_7^+$ fragment, although this would require significant rearrangement. Furthermore, the peak at m/z 82 might correspond to a fragment resulting from the loss of larger portions of the molecule, potentially corresponding to a $C_4H_4N_2^+$ fragment.

In the case of benzoic acid ($C_7H_6O_2$), the molecular ion was reported to have a mass-to-charge ratio (m/z) of 122. The peak at m/z 122 corresponds to the molecular ion itself, while the peak at m/z 105 was attributed to the loss of an OH (hydroxyl group), resulting in a fragment with the formula $C_7H_5O^+$. Additionally, the peak at m/z 77 was noted to result from the loss of a COOH (carboxyl group), leading to a fragment with the formula $C_6H_5^+$ (phenyl group) [18]

The molecular ion of caffeine ($C_8H_{10}N_4O_2$) has a mass-to-charge ratio (m/z) of 194. It was suggested that the peak at m/z 109 could arise from the loss of a methyl group (CH_3) and the imidazole ring, resulting in a fragment with the formula $C_4H_4N_3^+$. Additionally, the peak at m/z 179 was noted to potentially be due to the loss of a methyl group (CH_3, 15 Da) from the molecular ion, leading to a fragment with m/z 179 (194 - 15 = 179).

For dimethyl phthalate ($C_{10}H_{10}O_4$), the molecular ion was reported to have a mass-to-charge ratio (m/z) of 194. The peak at m/z 194 corresponds to the molecular ion of dimethyl phthalate (DMP). The peak at m/z 163 was suggested to result from the loss of a methoxy group (OCH_3, 31 Da) from the molecular ion, leading to a fragment with m/z 163 (194 - 31 = 163). The peak at m/z 77 was noted to potentially correspond to a phenyl cation (C_6H_5+), which could arise from further fragmentation of the molecule. However, the peak at m/z 50 was described as less straightforward to assign without additional context on the fragmentation pathway, but it might relate to further fragmentation of smaller aromatic or aliphatic fragments [3].

Hexadecanoic acid, methyl ester (also known as methyl palmitate), was identified as a compound that can be analyzed using mass spectrometry (MS). The molecular ion of methyl palmitate ($C_{17}H_{34}O_2$) was reported to have a mass-to-charge ratio (m/z) of 270. The fragmentation patterns were analyzed, revealing that the peak at m/z 227 did not directly fit common fragments without additional context, as the loss of CH_3CO^+ from the ester group does not align perfectly without further information on possible rearrangements or specific losses [12].

The peak at m/z 143 was suggested to potentially result from a McLafferty rearrangement or other specific cleavages relevant to fatty acid methyl esters, although it did not have a clear fit to common patterns for this compound. The peak at m/z 74 was characterized as typical of the McLafferty rearrangement ion for methyl esters, with the formula $C_3H_6O_2^+$, which is a common and diagnostic fragment for methyl esters.

Lastly, the peak at m/z 43 was indicated to correspond to an acetyl group (CH_3CO^+) or other $C_3H_7^+$ fragments, which are frequently observed in the mass spectra of organic compounds [21].

The analysis of the mass spectra of 9-Octadecanoic acid (Z)-methyl ester, also known as methyl oleate, revealed that the compound has a molecular formula of $C_{19}H_{36}O_2$ and a molecular weight of 296.49 g/mol. Significant peaks were observed at m/z of 264.0, 55.0, 83.0, 111.0, and 137.0, which were attributed to various fragmentation patterns.

The peak at m/z 264.0 might correspond to the loss of a methoxy group (OCH3) from the molecular ion, resulting in a fragment with m/z 296 - 32 = 264. The peak at m/z 55.0 could be attributed to a hydrocarbon fragment, possibly $C_4H_7^+$ or $C_3H_3O^+$, resulting from fragmentation of the fatty acid chain.

The peak at m/z 83.0 might correspond to a fragment resulting from cleavage of the fatty acid chain, possibly $C_5H_7O^+$ or $C_6H_{11}^+$. The peak at m/z 111.0 could be attributed to a fragment resulting from further fragmentation of the fatty acid chain. The peak at m/z 137.0 might correspond to a fragment resulting from cleavage of the fatty acid chain, possibly $C_8H_{13}O^+$ or $C_9H_{17}^+$. The mass spectra showed significant peaks that provided valuable information about the molecular structure, which could be used to identify the compound. However, it was noted that mass spectral analysis can be complex, and further analysis or comparison with reference spectra might be necessary for definitive identification [7].

4. Conclusion

The comprehensive characterization of the tea leaf fiber extract established its significant value as a multi-functional natural resource. The Soxhlet extraction method proved most efficient, delivering a high yield of 26.42%. This extract possesses a rich and diverse phytochemical profile, confirming the presence of numerous valuable secondary metabolites, including saponins, alkaloids, flavonoids, phenolic acids, and tannins. Crucially, Gas Chromatography-Mass Spectrometry (GC-MS) revealed high concentrations of two key functional compounds: benzoic acid (28.62%) and caffeine (22.09%). These findings are the basis for the extract's primary industrial potential. Specifically, the high yield combined with the benzoic acid content strongly suggests the extract's utility as a natural preservative, while the significant caffeine concentration points to its potential as an effective stimulant. Thus, the tea leaf fibers can serve as a high-value, sustainable raw material for the nutraceutical and functional ingredient industries.

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