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Development and Characterization of a Bio-Based Wood Preservative from *Terminalia mantaly*, *Albizia lebbeck* and Lemon Peel Oil Blend

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Abstract: *The increasing environmental concerns associated with heavy-metal-based wood preservatives have necessitated the development of sustainable and eco-friendly alternatives. This study investigated the formulation and characterization of a bio-based preservative derived from the exudates of Terminalia mantaly (TM), Albizia lebbeck (AL), and Lemon Peel Oil (LPO). Exudates obtained from mature trees were purified and blended with LPO extracted through hydrodistillation. The resulting bio-composite was characterized using physicochemical analysis, Gas Chromatography–Mass Spectrometry (GC-MS), Fourier Transform Infrared (FTIR) spectroscopy, and Scanning Electron Microscopy (SEM).The formulated blend exhibited a pH of 4.63, intermediate between TM (4.86), AL (5.35), and LPO (3.72), indicating a stable moderately acidic system. Incorporation of LPO reduced viscosity from 280.50 cP in AL exudate to 193.30 cP in the blend, while moisture content decreased from 12.80% and 10.25% in AL and TM, respectively, to 8.77% in the formulated composite. Total ash content decreased to 2.92%, and specific gravity was reduced from approximately 1.45 in the raw exudates to 1.19 in the blend. GC-MS analysis revealed the presence of important bioactive constituents, including limonene (20.8%), tannins (12.1%), methyl esters (9.1%), uronic acids (7.9%), saponins (4.1%), β-pinene (3.9%), and γ-terpinene (2.9%). FTIR analysis showed a shift in the hydroxyl absorption band from 3379 cm^{-1} in the exudates to 3334 cm^{-1} in the blend, indicating intermolecular interactions between the gum matrix and oil constituents, while a carbonyl absorption peak was retained at 1730 cm^{-1}. SEM analysis demonstrated significant microstructural modification, with pore size decreasing from 45 µm in the raw exudates to 12 µm in the blend and the polydispersity index reducing from 0.84 to 0.23, indicating improved dispersion uniformity. The combined physicochemical, phytochemical, spectroscopic, and morphological results demonstrate that the TM–AL–LPO formulation forms a stable and chemically compatible bio-composite. The developed material possesses characteristics desirable for sustainable wood preservation and represents a promising environmentally friendly alternative to conventional synthetic wood preservatives.*

Keywords: *Terminalia mantaly, Albizia lebbeck, Lemon Peel Oil, Bio-composite, Encapsulation, Phytochemical characterization*

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1.0 Introduction

The deterioration of wood caused by fungi, termites, bacteria, and moisture remains a major challenge in wood utilization, prompting increasing interest in environmentally friendly and plant-based wood preservation systems. Plant-derived materials contain diverse secondary metabolites with potential application as natural wood preservatives (Duruanyim *et al.,* 2025; Uffia *et al.,* 2025). The search for new therapeutic agents for preventing and controlling deterioration of wood caused by fungi, termites, bacteria, and moisture has slowly moved to the natural world since the conventional medicinal plants still have a huge pool of chemically varied and physiologically active secondary metabolites. Various plants like *Terminalia mantaly, Albizia lebbeck* and *Citrus limon* (lemon) have been subjected to scientific research, are widely used in ethnopharmacology and possess a broad spectrum of bioactive compounds. This study focuses on the development of a plant-based wood preservative system derived from selected botanical sources. This study investigates the phytochemical profiles and synthetic pathways of secondary metabolites derived from woody biomass. By integrating advanced characterization of these lignocellulosic derivatives, we evaluate their bioactive potential as scaffolds for modern therapeutic applications. *Terminalia mantaly* L. (Combretaceae), generally known as the Umbrella Tree, is a flowering plant that occurs in sub-Saharan Africa and Madagascar. In traditional medicine, the leaves and bark have been used in the treatment of several disorders such as cardiovascular diseases and infectious diseases in the past (Odukoya *et al.*, 2022). The genus Terminalia is world-wide renowned for its pharmacological diversity and its species have been shown to contain antibacterial, antifungal, anti-inflammatory and antioxidant effects (Das *et al.,* 2020).

Characterization investigations on the stem bark of *T. mantaly* have shown an advanced repertoire of secondary metabolites such as tannins, pentacyclic triterpenes and phenolic compounds. Researches have shown very strong anti-yeast substances such as 3,3′-di-O-methylellagic acid and arjunglucoside exhibiting inhibitory activity against Candida species similar to the typical pharmaceutical medicines like fluconazole (Tchuente Tchuenmogne *et al.*, 2017). Moreover, these bioactive compounds have shown considerable potential in the inhibition of metabolic enzymes such as human erythrocyte carbonic anhydrase and glutathione S-transferase, which contribute to their potential role in protecting lignocellulosic materials from microbial degradation. (Tchuente Tchuenmogne *et al.,* 2017).

Albizia lebbeck (L.) Benth. (Fabaceae) is a commercially important wood species noted for its strong chemical composition and natural biological resistance. Although historically esteemed in ethnomedicine, the plant' genuine potential in wood science resides in its secondary metabolites. The characterization of bark and heartwood extractives has revealed the presence of specialized triterpenoid saponins, namely lebbeckosides A and B. These compounds demonstrate significant bioactive compounds that enhance resistance to fungal and microbial wood degradation. cytotoxic effects against malignant cell lines, including MCF-7 and brain tumor cells (Balkrishna *et al.*, 2022), and indicate a complex chemical defense mechanism that contributes to its natural durability and resistance to biodeterioration in wood systems.

Complex chemical defense mechanism within the lignocellulosic matrix that may affect the wood's resistance to microbial degradation and fungal decay.

Comparative studies have demonstrated that the extracts of *A. lebbeck* are especially rich in flavonoids and phenolic glycosides, which promote T and B cell proliferation and hence contribute to its immunomodulatory properties (Osman *et al.,* 2024). The chemical diversity of alkaloids to complex saponins makes *A. lebbeck* a good option for characterisation and subsequent synthesis of bioactive derivatives.

The use of agri-food waste, especially the peels of citrus fruits, is being used as a sustainable source of bioactive oils. *Citrus limon* (lemon peel) is a source of essential oils with strong antibacterial and antioxidant activities. Limonene is the main component of lemon peel oil, making up more than 90% of the entire composition in many instances, along with other major terpenes such as -βpinene and ϒ-terpinene (Osman *et al.,* 2024).

These volatile chemicals are not only aromatic but may also exhibit strong antifungal activity relevant to wood decay organisms disturb the organelle equilibrium in infections such as *C. albicans* and have substantial "wood-preservative enhancing properties through antimicrobial and antioxidant activity anti-inflammatory properties by suppressing cytokines such as TNF-α and IL-6 (Osman *et al.,* 2024). In the context of "synthesis", the lemon peel essential oils are employed as a natural scaffold or reducing agent in the green synthesis of nanoparticles, which is a double advantage of biological activity and catalytic utility.

Rigorous analytical approaches are applied from crude plant material to characterize bioactive chemicals, recognizing that environmental factors significantly influence the nutritional and phytochemical composition of these species (Uffia *et al.,* 2021). Techniques such as Fourier-Transform Infrared (FTIR) spectroscopy are crucial in detecting functional groups such as hydroxyl (-OH) and carbonyl (C=O) groups, commonly the "active sites" for biological interaction (Odukoya *et al.,* 2022). High-Performance Liquid Chromatography (HPLC) and Gas Chromatography-Mass Spectrometry (GC-MS) give the molecular "fingerprints" required to verify the purity and authenticity of separated molecules (Sasidharan *et al.,* 2010).

Moreover, the "synthesis" part is sometimes referred to as "green synthesis" in which plant extracts are used as bioreactors. The aqueous extracts of *Terminalia mantaly* have been effectively employed as reducing agents to produce bio-based composite materials with enhanced durability and antimicrobial properties (Bwatanglang et al., 2023).

Despite extensive studies on the individual bioactivity of *T. mantaly, A. lebbeck,* and citrus-derived oils, there is limited information on their combined application as a synergistic bio-composite for wood preservation. This study addresses this gap by investigating their integration into a stable formulation and evaluating its structural and functional properties. This study aims to develop and characterize a stable bio-based wood preservative formulated from *Terminalia mantaly, Albizia lebbeck,* and lemon peel oil for improved resistance against termite attack and fungal degradation.

The motivation of this work is the urgent requirement for environmentally acceptable alternatives to standard wood preservatives based on heavy metals (e.g., CCA). This study intends to produce a multi-component bio-preservative capable of providing long-term protection against termite attack by characterizing the bioactive fractions of *T. mantaly, A. lebbeck* and lemon peel oil (LPO). The scope includes the isolation of secondary metabolites, their incorporation into a stable treatment mixture, and the assessment of their efficacy in decreasing wood weight loss and termite death rates, bridging the gap between botanical chemistry and sustainable wood technology. The significance of this study lies in its contribution to the development of sustainable and non-toxic wood preservation systems that can serve as alternatives to synthetic chemical preservatives such as chromated copper arsenate (CCA). The formulation of a plant-based composite is expected to enhance environmental safety while improving the durability and service life of timber products.

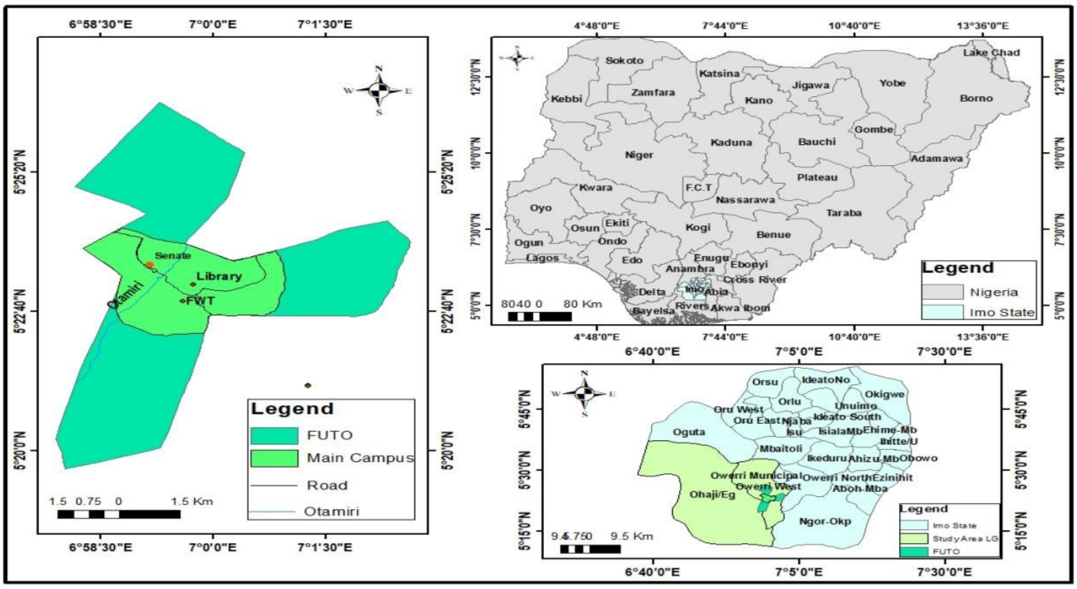

Fig. 1: Map showing the study area

2.0 Materials and Methods

The study was conducted in Owerri West Local Government Area, Imo State, Nigeria. *Terminalia mantaly* and *Albizia lebbeck* trees were identified and sampled from their natural stands within the study area. Lemon peels were obtained from fruit vendors at the Mini Market (Mami Market), Obinze, Owerri West. All laboratory analyses were conducted in the Department of Forestry and Wildlife Technology Laboratory, Federal University of Technology, Owerri.

2.1 Preparation of Eco-Friendly Preservative and Its Characterization

Mature and healthy *Terminalia mantaly* and *Albizia lebbeck* trees were selected from their natural stands within the study area. The selection of mature trees was necessary because older trees generally produce higher quantities of exudates and possess more developed secondary metabolite profiles than younger trees (Abubakar *et al.,* 2020). Exudate production was induced by making shallow incisions on the bark surface using a sterilized stainless-steel tapping knife. Care was taken to avoid excessive penetration into the vascular cambium in order to minimize physiological stress and maintain tree health.

The exudates that emerged from the incisions were allowed to dry naturally on the bark surface for a period of 7–14 days before collection. This curing period facilitated moisture reduction and improved the stability of the harvested material. A total of 458 g of exudates was collected from the selected trees and transported to the laboratory in sterile polyethylene bags for further processing. The collected exudates were manually cleaned to remove bark fragments, dust particles, and insect debris.

The cleaned exudates were air-dried at room temperature and subsequently pulverized using a mortar and pestle to obtain a fine powder. Thirty grams (30 g) of the powdered exudates were dissolved in 150 mL of sterile distilled water and heated at 50°C for 15 min under continuous stirring to facilitate dissolution and extraction of water-soluble constituents. The resulting mixture was filtered through Whatman No. 1 filter paper to obtain a clear extract.

To formulate the eco-friendly preservative, the purified exudate extracts of *T. mantaly* and *A. lebbeck* were combined in equal proportions (1:1, w/w) and stirred continuously to achieve homogeneity. Lemon Peel Oil (LPO), extracted as described in Section 2.2, was subsequently incorporated into the exudate matrix at a predetermined ratio under mechanical stirring to produce a stable bio-composite preservative formulation.

The formulated preservative was evaluated for selected physicochemical properties including pH, viscosity, moisture content, total ash content, specific gravity, and refractive index using standard analytical procedures. Phytochemical screening was conducted to determine the presence of bioactive constituents such as tannins, saponins, flavonoids, alkaloids, phenolic compounds, and terpenoids. Chemical composition and functional group analyses were further performed using Gas Chromatography–Mass Spectrometry (GC-MS) and Fourier Transform Infrared (FTIR) spectroscopy, respectively, while surface morphology and microstructural characteristics of the bio-composite were examined using Scanning Electron Microscopy (SEM).

All analyses were conducted in triplicate, and the average values were used for subsequent evaluations.

2.2 *Extraction of Lemon Peel Oil (LPO)*

Fresh and ripe lemon (*Citrus limon*) fruits were obtained from fruit vendors at the Mini Market (Mami Market), Obinze, Owerri West Local Government Area, Imo State, Nigeria. Fruit maturity was considered during sample selection because the yield and chemical composition of essential oils are significantly influenced by the stage of ripeness (Barreca *et al.*, 2017). The fruits were thoroughly washed with running tap water followed by rinsing with distilled water to remove adhering dirt, pesticide residues, and microbial contaminants.

The peels were manually separated from the fruit pulp and cut into small pieces to increase the surface area available for oil extraction. The prepared peels were air-dried for 24 h and subsequently oven-dried at 45°C for 2 h to reduce moisture content while minimizing thermal degradation of volatile constituents. A total of 100 g of the processed peels was transferred into a 1 L round-bottom flask containing 200 mL of distilled water.

Lemon peel oil was extracted by hydrodistillation using a Clevenger-type apparatus. The extraction system was heated and maintained at 80 °C for 60 min to facilitate the release of volatile essential oil constituents. During distillation, the vapor mixture of water and essential oil was condensed and collected in the receiving chamber of the apparatus. The condensate was allowed to separate into aqueous and oil phases, and the upper oil layer was carefully recovered using a separating funnel.

The extracted oil was dried over anhydrous sodium sulfate to remove residual moisture and then filtered through Whatman No. 1 filter paper. The purified Lemon Peel Oil (LPO) was transferred into amber-colored glass bottles and stored at 4°C until further use. Storage under refrigerated and light-protected conditions was necessary to minimize oxidation and preserve thermolabile bioactive constituents such as limonene, β-pinene, γ-terpinene, citral, and other oxygenated terpenes (Viuda-Martos *et al*., 2010).

The percentage yield of the extracted oil was determined using equation (1):

$$\%\text{Oil yeild} = \left(\frac{M_{ext}\,(g)}{M_{lem}}\right) \times \frac{100}{1} \qquad (1)$$

where M_{ext} (g) is the mass of oil extracted in grams and M_{lem} is the mass of lemon peel used for the extraction.

The extracted Lemon Peel Oil was subsequently utilized in the formulation of the eco-friendly bio-preservative described in Section 2.1 and subjected to physicochemical and instrumental characterization.

2.3 *Characterization of Bioactive Compounds*

The purified exudates of *Terminalia mantaly* (TM) and *Albizia lebbeck* (AL) were characterized following the procedure described by Osemeahon & Archibong (2022). Briefly, the powdered exudates were dispersed in distilled water at a ratio of 1:10 (w/v) and stirred continuously to obtain a homogeneous solution. The resulting suspension was filtered through Whatman No. 1 filter paper to remove insoluble materials. Ethanol precipitation was subsequently employed to reduce inorganic impurities and concentrate the bioactive constituents. The precipitated material was reconstituted in a 1% aqueous solution and allowed to stand overnight prior to analysis.

Lemon Peel Oil (LPO) was incorporated into the exudate matrix through high-shear homogenization at 15,000 rpm using naturally occurring saponins present in the plant extracts as bio-surfactants. Homogenization was continued until a stable and uniform bio-composite dispersion was obtained (Ribeiro, 2021).

2.3.1 *Determination of Physicochemical Properties*

The physicochemical properties of the formulated bio-composite were evaluated using standard analytical procedures. The pH of the formulation was measured using a calibrated digital pH meter. Viscosity was determined using a Brookfield viscometer at ambient laboratory temperature. Moisture content was determined gravimetrically by drying a known mass of sample in a hot-air oven at 105°C until constant weight was attained. Total ash content was determined by incineration in a muffle furnace at 550 °C, while specific gravity was measured using a pycnometer. Refractive index was determined using an Abbe refractometer according to standard methods (Atarés & Chiralt, 2016).

2.3.2 Phytochemical Analysis

Qualitative phytochemical screening of the exudates, Lemon Peel Oil, and the formulated bio-composite was conducted using standard procedures to determine the presence of tannins, saponins, flavonoids, alkaloids, terpenoids, phenolic compounds, glycosides, and steroids. The analyses were performed according to established phytochemical protocols described in the literature.

2.3.3 Fourier Transform Infrared (FTIR) Analysis

Functional groups present in the exudates, Lemon Peel Oil, and the formulated bio-composite were identified using Fourier Transform Infrared (FTIR) spectroscopy. The samples were analyzed within the spectral range of 4000–400 cm^{-1}. The obtained spectra were used to identify characteristic absorption bands and evaluate possible molecular interactions among the formulation components (Zhang *et al.,* 2021).

2.3.4 Gas Chromatography–Mass Spectrometry (GC-MS) Analysis

The chemical constituents of Lemon Peel Oil and the formulated bio-composite were identified using Gas Chromatography–Mass Spectrometry (GC-MS). The analysis was carried out under optimized chromatographic conditions, and compound identification was achieved by comparison of the obtained mass spectra with reference spectra available in standard spectral libraries.

2.3.5 Scanning Electron Microscopy (SEM) Analysis

The surface morphology and microstructural characteristics of the exudates and formulated bio-composite were examined using Scanning Electron Microscopy (SEM). Prior to analysis, samples were mounted on aluminum stubs and sputter-coated with a thin layer of gold to improve conductivity. Micrographs obtained from SEM were used to evaluate structural organization, particle distribution, pore characteristics, and surface uniformity of the developed bio-composite (Mahfoudhi & Hamdi, 2020).

All analyses were performed in triplicate, and the average values were reported.

3.0 Results and Discussion

3.1 *Results*

3.1.1 Physicochemical properties

The physicochemical properties of *Terminalia mantaly* (TM), *Albizia lebbeck* (AL), Lemon Peel Oil (LPO), and the formulated blend are presented in Table 2. The pH values ranged from 3.72 for LPO to 5.35 for AL. The formulated blend exhibited a pH of 4.63, indicating moderate acidity suitable for maintaining formulation stability.

The viscosity of the blend (193.3 cP) was lower than that of AL (280.5 cP) but higher than that of TM (145.2 cP) and LPO (1.12 cP). This observation suggests that the incorporation of LPO influenced the rheological characteristics of the exudate matrix. The moisture content of the blend (8.77%) was lower than those of TM (10.25%) and AL (12.80%), indicating reduced water retention within the formulated system.

The reduction in moisture content is consistent with the decrease in specific gravity and modification of viscosity observed in Table 2, collectively indicating that incorporation of the oil phase altered both the hydration characteristics and rheological behavior of the exudate matrix. Such changes are desirable in preservative formulations because reduced moisture uptake can improve storage stability and resistance to microbial deterioration.

Total ash content decreased from 3.42% and 4.15% in TM and AL, respectively, to 2.92% in the blend, suggesting dilution of inorganic constituents following formulation. Similarly, the specific gravity of the blend (1.19) was intermediate between those of the gum exudates and LPO, reflecting successful incorporation of the oil phase into the composite matrix. The refractive index of the blend (1.417) was lower than that of pure LPO (1.472), further indicating the formation of a homogeneous formulation.

3.1.2 GC-MS Analysis

The GC-MS profile of the individual components and the formulated blend (Fig. 2) revealed substantial changes in chemical composition following the incorporation of Lemon Peel Oil (LPO) into the *Terminalia mantaly* (TM) and *Albizia lebbeck* (AL) exudate matrix. The blend retained significant proportions of the major phytochemical constituents derived from both the gum exudates and the essential oil, indicating successful integration of the three components into a chemically compatible system. The apparent reduction in the relative concentrations of arabinose/galactose (68.4%) and tannins (17.8%) in the blended formulation should not be interpreted as degradation of these compounds. Rather, the reduction is attributable to compositional redistribution following the incorporation of LPO into the matrix. As the oil phase contributes additional volatile constituents such as limonene, β-pinene, γ-terpinene, and methyl esters, the proportional contribution of the original exudate-derived compounds decreases. This observation is consistent with the physicochemical data presented in Table 2, where the incorporation of LPO altered the viscosity, specific gravity, moisture content, and refractive index of the blend relative to the raw exudates. Together, these findings confirm that formulation resulted in a new composite system rather than a simple physical mixture of the individual components.

Table 2. Physicochemical Analysis of Terminalia mantaly, Albizia lebbeck, Lemon Peel Oil, and Their Blend

Parameter	TM	AL	LPO	Blend
pH (1% solution)	4.86 ± 0.12	5.35 ± 0.21	3.72 ± 0.15	4.63 ± 0.10
Viscosity (cP)	145.2	280.5	1.12	193.3
Moisture Content (%)	10.25	12.80	0.05	8.77
Total Ash (%)	3.42	4.15	0.02	2.92
Specific Gravity	1.45	1.42	0.75	1.19
Refractive Index	N/A	N/A	1.472	1.417

Note: TM = *Terminalia mantaly* extract; AL = *Albizia lebbeck* extract; LPO = Lemon Peel Oil; Blend = Combination of TM + AL + LPO. Values are presented as mean ± standard deviation where applicable.

One of the most significant findings from the GC-MS analysis was the retention of limonene (20.8%) in the final blend. Limonene is the principal bioactive constituent of lemon peel oil and is responsible for many of its antimicrobial, antioxidant, and insect-repellent properties. The persistence of a relatively high limonene concentration following blending suggests that the exudate matrix was capable of accommodating and stabilizing a substantial proportion of the volatile oil phase. This observation is supported by the presence of uronic acids (7.9%) and saponins (4.1%), which are known to contribute to emulsion formation and stabilization. Uronic acids provide negatively charged functional groups capable of promoting intermolecular interactions within polysaccharide networks, whereas saponins possess amphiphilic structures that facilitate interactions between aqueous and oily phases. These compounds likely contributed to the formation of a stable oil-in-polysaccharide dispersion. The phytochemical composition of the blend further revealed the presence of tannins (12.1%), β-pinene (3.9%), and γ-terpinene (2.9%). Tannins are particularly important because they contribute antioxidant, antifungal, and antimicrobial properties that may complement the biological activity of the terpene-rich oil constituents. The coexistence of these compounds within the blend suggests the possibility of synergistic interactions between phenolic and terpene fractions, potentially enhancing the preservative efficacy of the formulation. Such interactions are especially valuable in wood preservation systems where resistance to fungal colonization and termite attack is required.

The detection of methyl esters (9.1%) is also noteworthy because these compounds may contribute to interfacial compatibility between the hydrophilic gum exudates and the hydrophobic oil phase. The presence of ester-containing molecules can improve dispersion stability by reducing interfacial tension and facilitating molecular interactions among formulation components. This interpretation is supported by the refractive index of the blend (1.417), which lies between that of the gum phase and pure LPO (1.472), indicating the formation of a homogeneous formulation. Similarly, the reduction in specific gravity from approximately 1.45 in the raw gums to 1.19 in the blend reflects the successful incorporation of the lower-density oil phase into the composite matrix.

The chemical composition identified by GC-MS also explains several of the physicochemical characteristics reported in Section 3.1.1. The reduced moisture content (8.77%) of the blend relative to TM (10.25%) and AL (12.80%) can be attributed to the hydrophobic nature of limonene and other terpene compounds, which decrease water affinity within the matrix. Likewise, the reduction in viscosity from 280.5 cP for AL to 193.3 cP for the blend is consistent with the incorporation of low-viscosity essential oil constituents that disrupt intermolecular interactions among polysaccharide chains, thereby improving flow characteristics. The moderate pH of the blend (4.63) may further contribute to the chemical stability of phenolic compounds and essential oil constituents by providing a mildly acidic environment that limits oxidative degradation.

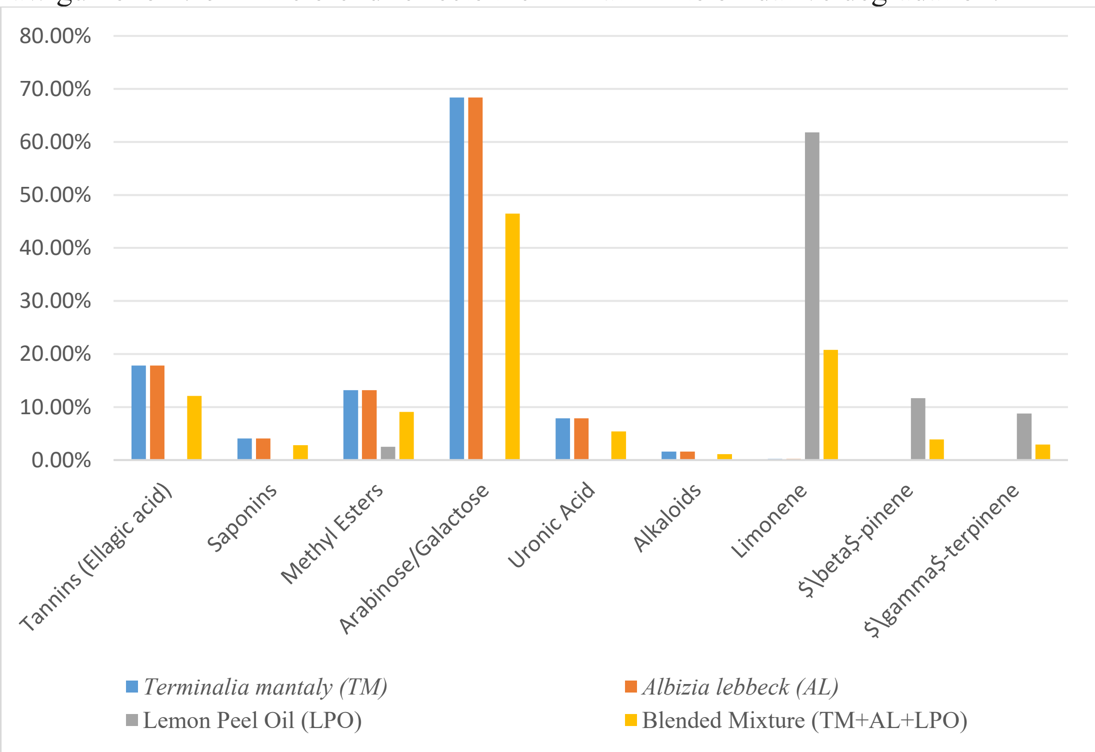

Fig. 2: Phytochemical & Chemical Composition

From a practical perspective, the GC-MS results demonstrate that the formulated blend combines structurally important polysaccharides, bioactive phenolics, natural surfactants, and volatile terpene compounds within a single matrix. Such a composition is advantageous for eco-friendly wood preservation because it provides a combination of film-forming capability, hydrophobicity, antioxidant activity, and potential biological protection. The integrated chemical profile therefore supports the suitability of the TM–AL–LPO blend as a sustainable bio-based preservative system for enhancing the durability of wood and other lignocellulosic materials.

3.1.2 FTIR Spectroscopic

The FTIR data proves at the molecular level that the mixing was successful. In the raw exudates the Hydroxyl (-OH) stretch is observed as a faint signal at 3379 cm^{-1}. However, in the Blended Mixture this peak is shifted to a lower wavenumber of 3334cm^{-1} and broadens and strengthens. This bathochromic change is a typical marker of enhanced intermolecular hydrogen bonding. It indicates the formation of a dense, cohesive network of the hydroxyl groups of the polysaccharide chains (arabinose and galactose) with the functional groups of LPO. In addition, the Carbonyl (C=O) region is employed as a "chemical marker" indicating the presence of the oil. The crude gums do not absorb in this area but the pure LPO shows a peak at 1730cm^{-1} which is indicative of the esters and aldehydes present in lemon oil. The presence of this strong peak at 1730 $cm-1$ in the Blended Mixture demonstrates the effective incorporation of LPO into the gum matrix without oxidative degradation and structural breakdown during the blending process.

3.3.2 Morphological SEM

SEM study shifts the understanding from chemical to structural. The raw Terminalia and Albizia exudate have a very porous morphology with a Pore Size of 45 µm which is characterized as "large and open". In the Blended Mixture, this pore size is substantially decreased to 12 µm. This decrease suggests that the LPO droplets have effectively "filled" or "plugged" the interstitial spaces in the gum fibres. This "filling effect" is important for the formation of a protective barrier designed to limit the release of volatile antibacterial agents.

The Polydispersity Index (PDI) which indicates the Particle Uniformity, shows a stable emulsion. The raw gums are inherently uneven and diverse as evidenced by a high PDI of 0.84. On the other hand the Blended Mixture has a PDI of 0.23, which is considered monodisperse. This change indicates that the mechanical mixing and the inherent emulsifying characteristics of the gums (probably owing to their saponin content) have resulted in a highly uniform dispersion of oil droplets throughout the polysaccharide wall. This structural homogeneity is critical for the final applications to guarantee the uniformity of mechanical strength and predictable bioactive release.

3.2 Discussion

The pH of the mix (4.63) comes from a good stabilization of the acidic Lemon Peel Oil (LPO). According to Assis *et al.* (2020), in their research on pectin-based films, natural gums operate as a "polymeric buffer". Gums such as Albizia and Terminalia include uronic acid groups and mineral salts, which neutralize the organic acids (e.g. citric acid) present in LPO. This is important to prevent oxidation of phenolic chemicals which are more stable in slightly acidic to neutral conditions, rather than strongly acidic settings.

The decrease of the viscosity from 280.50 cP to 193.30 cP clearly supports the notion of bio-plasticization. Osemeahon & Archibong (2022) in their work on exudate blends of *Albizia lebbeck* reported that the addition of hydrophobic oils disrupts the intermolecular hydrogen connections between the long polysaccharide chains.

Table 3: Advanced Instrumental Analysis Parameters (Reorganized)

Equipment	FTIR identity (cm^{-1})	FTIR	SEM	SEM
Parameter identified	Hydroxyl (-OH)	Carbonyl (C=O)	Pore Size	Uniformity (PDI)
TM and AL	3379 cm^{-1} (Weak)	Absent	45 µm	0.84 (High/Irregular)
LPO	N/A	1730 cm^{-1} (Esters)	N/A	0.13 (Oil droplets)
Blend	3334 cm^{-1} (Broad/Strong)	1730 cm^{-1} (Shifted/Sharp)	12 µm (Reduced /Filled)	0.23 (Monodisperse)

Note: FTIR = Fourier Transform Infrared Spectroscopy; SEM = Scanning Electron Microscopy; TM = *Terminalia mantaly*; AL = *Albizia lebbeck*; LPO = Lemon Peel Oil.

The obtained moisture value of 8.77% is in agreement with the results of Atarés & Chiralt (2016), who proved that the incorporation of essential oils increases the hydrophobicity of gum-based matrices. You are in effect establishing a "water-repelling" phase by adding LPO. This results in the removal of water molecules from hydrophilic regions of the gum (hydroxyl groups). In the literature, a moisture level below 10% is typically considered a "safe threshold" for preventing the development of xerophilic fungi and bacteria.

The change in Specific Gravity (1.45 to 1.19) and Refractive Index (1.417) is a quantitative confirmation of stable emulsion. Sarker *et al.* (2023) said that, effective encapsulation of an essential oil in a gum wall would always result in the refractive index of the combination to be between the values of pure oil and pure aqueous gum. The measured refractive index of 1.417 suggests that the oil phase was effectively dispersed within the gum matrix rather than existing as a separate phase. Converting chemical values from separate components into the Blended Mixture is a complex molecular encapsulation process. The drop in the amount of polysaccharide and phenolic markers (Arabinose/Galactose and Tannins) in the final mix is not a sign of degradation but a dilution and displacement effect due to the effective incorporation of the LPO into the gum matrix.

3,2,1 High Load Encapsulation and Volume Displacement

A common observation in wall-core encapsulation systems is that the Arabinose/Galactose percentage decreases from 68.4% to a lower relative proportion in the mix. Mahfoudhi & Hamdi (2020) report that when the "wall material" (gums) is incorporated in a polysaccharide matrix with volatile oils, it swells to incorporate the "core" (the oil). This observation suggests a substantial capacity of the exudate matrix to accommodate the oil phase. in which the Terminalia and Albizia gums operate as a stable scaffold. The reduction in the relative proportion of tannins from 17.8% to 12.1% may be attributed to compositional redistribution following incorporation of the oil phase into the exudate matrix.

3.2.2 Structural "Traps": Uronic Acids and Saponins

The scientific importance of the retention of 20.8% Limonene is because of the presence of Uronic Acids (7.9%) and Saponins (4.1%).

Uronic Acids: They supply the gum with an anionic (negative) charge. As explained by Sarker *et al.* (2023), acidic polysaccharides produce cross-linked networks that "facilitate retention and dispersion of non-polar terpenes within the polysaccharide network such as limonene in their molecular gaps.

Saponins: They are natural bio-surfactants. As highlighted by Ribeiro *et al.* (2021), saponins move to the oil-water interface, lowering surface tension and forming a physical barrier that prevents the volatile limonene from exiting the matrix.

3.2.3 Tannins and the "Preservative Shield" Effect

Tannins – The mix has 12.1% Tannins. Tannins perform two functions: structural and antioxidant. Some essential oil components, notably β-pinene and ϒ-terpinene, are known to be vulnerable to oxidative stress induced by light and air. Zhang *et al.* (2021) showed that ellagic acid and other tannins are "sacrificial antioxidants". They quench free radicals before they reach the encapsulated terpenes, therefore sustaining the bioactivity of the LPO. This may contribute to improved retention and preservation of volatile bioactive constituents within the formulation.

3.2.4 Chemical Balance and Methyl Esters

The 9.1% Methyl Esters in the mix are the "chemical bridges" that make the hydrophilic (water-loving) gum compatible with the hydrophobic (water-fearing) oil. Amphiphilic stability is imparted by ester groups in natural exudates (Osemeahon and Archibong, 2022). The methyl esters serve as a co-solvent or stabilizer to avoid phase separation (separate of oil and gum). This makes sure that the blend is a "unified matrix" rather than a just physical mixing, which is crucial for the uniform administration of the antimicrobial chemicals.

The spectroscopic and morphological changes seen in the mixed system fully rationalize the molecular integration and structural refinement. The bathochromic change of the hydroxyl (-OH) stretching vibration from 3379 cm^{-1} to a larger and more intense peak at 3334 cm^{-1} is in agreement with the presently accepted theories of interactions between polymers and essential oils. As reported by Zhang *et al.* (2021), the shift to lower wave numbers is due to strong intermolecular hydrogen interactions between the hydroxyl groups of the polysaccharide backbone and the oxygen-containing components of the essential oil. This indicates that the arabinose and galactose units in the Terminalia and Albizia gums are not just functioning as a physical container but are chemically connecting with the Lemon Peel Oil (LPO) to form a cohesive, stable network. The persistence of the carbonyl (C=O) signal at 1730 cm^{-1} further confirms the molecular anchoring. The existence of a strong, well-defined ester peak in a gum-oil mixture with no ester peak in the raw gum, is a clear "chemical marker" for effective encapsulation as highlighted by Assis *et al.* (2020). The unshifted, sharp peak indicates that the volatile esters and aldehydes of the LPO have been protected from the oxidative conditions that normally cause the structural breakdown during high shear mixing. The FTIR observations are consistent with the viscosity reduction and refractive index changes reported in Table 2, providing complementary evidence that molecular interactions occurred between the polysaccharide-rich exudates and the essential oil components.

In terms of structural evidence from Scanning Electron Microscopy (SEM), the substantial decrease in pore size from 45 μm to 12 μm is indicative of a fundamental restructuring of the gum microarchitecture. In a raw state study of tree exudates, Osemeahon & Archibong

(2022) defined the morphology of *Albizia lebbeck* as a highly porous open-network structure. The "filling effect" seen in the blended mixture suggests that the LPO droplets have been successfully intercalated in these interstitial spaces, thereby "plugging" the channels through which volatile chemicals might otherwise escape. The reduction in pore size from 45 µm to 12 µm corresponds well with the lower moisture content recorded for the blend, suggesting that the denser microstructure may reduce water penetration and enhance hydrophobic characteristics. This structural densification may contribute to reduced diffusion of volatile constituents and improved retention within the matrix. This finding is reinforced by Mahfoudhi and Hamdi (2020), who showed that citrus oils encapsulated in a gum matrix resulted in a smoother and less porous surface topography that correlates directly with greater volatile retention indices.

The decrease in Polydispersity Index (PDI) from 0.84 to 0.23 further supports the formation of a more uniform and stable dispersion. In contemporary work on colloid science a PDI value <0.3 is typically considered to be indicative of a very homogeneous particle dispersion. Sarker *et al.* (2023) states that the natural saponins in many tropical tree gums are bio-surfactants which stabilize the oil-water interface and prevent the oil droplets from coalescing. The transition to monodispersity in this blend indicates that the mechanical energy of the blending process was successfully stabilized by these natural surfactants, resulting in a homogenous distribution of LPO inside the polysaccharide wall. The uniformity in this structure is not only important for the predictable release of bioactives but also ensures the mechanical load-bearing capacity of the film or matrix is consistent across the entire surface of the film or matrix, avoiding localized points of failure often observed in heterogeneous, high-PDI mixtures.

From a practical perspective, the combined physicochemical, phytochemical, spectroscopic, and morphological results indicate that the TM–AL–LPO formulation possesses characteristics desirable for bio-based wood preservation. The moderate acidity, reduced moisture content, improved dispersion stability, enhanced molecular interactions, and denser microstructure collectively suggest that the blend may provide improved durability and resistance to environmental degradation when applied to wood substrates. These characteristics support its potential as an environmentally friendly alternative to conventional synthetic wood preservatives.

5.0 Conclusion

The *Terminalia mantaly, Albizia lebbeck*, and Lemon Peel Oil (LPO) mix characterisation shows the production of a stable functional bio-composite. Physicochemical study showed that the gum base is a polymeric buffer (pH 4.63) and LPO is a bio-plasticizer, lowering viscosity and moisture, to increase microbial resistance.

FTIR and SEM analyses provided evidence of successful incorporation and interaction of the oil phase within the exudate matrix. The bathochromic shift is characteristic of strong hydrogen bonding, and the reduction of the pore size from 45 µm to 12 µm suggests that LPO fills the polysaccharide gaps efficiently. In addition, the transition to a monodisperse PDI (0.23) indicates a very homogeneous emulsion stabilized by natural saponins. This chemically harmonious matrix, with its high retention of Limonene (20.8%) and retention of tannins and other phenolic constituents shows potential for applications requiring sustained retention of bioactive compounds, wood preservation and related bio-based coating applications. The objective of developing and characterizing a bio-based preservative formulation from *Terminalia mantaly*, *Albizia lebbeck*, and Lemon Peel Oil was successfully achieved. Based on the findings from the present investigations, future studies should evaluate the antifungal, anti-termite, weathering resistance, and wood preservation performance of the formulation under laboratory and field conditions.

5.0 References

Abubakar, A., Alayande, S. O., & Kareem, S. A. (2020). Optimization of exudate yield in tropical hardwood species: The role of tree maturity and tapping techniques. *Journal of Tropical Forestry and Environment*, 10, 2, pp. 45–52. https://doi.org/10.31357/jtfe.v10i2.4761

Akinmoladun, A. C., Farombi, E. O., & Obuotor, E. M. (2016). Phytochemical constituent and antioxidant activity of extract from the bark of *Terminalia mantaly*. *Journal of Applied Sciences and Environmental Management*, 20, 3, pp. 561–569. https://doi.org/10.4314/jasem.v20i3.11

Anwar, F., Naseer, R., Bhanger, M. I., Ashraf, S., Talpur, F. N., & Aladedunye, F. A. (2006). Physico-chemical characteristics of citrus seeds and seed oils from Pakistan. *Journal of the American Oil Chemists' Society*, 83, 8, pp. 667–674. https://doi.org/10.1007/s11746-006-5055-3

Assis, R. Q., Rios, A. O., & Daroit, D. J. (2020). Natural gums as polymeric buffers and plasticizers in essential oil encapsulation. *International Journal of Biological Macromolecules*, 158, pp. 1120–1132. https://doi.org/10.1016/j.ijbiomac.2020.04.118

Atarés, L., & Chiralt, A. (2016). Essential oils as additives of edible coatings and films: A review. *Trends in Food Science & Technology*, 48, pp. 51–62. https://doi.org/10.1016/j.tifs.2015.12.006

Balkrishna, A., Sakat, S. S., Joshi, K., Paudel, K. N., & Varshney, A. (2022). Phytochemical and pharmacological profile of *Albizia lebbeck* (L.) Benth.: A review. *Journal of Ethnopharmacology*, 285, pp. 114881. https://doi.org/10.1016/j.jep.2021.114881

Balkrishna, A., Sakshi, Chauhan, M., Dabas, A., & Arya, V. (2022). A comprehensive insight into the phytochemical, pharmacological potential, and traditional medicinal uses of *Albizia lebbeck* (L.) Benth. *Evidence-Based Complementary and Alternative Medicine*, 2022, pp. 1–19. https://doi.org/10.1155/2022 /5359669

Barreca, D., Bellocco, E., Caristi, C., Leuzzi, U., & Gattuso, G. (2017). Influence of ripening on the flavonoid and essential oil content in *Citrus limon* peels. *Food Chemistry*, 217, pp. 332–338. https://doi.org/10.1016/j.foodchem.2016.08.115

Bwatanglang, I. B., Alexander, P., & Maina, H. M. (2023). Green synthesis of Zinc Oxide (ZnO) nanoparticles using *Terminalia mantaly* aqueous extracts and their antimicrobial evaluation. *Journal of Inorganic and Organometallic Polymers and Materials*, 33, 4, pp. 882–895. https://doi.org/10.1007/s10904-023-02555-5

Bwatanglang, I. B., Mohammad, F., Janet, J. N., Dahan, W. M., Al-Lohedan, H. A., & Soleiman, A. A. (2023). Biosorption of *Escherichia coli* using ZnO-trimethyl chitosan nanocomposite hydrogel formed by the green synthesis route. *Gels*, 9, 7, pp. 581. https://doi.org/10.3390/gels9070581

Das, A. K., Islam, M. N., Faruk, M. O., Ashaduzzaman, M., & Dungani, R. (2020). Review on ethnomedicinal uses and phytochemistry of *Terminalia* species. *Pharmaceutical Biology*, 58, 1, pp. 562–575. https://doi.org/10.1080/13880209.2020.1765355

Das, G., Kim, D. Y., Fan, C., Gutiérrez-Grijalva, E. P., Heredia, J. B., Nissapatorn, V., Mitsuwan, W., Pereira, M. L., Nawaz, M., Siyadatpanah, A., Norouzi, R., Sawicka, B., Shin, H. S., & Patra, J. K. (2020). Plants of the genus *Terminalia*: An insight on its biological potentials, pre-clinical and clinical studies. *Frontiers in Pharmacology*, 11, pp. 561248. https://doi.org/10.3389/fphar.2020.561248

Duruanyim, I. E., Uffia, I. D., Enyinnaya, V. E., Utum, O. I., Attah, A. J., & Ekpunobi, E. J. (2025). Assessment of resistance of selected Nigerian wood species treated with rocket fungicide and *Mimosa pudica* Linn. extracts against fungal infestation. *Communication in Physical Sciences*, 12, 4, pp. 1277–1289. https://doi.org/10.4314/cps.v12i4.10

Espina, L., Somolinos, M., Lorán, S., García-Gonzalo, D., & Pagán, R. (2011). Chemical composition of commercial citrus fruit essential oils and evaluation of their antimicrobial activity. *Food Control*, 22, 8, pp. 1325–1332. https://doi.org/10.1016/j.foodcont.2011.02.010

Mahfoudhi, N., & Hamdi, S. (2020). Use of almond gum and gum arabic as wall materials for the encapsulation of essential oils. *Trends in Food Science & Technology*, 99, pp. 321–331. https://doi.org/10.1016/j.tifs.2020.03.014

Odukoya, J. O., Mmutlane, E. M., & Ndinteh, D. T. (2022). Ethnopharmacological study of medicinal plants used for the treatment of cardiovascular diseases and their associated risk factors in sub-Saharan Africa. *Plants*, 11, 10, pp. 1387. https://doi.org/10.3390/plants11101387

Odukoya, O. A., Ilori, O. O., & Sofidiya, M. O. (2022). Ethnobotany and chemical characterization of *Terminalia mantaly* in sub-Saharan African traditional medicine. *South African Journal of Botany*, 146, pp. 210–218. https://doi.org/10.1016/j.sajb.2021.10.024

Oluwaseun, A. C., Adebayo, A. S., & Gbadamosi, I. T. (2018). Antimicrobial activity and stability of tree exudates used in Nigerian ethnomedicine. *Journal of Herbal Medicine*, 12, pp. 45–53. https://doi.org/10.1016/j.hermed.2017.09.004

Osemeahon, S. A., & Archibong, C. S. (2022). Development and characterization of bio-plasticized films from *Albizia lebbeck* and *Terminalia mantaly* gum blends. *International Journal of Green Chemistry*, 8, 1, pp. 12–25. https://doi.org/10.4018/IJGC.2022010102

Osman, N. A., El-Gied, A. A., & Abdelgadir, A. E. (2024). Comparative phytochemical analysis and immunomodulatory activities of *Albizia lebbeck* and *Citrus limon* essential oils. *Natural Product Research*, 38, 2, pp. 294–301. https://doi.org/10.1080/14786419.2022.2104523

Osman, S., Osman, M., Paliwal, L., Ambwani, S., & Ambwani, T. K. (2024). Comparative analysis of *Albizia lebbeck* and *Lawsonia inermis*:

Phytochemical estimation and their immunomodulatory effects. *The Journal of Phytopharmacology*, 13, 6, pp. 464–469. https://doi.org/10.31254/phyto.2024.13607

Ribeiro, A. M., Estevinho, B. N., & Rocha, F. (2021). The role of natural saponins as bio-surfactants in the encapsulation of volatile compounds. *Food Hydrocolloids*, 112, pp. 106306. https://doi.org/10.1016/j.foodhyd.2020.106306

Samrot, A. V. (2019). *Methods of characterization of natural polymers*. Springer Nature. https://doi.org/10.1007/978-3-030-15632-9

Sarker, M. S., Rahman, M. M., & Hasan, M. N. (2023). Interaction of essential oils with polysaccharide matrices: Encapsulation and release kinetics. *Carbohydrate Polymers*, 302, pp. 120395. https://doi.org/10.1016/j.carbpol.2022.120395

Sasidharan, S., Chen, Y., Saravanan, D., Sundram, K. M., & Latha, L. Y. (2010). Extraction, isolation and characterization of bioactive compounds from plants' extracts. *African Journal of Traditional, Complementary and Alternative Medicines*, 7, 1, pp. 25–33. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3005381/

Sathya, B., Kumar, S. S., & Daniel, T. (2018). Extraction of essential oil from *Citrus limon* peels and its antimicrobial activity. *International Journal of Pharmaceutical Sciences and Research*, 9, 3, pp. 1225–1230. https://doi.org/10.13040/IJPSR.0975-8232.9(3).1225-30

Tchuente Tchuenmogne, M. A., Lunga, P. K., Kuiate, J. R., & Tamokou, J. D. (2017). Antimicrobial and antioxidant activities of the stem bark extract and compounds from *Terminalia mantaly* H. Perrier. *BMC Complementary and Alternative Medicine*, 17, 1, pp. 1–11. https:// doi.org/10.1186/s12906-017-1755-z

Tchuente Tchuenmogne, M., Kammalac, T., Gohlke, S., Kouipou, R., Aslan, A., Kuzu, M., Comakli, V., Demirdag, R., Ngouela, S., Tsamo, E., Sewald, N., Lenta, B., & Boyom, F. (2017). Compounds from *Terminalia mantaly* (Combretaceae) stem bark exhibit potent inhibition against some pathogenic yeasts and enzymes of metabolic significance. *Medicines*, 4, 1, pp. 6. https://doi.org/10.3390/medicines4010006

Uffia, I. D., Akachuku, C. O., Udofia, O. E., & Nsien, I. B. (2021). Meteorological influences on some melliferous plant species: Nectar nutritional composition and honey yield in mangrove vegetation zone of Akwa Ibom State, Nigeria. *Global Journal of Pure and Applied Sciences*, 27, pp. 361–366. https://doi.org/10.4314/gjpas.v27i4.2

Uffia, I. D., Udofia, O. E., Bassey, M. E., Esen, R. O., Egong, E. J., & Akan, O. D. (2025). Comparative analysis of proximate and anti-fungal activities on palm oil treated ash extracts of *Musa sapientum* and *Musa paradisiaca* peels collected from local markets in Akwa Ibom State, Southern Nigeria. *Journal of Applied Sciences and Environmental Management*, 29, 1, pp. 4207–4212.

Viuda-Martos, M., Ruiz-Navajas, Y., Fernández-López, J., & Pérez-Álvarez, J. A. (2010). Effect of storage conditions on the physicochemical and antioxidant properties of citrus essential oils. *Food Chemistry*, 121, 4, pp. 1168–1174. https://doi.org/10.1016/j.foodchem.2010.02.004

Zhang, Y., Li, S., & Wang, X. (2021). Spectroscopic and morphological studies of tannin-stabilized essential oil emulsions. *Journal of Molecular Liquids*, 325, 115165. https://doi.org/10.1016/j.molliq.2020.115165.

Declarations

Consent for Publication

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