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Research Article

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Posted Date: September 19th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7432808/v1

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Additional Declarations: No competing interests reported.

Sustainable Bioresin from Fruit Waste and Natural Gum for Circular Economy in Non-Load-Bearing Application

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Abstract

Background: Petroleum-based plastics have significant environmental impacts, including harm to marine ecosystems, terrestrial wildlife, human health, and global warming. In response, bio-based resins are emerging as viable alternatives in composite manufacturing, driven by the growing demand for sustainable and eco-friendly materials.

Methods: This research focuses on developing bio-resins derived from Acacia gum and orange peel waste for lightweight structural applications. Acacia gum and fruit peels were extracted, washed, dried, and ground into powder form, then combined in specific ratios to produce bio-resins.

Results: In line with circular economy principles, these agricultural wastes were used as alternative raw materials to create valuable synthetic resins. FTIR analysis of Acacia gum revealed O–H functional groups at an absorption band of 3300 cm^{-1}, indicating the hygroscopic nature of the lab-prepared resin. This issue was mitigated by incorporating fruit peel powder, which acted as a natural plasticizer.

Conclusions: This study demonstrates the potential of renewable agricultural wastes in bio-resin development, supporting the transition toward sustainable composite manufacturing. The findings establish a framework for utilizing eco-friendly matrices, particularly suited for non-load-bearing structural components.

Key Word: Frankincense Gum, Orange Peel, Sustainable Bioresin, Eco-Friendly Composite, Circular Economy, Non-load-bearing.

1. Introduction

Climate change is one of the most critical consequences of industrialization and the excessive use of petrochemical products, particularly plastics (Amooshahi, Pourebrahim, and Nejadkoorki 2018; Mateusz 2024; Deepak 2019; El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021). The petrochemical industry is energy-intensive and involves complex processes that convert crude oil and natural gas into a wide range of products. Petrochemicals, including derivatives of petroleum and natural gas, serve as the primary feedstocks for plastics, adhesives, and coatings, over 400 million tonnes of which are produced annually for global consumption (Amooshahi, Pourebrahim, and Nejadkoorki 2018; Mateusz 2024; Deepak 2019; El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021). Approximately 98% of the raw materials used in plastic production are derived from fossil fuels (Amooshahi, Pourebrahim, and Nejadkoorki 2018; Mateusz 2024; Deepak 2019; El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021), and many harmful plastic additives also originate from these sources. As a major emitter of methane and carbon dioxide, the petrochemical sector contributes significantly to climate change, which is associated with rising sea levels, extreme weather events, and increasing global temperatures (Amooshahi, Pourebrahim, and Nejadkoorki 2018; Mateusz 2024; Deepak 2019; El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021).

The environmental footprint of the industry is further exacerbated by non-degradable polymers, which contribute to greenhouse gas emissions, waste accumulation, and air and water pollution (El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021). These effects present significant risks to both human health and ecosystems (El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Rovira et al. 2021; Islam et al. 2024). Despite posing environmental challenges, synthetic polymers are crucial in everyday life because of their outstanding physical and chemical properties (El-Houbi, Tovar-Silos, and Thapa 2024; Jambeck and Walker-Franklin 2023; Islam et al. 2024). They are extensively used in electronics (Zhang et al. 2024; Austin et al. 2018), healthcare (Zhang et al. 2024; Neu and Hammes 2020), construction (Zhang et al. 2024; Zarei et al. 2023), and packaging industries (Zhang et al. 2024; Mallakpour et al. 2021). Their versatility and durability have led to widespread and growing use, but this has also intensified environmental concerns. Their resistance to natural degradation allows

these polymeric materials to persist in ecosystems, leading to considerable environmental pollution (Zhang et al. 2024; Fortună et al. 2022; Pinaeva and Noskov 2024).

While existing literature has addressed the sources, toxicity, and environmental fate of micro-plastics, there remains a pressing need to examine the most common classes of micro-plastics, particularly those with small sizes and high aspect ratios, which are more hazardous due to their extensive use and physical characteristics (Surana et al. 2024). Rising environmental awareness has spurred interest in developing safer and more sustainable materials. As a result, biodegradable and eco-friendly polymers are increasingly being explored as alternatives to conventional synthetic polymers. These materials are gaining attention in research and industry alike for their potential to reduce the environmental impact of composite manufacturing and related applications (Munimathan et al. 2024).

Synthetic matrix materials, such as epoxy resins commonly used in composites, present significant environmental concerns throughout their life cycle, from production to disposal (Abhiram et al. 2021; Barreira-Pinto et al. 2023). These impacts include greenhouse gas emissions, resource depletion, and considerable waste generation. Moreover, due to their environmental persistence, synthetic matrices contribute to microplastic pollution, which poses risks to ecosystems and human health (Abhiram et al. 2021; Barreira-Pinto et al. 2023). Matrix materials are generally classified into two categories: thermosets and thermoplastics. Thermosets dominate structural applications because of their superior mechanical and thermal properties. However, thermoplastics, though typically less rigid and versatile, are increasingly gaining attention as more sustainable and recyclable alternatives in response to escalating environmental and regulatory pressures (Barreira-Pinto et al. 2023).

Natural resources such as vegetable oils, lignin, rosin, and other plant-based materials are commonly used to produce bio-based epoxy resins (Barreira-Pinto et al. 2023; Temesgen and Sah 2021; Omprakash et al. 2021). The most widely used bioresins derive from plant-based monomers, including castor oil, linseed oil, and epoxidized soybean oil (Barreira-Pinto et al. 2023; Temesgen and Sah 2021; Omprakash et al. 2021). Sugars and carbohydrates, such as sorbitol and isosorbide, are also utilized in epoxy resin synthesis, offering a sustainable and abundant source of raw materials. Sugar-derived epoxies provide a favorable balance between mechanical performance and biodegradability, making them suitable for applications in adhesives, composites, and coatings (Barreira-Pinto et al. 2023; Temesgen and Sah 2021; Omprakash et al. 2021). Additional bio-based

components include biopolymers such as polylactic acid (PLA) and cellulose (Barreira-Pinto et al. 2023; Temesgen and Sah 2021; Omprakash et al. 2021). Furthermore, although still thermoplastic, renewable organic matrices have emerged as an important class of materials, gaining significance particularly in biological and medicinal applications (Barreira-Pinto et al. 2023; Temesgen and Sah 2021; Omprakash et al. 2021).

The purpose of this paper is to explore the bio-economy-driven processing of agricultural waste, specifically orange peel and acacia gum powder, for the production of intermediate, homemade bioresins suitable for use in composite manufacturing and low-load structural applications. Utilizing agricultural waste as feedstock for bio-based matrix development presents an environmentally sustainable alternative to petrochemical-derived resins, aligning with circular economy principles and contributing to solutions for the growing energy crisis. In particular, the exploration of acacia gum as a bio-resource has been limited, with most studies focusing on Acacia senegal, leaving significant gaps in the understanding of its composition, structure, polydispersity, and functional properties. This paper aims to address these gaps by evaluating the potential of underutilized agricultural resources in resin production, examining the drawbacks of petrochemical-based resins, and proposing policy directions to support the advancement of green composite technologies.

1.1. Botany of Acacia Tortilis Plant and its Gum

Acacia tortilis, commonly known as the umbrella thorn acacia, is a deciduous tree or shrub characterized by its distinctive flat-topped, umbrella-shaped crown and exceptional drought tolerance (Abdalbasit, Mohamed, and Ismail 2017; Kariuki et al. 2021). A slow-growing, small to medium-sized species belonging to the Fabaceae family, Acacia tortilis is native to parts of Africa and the Middle East (Abdalbasit, Mohamed, and Ismail 2017; Kariuki et al. 2021). It thrives particularly in arid and semi-arid environments, including dry forests and savannas, with a geographical range extending from Senegal to Somalia in Africa and across regions of the Middle East, such as Iran, Israel, and southern Arabia (Abdalbasit, Mohamed, and Ismail 2017; Kariuki et al. 2021). Globally, there are over 900 species of acacia, with the most prevalent species distributed across Africa, the Americas, Australia, and India (Bhushette and Annapure 2017). The distribution of acacia trees in Africa is illustrated in Figure 1.



Figure 1: Acacia Tree Distribution in Africa (Source: Esculapio, 2008)

Acacia gum, also referred to as Gum Arabica, is a natural resin obtained from the sap of acacia trees, mainly Vachellia seyal and Senegalia senegal, as illustrated in Figure 2. According to the U.S. Food and Drug Administration (FDA), gum Arabic is defined in Title 21 of the Code of Federal Regulations (CFR 21) as "a dried, gummy exudate from the stems and twigs of trees of various species of the genus Acacia" (Glanbia Nutritionals 2024). This gum is secreted by the tree in response to environmental stress or physical injury to the bark—such as damage caused by insects, drought, wind, or human activity—as a natural defense mechanism to prevent infection and water loss (Glanbia Nutritionals 2024; Sanchez et al. 2018; Mudgil and Mudgil 2024). Due to its water solubility and complex composition of glycoproteins and polysaccharides, acacia gum is widely used in food and industrial applications as a thickening agent, stabilizer, and emulsifier (Glanbia Nutritionals 2024; Sanchez et al. 2018; Mudgil and Mudgil 2024).



Figure 2: Acacia gum or gum Arabic (Source: Sudanese gum Arabic, 2024)

1.2. Fruit-Waste Orange Peels as Sustainable Materials for Bio-Resin

Orange peels, a common form of fruit waste, offer a promising source of sustainable materials due to their abundance, biodegradability, and rich chemical composition (Leroma 2024; Tons 2021; Michael-Igolima et al. 2023; Andrianou et al. 2023). The anatomy of the orange fruit and its chemical constituents are illustrated in Figure 3. Globally, approximately 45 to 50 million metric tons of oranges are produced each year, resulting in over 8 million tons of orange peel waste. Europe alone generates more than 600,000 tons annually, and in Italy, an estimated 1 million tons of citrus peels are discarded each year, according to a 2021 report by Leroma (Leroma 2024; Tons 2021; Michael-Igolima et al. 2023; Andrianou et al. 2023). The production of concentrated orange juice yields over 2.85 kg of peel per liter, compared to about 1.33 kg per liter for single-strength juice (Andrianou et al. 2023). Due to their high starch and bioactive compound content, orange peels are well-suited for the production of bioplastics, providing an environmentally friendly alternative to fossil fuel-based polymers (Yaradoddi et al. 2022; Othman and Fadzil 2021). Beyond bioplastics, orange peels can be utilized in food packaging, the production of valuable bio-molecules, designer lamps, textiles, and limonene, a compound used in bio-based plastics (Yaradoddi et al. 2022; Othman and Fadzil 2021).

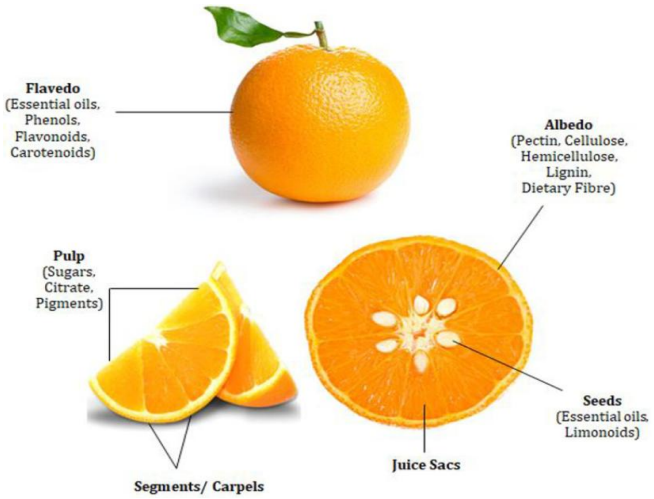


Figure 3: Orange Fruit Anatomy and Chemical Constituents (Source: Suri S. et al.,2022)

1.3. Ecological and Economic Benefits of Utilization of Fruit-Waste Materials

Improper and insufficient management of organic waste often results in its disposal in streets or landfills, negatively impacting ecosystems through leachate formation, pest infestations, and the release of greenhouse gases. The fruit production and processing industries generate substantial

quantities of by-products and waste, contributing to economic losses, methane emissions, soil degradation, and other environmental harms (Sial et al. 2024; Nirmal et al. 2023; Zema et al. 2018a). Inadequate handling disrupts ecosystems and nutrient cycles, affecting plant and animal life dependent on healthy habitats. The production, processing, and disposal of fruits and vegetables also result in the generation of environmental pollutants, including wastewater and non-biodegradable residues (Sial et al. 2024; Nirmal et al. 2023; Zema et al. 2018a).

However, the sustainable utilization of fruit waste—particularly orange peels—offers significant environmental and economic benefits. Diverting orange peel waste from landfills can reduce greenhouse gas emissions and mitigate pollution. Utilizing this waste to produce bioplastics reduces dependence on fossil fuels and helps to cut down carbon emissions. Such practices also support landfill reduction, income generation, job creation, and the development of valuable bio-based products (Sial et al. 2024; Nirmal et al. 2023; Zema et al. 2018a). Moreover, fruit waste can be converted into bioenergy, bioplastics, biofertilizers, and even new food ingredients, promoting a circular economy and reducing dependence on unsustainable practices (Sial et al. 2024; Nirmal et al. 2023; Zema et al. 2018a). Orange peels offer significant economic potential, yet improper handling or disposal can pose risks to both the environment and public health (Kumar et al. 2025; Suri, Singh, and Nema 2022; Gervasi and Mandalari 2024; Tahir et al. 2023; Mgeni et al. 2025). Converting orange peel waste into valuable products, rather than discarding it, can yield considerable economic and environmental benefits (Kumar et al. 2025; Suri, Singh, and Nema 2022; Gervasi and Mandalari 2024; Tahir et al. 2023; Mgeni et al. 2025). These include the production of essential oils, biofuels, functional food ingredients, and biodegradable materials (Kumar et al. 2025; Suri, Singh, and Nema 2022; Gervasi and Mandalari 2024; Tahir et al. 2023; Mgeni et al. 2025). Such utilization supports a circular bioeconomy by reducing waste, conserving resources, and minimizing reliance on traditional petrochemical-based production and disposal models.

Proper management of fruit waste not only enhances sustainability but also creates new economic opportunities. These include job creation in waste collection, processing, and product manufacturing, as well as the development of value-added products across industries such as food, cosmetics, and energy (Kumar et al. 2025; Suri, Singh, and Nema 2022; Gervasi and Mandalari 2024; Tahir et al. 2023; Mgeni et al. 2025). Additionally, using orange peel waste as a feedstock for bioethanol production can decrease dependence on fossil fuels and contribute to a more

sustainable energy system. Overall, the effective reuse of orange peel waste promotes sustainable resource management, advances the circular bioeconomy, and mitigates environmental harm (Kumar et al. 2025; Suri, Singh, and Nema 2022; Gervasi and Mandalari 2024; Tahir et al. 2023; Mgeni et al. 2025).

2. MATERIALS AND METHODS

2.1. Materials

Orange peels from various types of oranges were gathered from the local market to ensure consistency in sourcing. The collected peels were gently washed, dried, ground into powder, and stored at room temperature in the refrigerator until needed, as shown in Figure 4a. Similarly, acacia gum was obtained from the local market in Ethiopia, derived from two Acacia species varieties originating from Tigray and Sudan, as shown in Figure 4b. Additionally, for preparing homemade bioplastic or bio-resin materials, the following ingredients were used: 20 ml of distilled water, 5 gm of glycerol, 25 gm of cornstarch, and 15 ml of white vinegar.



Figure 4: Materials used for home-made bioresins preparations: a) Orange peel, b) Acacia gum powder

2.2. Methods

2.2.1. Collection and Preparation of Orange Peel-Acacia Gum Powder Bioresin

Orange peels and acacia gum were collected, cleaned, and dried before being ground into a fine powder. In the laboratory, this powder was combined to form a bio-matrix. To prepare the bioresin, the orange peel and acacia gum powders were gradually added to boiling water along with 20 ml distilled water, 5 g glycerol, 25 g cornstarch, and 10 ml white vinegar. The powders were mixed at an 85:15 ratio of acacia gum to orange peel, respectively. The bio-matrix was prepared using a

powder-to-liquid (water) ratio of 1:15 at a temperature of 40 ± 3°C for 2 hours, with additional water added as needed. After stirring the mixture continuously for 3 minutes, it was left to stand for 15 minutes. Finally, the mixture was allowed to cool for 30 minutes to promote gelation and the formation of sticky bioresins (Ravichandran et al. 2023; Aykut, Eren, and Getu 2021; Temesgen 2021).

2.2.2. Orange Peel and Acacia Gum Powder Density Analysis via Pycnometer

The density of orange peel and acacia gum powders was measured using a Gas Pycnometer (Anton Paar – Ultrapyc 5000) (Aziz, Joshua, and Christina 2023; Temesgen 2021). Samples were prepared according to standardized procedures and placed in the pycnometer chamber. A predetermined volume of gas was added, followed by measurement of the resulting pressure. The volume of each sample was calculated based on the pressure change observed when the gas expanded into a calibrated volume expansion chamber. Finally, the density of the orange peel and acacia gum powders was determined by dividing the sample mass by its measured volume.

2.2.3. Chemical Composition Analysis of Orange Peel and Acacia Gum Powder via FTIR Test

Spectroscopic analysis of the Enset fiber was conducted using a Vertex 70 Platinum Fourier Transform Infrared (FTIR) Spectrometer with Attenuated Total Reflectance (ATR) mode. The samples were prepared following standard protocols. The instrument's detector emitted a broad spectrum of infrared light onto the orange peel and acacia gum powder samples. The resulting time-dependent signal, known as an interferogram, was recorded to capture the interference patterns of the samples. The FTIR then transformed the interferogram into a frequency spectrum, providing detailed information on the infrared absorption frequencies characteristic of the orange peel and acacia gum powders.

2.2.4. Moisture Absorption Tester of Orange Peel and Acacia Gum Powder

The water content of the orange peel and acacia gum powders was determined using a Mechatronic press machine. Initially, the powders were weighed to obtain their initial mass. The samples were then placed in an open container with the chamber lids securely closed. The oven was operated at 105 ± 5°C for approximately 20 minutes. After heating, the containers were opened, and the samples were weighed again. Subsequent weighings were performed every 5 minutes until the weight difference between consecutive measurements was less than or equal to 0.05%. The final recorded weight was considered the dry mass of the sample (Alhayat 2012; Temesgen 2021).

Moisture content and moisture regain of the orange peel–acacia gum bioresin sheets (3 cm × 3 cm × 2 mm) were calculated using the formulas provided below.

$$Water\ absorption\ (\%) = [(Wf-Wi)/Wi] *100$$

Where Wi and Wf are the initial and final weights of Enset fiber samples

2.2.5. Thermogravimetric Analysis (TGA) of Orange Peel and Acacia Gum Powder

Thermogravimetric analysis (TGA/DSC) was performed to measure the mass changes of orange peel and acacia gum powder samples during heating or cooling under controlled conditions, capturing processes such as decomposition, oxidation, and dehydration (Temesgen, Eren, and Aykut 2021; Temesgen 2021). The analysis was conducted using a Mettler Toledo TGA/DSC-2 Star System, with a heating rate of 5 K/min over a temperature range of 25 to 600°C. The samples were maintained at 600°C for a duration of 4 hours. Throughout the test, nitrogen gas was flowed at 20 ml/min to create an inert atmosphere. Samples were prepared according to standard protocols, placed in the furnace, and heated at a controlled rate. The microbalance continuously recorded the mass changes as the samples underwent thermal processes that resulted in mass loss (e.g., decomposition, dehydration) or mass gain (e.g., oxidation).

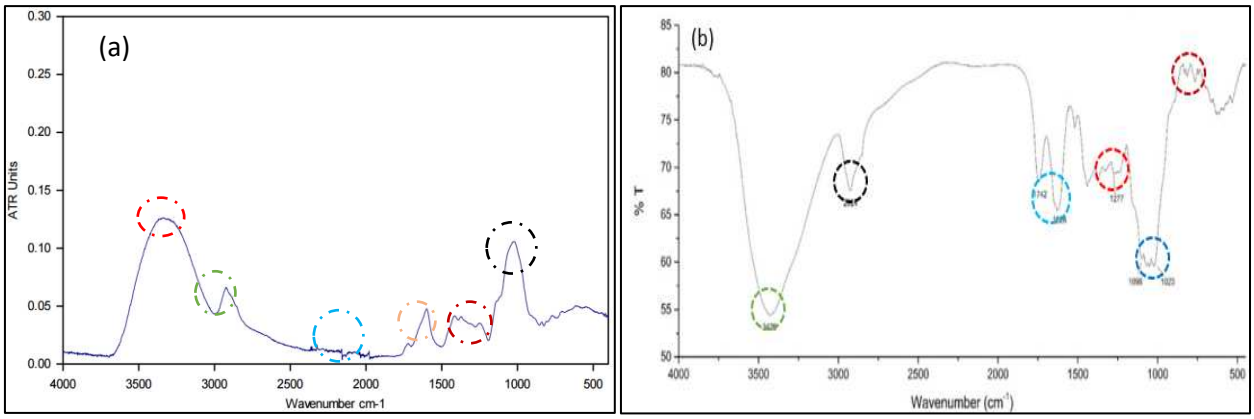
3 RESULTS AND DISCUSSION

3.1. Chemical composition of Orange peel, Acacia Tortilis Gum Powder and Bioresin

Figure 5 presents the FTIR spectra of orange peel and acacia gum powder, highlighting their functional groups and comparing spectral differences during bioresin development. In the acacia gum powder (Figure 5a), identified functional groups include C-C bending, CO_2, C-O stretching, C-H wagging and in-plane bending, C=C stretching, C-H stretching, C=O asymmetric stretching, and O-H stretching vibrations. A broad absorption band between 3200 and 3413 cm^{-1} indicates hydrogen-bonded O-H groups, with a characteristic band between 3400 and 3500 cm^{-1} potentially masking amino groups. Other notable bands include C=C stretching, amide NH bending, NO_2 groups from aliphatic and aromatic galactoproteins, and amino acids around 1635 cm^{-1}. The 1260 cm^{-1} band corresponds to alkane CH_3 bending, alcohol C-O stretching, ether C-O-C stretching, carboxylic acid CO stretching, amine C-N stretching, and sugar backbone alkane bending and alcohol stretching. C-O stretching appears at 1060 cm^{-1}, C-H wagging at 1270 cm^{-1}, aliphatic C-H stretching at 2930 cm^{-1}, and asymmetric carbonyl (C=O) stretching at 2383 cm^{-1}. These

observations align with previous studies [46–48]. Figure 5b shows the FTIR spectrum of orange peels, which are primarily composed of organic functional groups typical of lignocellulosic materials. The band at 1740 cm^{-1} corresponds to carbonyl groups in esters, while the broad band at 3429 cm^{-1} is attributed to O-H stretching. The absorption peaks at 1100 cm^{-1} and 1020 cm^{-1} indicate C-O stretching associated with cellulose and hemicellulose. Additional functional groups identified include lactones at 1460 cm^{-1}, carbonyl groups at 1290 cm^{-1}, and aromatic C–H groups at 840 cm^{-1}, consistent with earlier research findings (Puccini et al. 2016; Deshmukh et al. 2022)..

As shown in Figure 5c, the FTIR spectrum of the bioresin formed from acacia and orange peel powders exhibited notable peak shifts compared to the spectra of pure acacia gum and orange peel powders. Specifically, the C-O stretching shifted to 1050 cm^{-1}, C-H wagging vibration moved to 1260 cm^{-1}, C=C stretching shifted to 1630 cm^{-1}, asymmetric C=O appeared at 2380 cm^{-1}, aliphatic C-H stretching shifted to 2920 cm^{-1}, and O-H stretching vibrations adjusted to 3870 cm^{-1}. Moreover, new functional groups not typically present in either acacia or orange peel were detected. The interaction between acacia gum and orange peel during mixing likely induced these spectral changes, suggesting the formation of new chemical bonds or altered molecular structures, which may confer unique properties to the bioresin. These FTIR frequency shifts are consistent with previous studies on acacia gum-based composites (Udo, Odoemelam, and Eddy 2017; Alhayat 2012; Temesgen 2021; Yakup et al. 2021; Ravichandran et al. 2023).



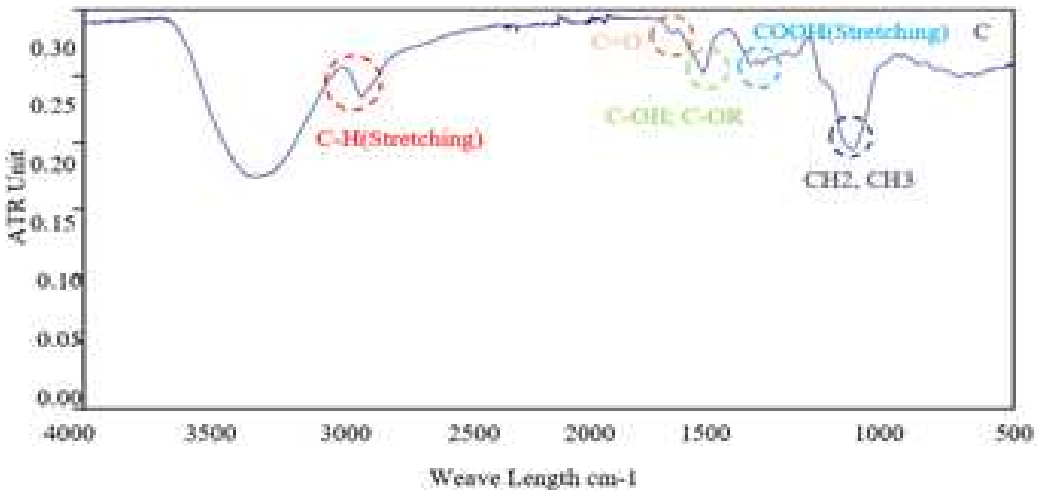


Figure 5. FTIR Analysis: a) Acacia Gum Powder, b) Orange Peel (Puccini et al. 2016; Yakup et al. 2021), and c) Acacia-Orange Peel Powder Bioresin (film).

3.2. Density Analysis of Orange Peel, Acacia Gum Powder and Bioresin

The densities of orange peel and acacia gum powders were measured using a pycnometer experiment, with results summarized in Table 1. The average densities for orange peel powder, acacia gum powder, and the orange peel–acacia gum bioresin were found to be 0.67, 1.38, and 1.29 g/cm³, respectively. Understanding the density of the individual powders is essential to evaluating their properties and suitability for various bioplastic applications. The mechanical performance of the bioresins is strongly influenced by density, which affects their behavior in composites, coatings, and other products. Generally, higher resin density correlates with improved compressive, tensile, and bending strength because a denser matrix provides a more robust foundation for reinforcing fibers, enabling the composite to withstand greater loads before failure. While increased density typically enhances strength, rigidity, and stiffness, it can also lead to increased weight and potentially reduced flexibility. The incorporation of agro-waste orange peel powder into acacia gum produces bioresins with a lower density (approximately 1.3 g/cm³), highlighting promising potential for the development of natural gum-based bioplastics through innovative extraction methods.

Table 1: Density Analysis of Orange Peel and Acacia Gum Powder Using a Pycnometer

Sample (Powder)	**cell size**	**Weight (gm)**	**Volume (ml)**	**Density (g/cm3)**	**RSD (%)**	**Avg. Density (g/ml)**	**uncertainty (%)**	**Depending on**
Acacia gum	Micro	2.47	1.65	1.502	0.0183	~1.5	0.2	Size and drying methods
Acacia gum(Cured)	-	-	-	1.384	-	~1.38	-	-
Orange peel	Micro	2.47	1.65	0.673		~0.67	0.2	Size and drying methods
Acacia-Orange peel-bio resin	Micro	2.47	1.65	1.295	0.178	~1.29	0.63	Size and drying methods

3.3. Moisture Absorption Properties of Orange Peel -Acacia Gum Powder Bioresin

The moisture content of acacia gum and orange peel powders shows significant variation. In this study, orange peel moisture content was found to be relatively high, typically ranging from 68% to 81%. However, drying methods can significantly reduce this moisture; for example, orange peel powder dried using the mechatronic press machine showed moisture contents between 15% and 30%, while sun-dried or tray-dried orange peel can reach moisture levels as low as 8–9% [53]. Similarly, the moisture content of the orange peel–acacia gum blended powder bioresin also varied, generally falling between 15% and 30%, as summarized in Table 2 and illustrated in Figure 6. The variability in moisture content across lab-made bioresin samples is mainly attributed to the hydrophilic nature of both orange peel and acacia gum. Moisture absorption in these bioresins is influenced primarily by the presence of OH groups, the resin's free volume, impurities, structural defects, and preparation methods. The relatively high moisture uptake limits the application of these bioresins to low-bearing load scenarios. Nonetheless, by modifying the formulation and processing of the lab-produced bioresin, its moisture absorption can potentially be reduced.

Table 2: Moisture Absorption Properties of Orange Peel and Acacia Gum Powder

Samples	Initial Weight (gm)	Dry Weight (gm)	Moisture Content(%)	Remark
Samples-1	17.65	14.88	15.69	It was noted that the uptake of moisture by these laboratory-produced bio-resins from agro waste and gum materials is mainly affected by hydroxyl groups, the resin's available void space, impurities, structural defects within the resin, and the methods used to prepare the bio-resin.
Samples-2	19.83	15.12	23.75	
Samples-3	18.34	14.56	20.61	
Samples-4	18.07	12.55	30.55	
Samples-5	19.45	15.02	22.78	
Average	**18.7**	**14.43**	**22.72**	

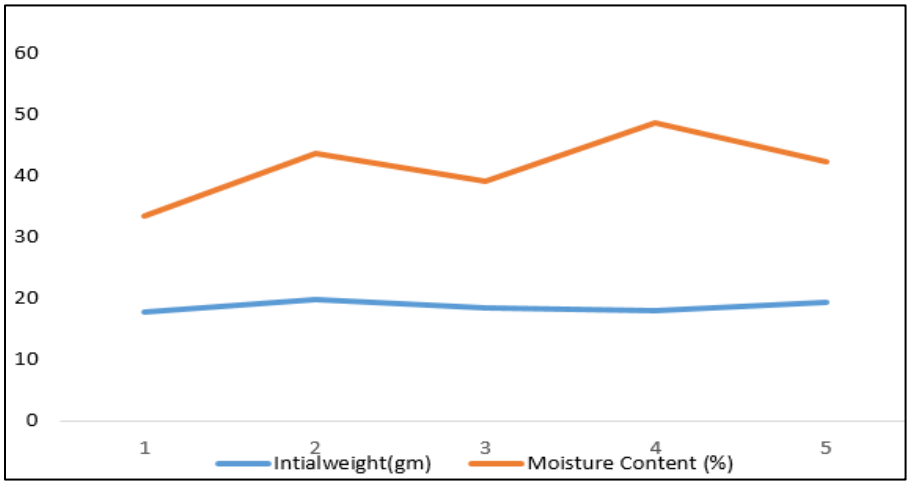


Figure 6: Moisture Absorption Properties of Orange Peel-Acacia Gum Powder Bioresin

3.4. DSC-Thermogravimetric Analysis (TGA) of Orange Peel -Acacia Gum Powder Bioresin

Thermogravimetric (TG) analysis of acacia gum powder, illustrated in Figure 7a, revealed two key stages of thermal degradation. The first stage occurs between 26 and 186°C, showing a 9.2% weight loss attributed to the removal of water or hydroxyl (OH) groups. The second stage, from 186 to 598°C, involves a significant weight loss exceeding 88 %, due to the decomposition of polysaccharides and glycoproteins and the release of gaseous compounds such as CH_4, consistent with previous reports [54]. Similarly, the TGA of orange peel powder shows moisture evaporation between 40 and 140°C with more than 9% weight loss, followed by pyrolysis and breakdown of solid residues between 140 and 600°C, accounting for over 88% weight loss (Chilla and Suranani 2023). For the lab-made bioresin film (2 mm thickness), initial weight loss between 23 and 154°C

(~2%) corresponds to water evaporation and volatile organic compounds such as oils and pigments (Pathak, Mandavgane, and Kulkarni 2017; Yaradoddi et al. 2022). The primary degradation phase occurs between 152°C and 599°C, resulting in an 88.21% weight loss, primarily due to the thermal decomposition of polysaccharide and glycoprotein components, as shown in Figure 7b. Overall, the bioresin exhibits high thermal stability, indicated by its TGA profile, making it suitable for applications requiring heat resistance and durability. The higher decomposition temperatures and char yields suggest the bioresin can endure elevated temperatures before significant degradation occurs, highlighting its potential for demanding uses.

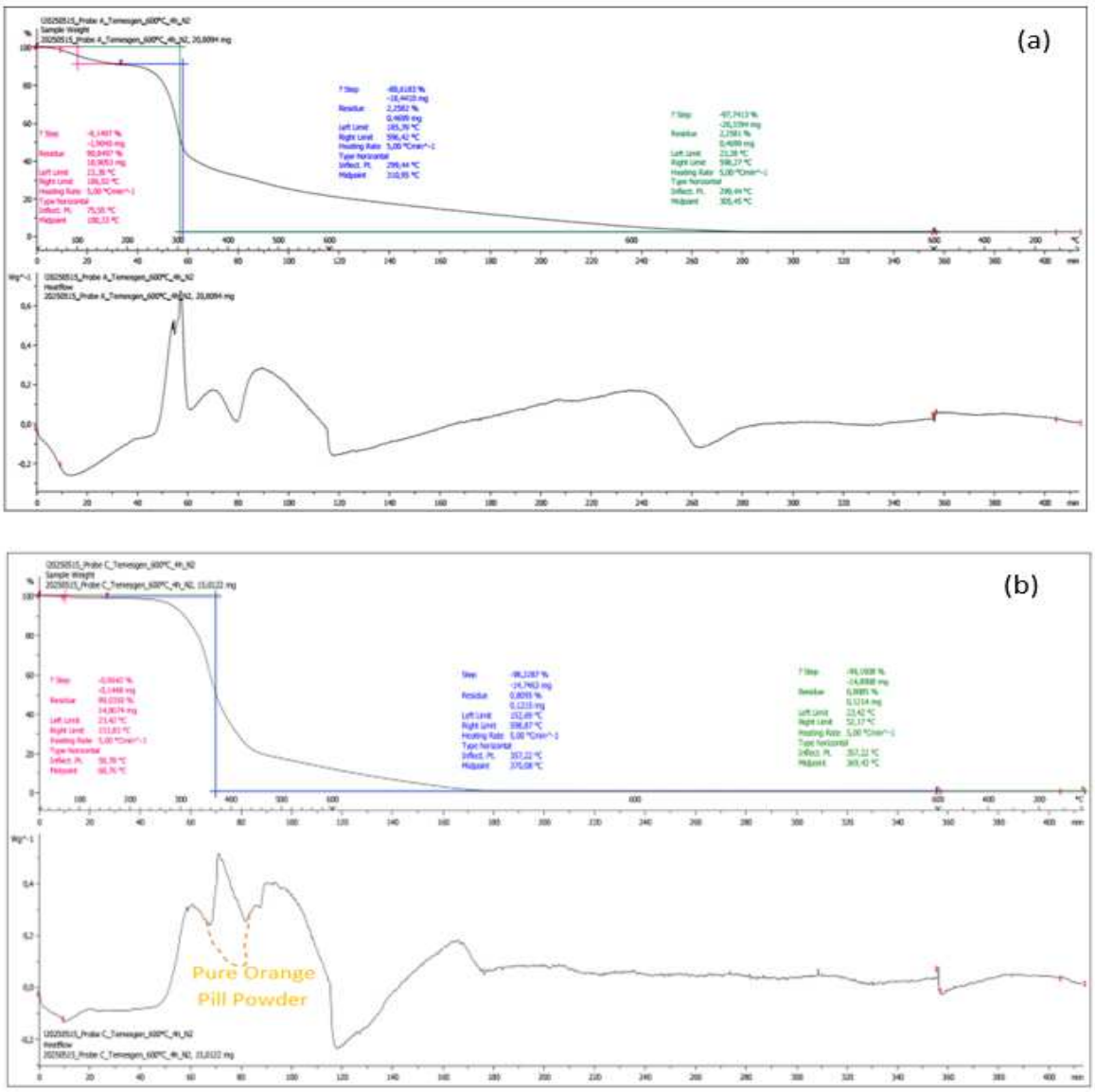


Figure 7. DSC-Thermogravimetric Analysis of Powders: a) TGA of Acacia gum powder, and B) TGA of Orange Peel-Acacia Gum Powder Bioresin (~2 mm thickness film).

3.5. Ecological Benefit of Utilization of Fruit Waste Peel as Sustainable Bioresin Materials

Orange peel waste, often discarded, is rich in valuable nutrients and bioactive compounds, making it ideal for various applications. It can be repurposed into functional foods, cosmetics, health supplements, bioplastics, and biofuels contributing to a circular and sustainable economy. Globally, around 32 million tons of orange peel waste are generated annually, accounting for more than half of the 60 million tons of total orange production. A significant portion of this waste is improperly managed, leading to environmental issues (Michael-Igolima et al. 2023). Bioresins made from renewable resources like orange peels offer several ecological advantages over fossil fuel-derived petrochemical resins. These include a lower carbon footprint, reduced toxicity during production, and decreased reliance on nonrenewable resources. Environmentally, using orange peel as animal feed can reduce organic waste buildup, cut greenhouse gas emissions from fruit decomposition, and lower the demand for resource-heavy grain-based feeds. Additionally, orange peel waste can be utilized in pollutant biosorption, biofuel production, and biodegradable film development. Repurposing this waste not only supports environmental goals but also generates economic value by converting waste into useful and profitable products.

3.6. Industrial Applications of Bio-Resins from Agricultural Wastes

Orange peel waste is produced in large quantities and contains high levels of bioactive compounds and organic matter. This makes it highly valuable for numerous industrial applications. Orange peel can be utilized in packaging materials, baked goods, and as a source of biologically active compounds for pharmaceuticals and cosmetics. It also contains a high amount of pectin, which functions as a natural emulsifying, stabilizing, gelling, and thickening agent. Within a biorefinery context, orange peel can be converted into animal feed, biofuels (such as ethanol), and various biochemicals. Additionally, it contains natural pigments, flavors, and essential oils used in the food, fragrance, and cosmetic industries. Other applications include biodegradable polymer production, wastewater treatment, and soil remediation (De la Torre et al. 2019; Tahir et al. 2023). Similarly, acacia gum has broad industrial relevance due to its unique properties, such as emulsifying, stabilizing, thickening, and microencapsulation. It is extensively used in the food and beverage sector as a stabilizer and emulsifier and is also applied in pharmaceuticals, cosmetics, textiles, adhesives, and composite materials (Mudgil and Mudgil 2024; Hassabo et al. 2023). Bio-resins derived from orange peel waste and acacia gum present a sustainable alternative to conventional

petrochemical-based resins, offering biodegradable, renewable, and environmentally friendly properties. These characteristics enable their application in a wide range of industrial sectors. One of the primary uses of these bio-resins is in biodegradable packaging. Their natural composition and film-forming capability allow them to serve as alternatives to single-use plastics in food packaging, wrappers, and disposable containers. These materials decompose naturally, reducing plastic pollution and landfill waste. The fabrication of lightweight composites using bio-resins enables their use in industries such as furniture, automotive, and interior design. These materials are appealing for such uses due to their strong mechanical properties and lightweight nature. These features make them appropriate for architectural and building material applications where sustainability and energy efficiency are important.

In agriculture, bio-resins may serve as biodegradable seed coatings or controlled-release systems for fertilizers. Their ability to degrade in soil without leaving toxic residues contributes to improved soil health and environmentally friendly farming practices. Additionally, the biocompatibility and presence of bioactive compounds from orange peel and acacia gum allow for potential applications in biomedical and cosmetic products. These resins could be used in the formulation of wound dressings, cosmetic gels, and transdermal patches. Moreover, bio-resins have shown effectiveness in environmental applications, particularly in wastewater treatment. Their functional groups enable them to adsorb heavy metals and organic pollutants, making them suitable for eco-friendly remediation strategies. The adhesive and thickening properties of acacia gum, combined with the natural polymers found in orange peels, make the bio-resin suitable as a binder in the paper, textile, and woodworking industries. It offers a safer and renewable alternative to synthetic glues and binding agents. Generally, bio-resins made from orange peel waste and acacia gum hold significant potential for diverse industrial applications, contributing to the advancement of green technologies and circular economy practices. Even though this study's lab-made bioresin demonstrates promise, particularly in biodegradable and eco-friendly composites, it still requires significant improvement in moisture resistance. Nonetheless, this research offers a foundation for advancing bioresin development and outlines potential directions for future investigations. As illustrated in Figure 8, the fabricated bioresin was applied in lightweight structural materials, coating films, and acoustic insulation, showcasing its practical potential.



Figure 8. Applications of Bioresins from Fruit Waste and Natural Gum in Composites

CONCLUSION

This article investigates the potential and challenges of using discarded fruit peels and acacia gum in the development of bioresins and bioplastics. Converting agricultural waste like orange peels and natural gums into lightweight bioresins supports the circular economy by offering sustainable, biodegradable, and eco-friendly alternatives to traditional petrochemical-based materials. Utilizing such agro-waste not only reduces environmental burden but also creates economic value by transforming waste into profitable resources. The approach leverages abundant, renewable materials to produce bioplastics with a lower environmental footprint. The TGA results revealed that the lab-developed bioresin exhibits high thermal stability, as indicated by favorable TGA values, including higher decomposition temperatures and char yields. This suggests the material can endure elevated temperatures before undergoing significant weight loss, making it suitable for applications requiring heat resistance. Additionally, blending orange peel powder with acacia gum results in a relatively low-density bioresin (approximately 1.3 g/cm^3), highlighting its potential for future development of natural gum-based bioplastics through an innovative extraction process. However, the current formulation still faces challenges, particularly regarding moisture absorption. Continued research is needed to enhance this property. Future studies will focus on evaluating the mechanical performance, biodegradability, and industrial applicability of these bioresins across various sectors.

Declaration of Competing Interests: Alhayat G. Temesgen, J. Kaufmann, H. Cebulla declare that they have no competing financial interests or personal relationships that could be perceived to influence the work reported in this paper.

Consent to Publish Declaration: Not applicable

Data Availability Statements: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding Declaration: The manuscript has not received any financial support

Ethics Declaration: Not applicable

Author Contributions: The authors, Alhayat G. Temesgen, J. Kaufmann, and H. Cebulla, participated in the conception of the study, presented the results, and prepared the manuscript.

Acknowledgment: The authors are grateful to the Alexander von Humboldt Foundation for providing financial assistance for this research through the Georg Forster Research Fellowship for Postdocs. A heartfelt thank you and acknowledgement to Prof. Dr. Klaus Stöwe, Ilka Günther, Prof. Dr. Recep Eren, and all laboratory technicians who assisted us in testing our samples at Professur Chemische Technologie, TU Chemnitz, and Bursa Uludag University.

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