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RESEARCH

Development and characterization of screen-printed Prosopis Africana Char thick film for electronic applications

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Abstract

The need for biomass materials that are both cost-effective and highly effective has increased rapidly in a number of areas, including flexible electronics. The aim of this research is to investigate the properties of a screen-printed thick film of Prosopis Africana charcoal (PAC) on an alumina substrate. The biochar was obtained from the Prosopis Africana strain by subjecting it to controlled pyrolysis at 500 °C for 3 h. The rheological properties of the PAC pastes were formulated at a powder-to-organic binder ratio of 40:60 wt%. An average 11.8-µm-thick layer was produced using the screen-printing process. X-ray diffraction analysis showed the presence of characteristic peaks at approximately 25.0° and 44.7°. These peaks correspond to the (002) and (004) reflections of the graphite structure. Thermogravimetric analysis revealed that the PAC film exhibited thermal stability in an airflow environment up to 650 °C. The surface morphology of the PAC thick film exhibits a reticulated appearance with patchy features, while elemental composition analysis (EDX) confirmed the high carbon content of the PAC thick film. The real and imaginary dielectric constants of the PAC thick film at 10 GHz were found to be 9.8 and 1.8, respectively. It can be concluded that the PAC biochar has promising electronic properties, making it a suitable candidate as an environmentally friendly material for a range of electronic applications.

Keywords Prosopis Africana biomass · Biochar · Thick film · Screen printing · Alumina substrate

Introduction

The increasing demand for advanced materials, driven by the imperative of efficiency and cost-effectiveness in diverse sectors such as flexible electronics [1, 2], carbon-based materials [3], wireless communication systems, and radar technologies, reflects the critical role these materials play in our modern technology-dependent world. In response to this demand, biomass materials have come to the fore as promising candidates, characterized by their high carbon content and excellent electrical properties [4]. These properties have brought biomass materials to the forefront of materials development for electronic applications and attracted significant attention in both research and industry[5, 6].

Beyond their potential to advance existing technologies, the unique properties of biomass materials also provide a path to meet the urgent need for more sustainable, cost-effective, and high-performance antenna materials [7], in line with the growing importance of environmental sustainability in today's society. These remarkable properties of biomass materials shed light on their applications in electronics, wireless communications, and radar technology and underscore their central role in driving innovation and addressing the evolving challenges of our interconnected world [6, 8].

Prosopis Africana biomass, originating from the Prosopis Africana tree commonly found in sub-Saharan Africa, represents a valuable and versatile natural resource. This biomass is renowned for its numerous applications, ranging from traditional uses in food, medicine, and timber to contemporary uses in sustainable energy production,

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environmental conservation, and advanced materials [9, 10]. The tree's pods are a source of nutritious fodder and have medicinal properties, making them crucial for livestock and human consumption, especially in arid regions [11]. Furthermore, Prosopis Africana biomass is increasingly harnessed for bioenergy production, offering a renewable and eco-friendly source of fuel and electricity [12]. Its adaptability to various climates and ability to restore degraded landscapes also highlight its role in combating desertification and land reclamation. Moreover, Pyrolysis serves as the initial stage in the thermochemical transformation of biomass resources. The intricate pyrolysis mechanisms governing biomass materials are contingent upon numerous variables, including their composition, size, heating rate, and related factors [13].

Biochar, a carbon-rich material produced through pyrolysis of biomass, has emerged as a compelling candidate for various electronic applications [14]. Its unique properties, such as high carbon content and excellent electrical conductivity, make it an attractive choice for a range of electronic components. Biochar can be used in particular in supercapacitors and energy storage devices [15, 16]. The large surface area and porosity of biochar enable efficient charge storage and result in increased energy storage capacity [17].

Additionally, its abundant carbon structure can be functionalized or modified to improve its electrochemical performance, making it a versatile material for developing energy storage solutions that are not only cost-effective but also environmentally sustainable. In addition, the compatibility of biochar with flexible electronics should be emphasized. Its mechanical flexibility combined with its electrical conductivity makes biochar a viable material for flexible, wearable electronics [18]. Biochar-based conductive inks can be used to print circuits on various substrates, enabling the creation of lightweight, flexible electronic devices. These developments have the potential to revolutionize the design and manufacturing of electronic components, reducing environmental impact and costs while opening up new opportunities for electronics in diverse areas, including healthcare, aerospace, and consumer technology [19, 20]. The introduction of biochar in electronic applications represents a step towards more sustainable and environmentally friendly technology solutions.

In recent years, printed electronics have become increasingly popular, attracting interest from both academia and industry. This increased excitement is due to the realization that the use of printing technologies has the potential to transform production processes and enable large-scale manufacturing of electronic devices at low cost [21]. In the field of printed electronics, the selection of substrates and inks plays a critical role in determining device performance [22]. In particular, the printing materials have a significant influence and influencing factors such as printability, wettability of the ink, flexibility, mechanical strength, and the environmental friendliness of the end product [23]. The use of substrates that possess these essential properties not only ensures high performance of printed electronics but is also in line with environmentally conscious practices [24]. Additionally, optimizing material properties is critical to producing electronic devices that offer world-class performance and environmental friendliness. To achieve this, effective and environmentally conscious fillers must be used, a key focus in this area. Therefore, the integration of biomass materials into electronic applications has attracted great interest. Researchers are therefore faced with the challenge of developing environmentally friendly materials that can serve as viable alternatives in the manufacture of electronic devices and thus contribute to the overall goal of promoting sustainability in the electronics industry [25].

The use of thick-film processing in electronic applications is a widely used method due to its key advantages such as simplicity, speed, and cost-effectiveness [26]. This technique offers the advantage of incremental layer deposition, enables tailoring to specific application requirements, and contributes to the miniaturization of electronic devices. About three decades ago, thick-film technology was introduced as a key approach to manufacturing hybrid circuits, which includes not only thick-film circuitry but also a variety of elements such as antennas, sensors, semiconductor devices, integrated circuits (ICs), and other discrete components [27]. A key feature that sets thick-film circuits apart is their method of application, particularly screen printing, one of the earliest methods of reproducing graphic art. Thick-film hybrid circuits are valued for their compact design, robustness, and cost-effectiveness and find applications in various fields including televisions, calculators, telecommunication equipment, automotive electronics, and missile guidance systems [26]. A relatively recent development of this technology can be observed in the field of thick-film sensors, with most research publications appearing in the last decade.

This research investigates a simple and environmentally friendly screen-printing approach to produce a robust PAC thick film on an alumina substrate. This PAC thick film can serve as a viable alternative to traditional metals in microwave antenna applications and include functions such as guiding antenna patches and electrodes for sensor-related applications. Various characterization techniques were used to analyze the properties of the prepared samples. It is important to note that, to the best of our knowledge, screen-printed PAC thick films are not documented in the existing literature, highlighting the groundbreaking nature of this study in this particular area.

Materials and method

Chemical reagents

The following substances were used in this study: linseed stand oil (CAS no. the primary component (67746–08-1) Daler-Rowney), m-xylene (CAS no. 108–38-3, Sigma-Aldrich, USA; Reagent Plus grade, 99% assay), and α-terpineol (CAS no. 10482–56-1, Sigma-Aldrich, USA; natural, ≥ 96% assay) [28]. No changes were made to the chemicals after purchase.

Experimental method

Collection of plant materials and identification

Plant materials collected were identified and authenticated by a plant taxonomist, from the Department of Plant Biology, Bayero University Kano, Nigeria. The plant samples used in this research were obtained from the Prosopis Africana tree, a plant species commonly found in the northern region of Nigeria. The samples were collected from various farms in the Jabo District region of Kafin Hausa Local Government Area in Jigawa State, Nigeria.

Pyrolysis of Prosopis Africana for char production

The collected Prosopis Africana sample was fragmented into smaller pieces to obtain a precursor for char production. The collected samples were subjected to controlled pyrolysis at 500 °C for 3 h. The sample was sieved to a size of 20 µm and used for thick-film fabrication. This method was developed from previous researches [12, 29, 30]. Figure 1 shows the stepwise pyrolysis of Prosopis Africana.

Prosopis Africana Char (PAC) thick-film fabrication

After obtaining the PAC powder, linseed oil, terpineol, and m-xylene were prepared as organic binders. The binder was mixed with 85 wt% established linseed oil and 12.5 wt% m-xylene using a stirring magnet at 250 rpm for 3 h, followed by the addition of 2.5 wt% α-terpineol and continued stirring for 2 h while maintaining both temperatures at 40 °C. The binder weight ratio was determined based on previously published work [26, 28, 31]. When producing the paste, the weight ratio of PAC to binder was set to 40% by weight of powder and 60% by weight of binder. The mixture was stirred with a magnetic stirrer at 300 rpm at 40 °C for 24 h to obtain a homogeneous paste. Applying pressure with a squeegee through a patterned stencil or mask is the process of screen printing used for depicting thick films. The binder was then removed by heat treatment. The overall process of depositing PAC thick films on alumina substrate using screen-printing method is shown in Fig. 2. To effectively remove the binders, the prepared thick films were annealed in an oven at 350 °C for 1 h after screen printing. This procedure was adopted from previous studies [32, 33].

Thick-film PAC characterization

The thick films produced were characterized using various techniques. Thermogravimetric and differential thermal analyses were performed in a 50 ml airstream with a heating rate of 10 °C/min and at temperatures ranging from room temperature to 800 °C. A rheometer (Anton-Paar Rheoplus MCR3301) was used to measure the viscosity and rheological properties of the paste. The crystallinity of the prepared thick films was evaluated by X-ray diffraction using Cu-K radiation at a wavelength of 1.540 Å using a (Phillips X-Part diffractometer) for 2θ values between 5° and 70°. A field emission scanning electron microscope (FEI Nova NanoSEM 230) was used to analyze the morphology of the

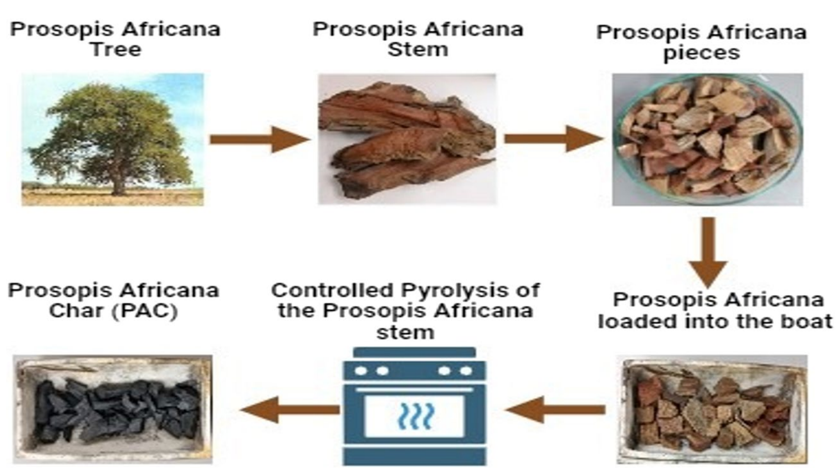

Fig. 1 Step-by-step pyrolysis of Prosopis Africana Char (PAC) synthesis

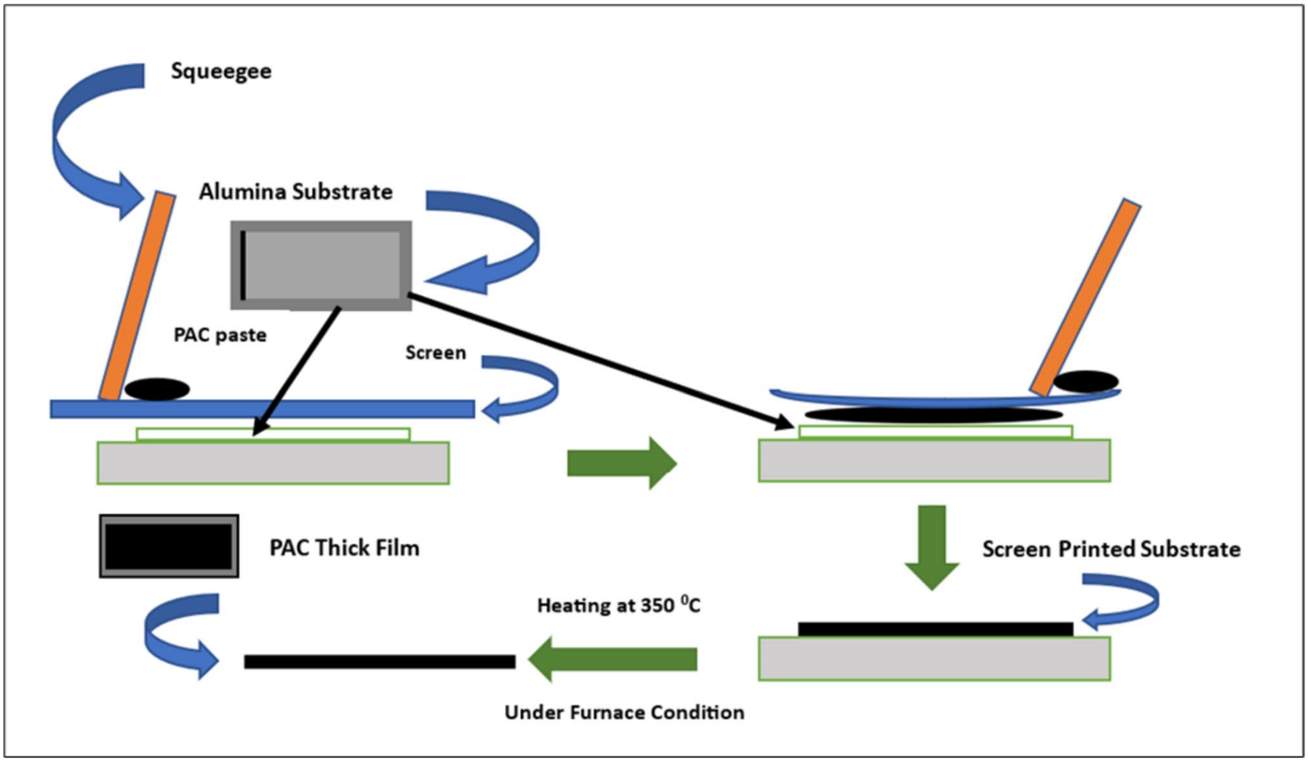

Fig. 2 The screen-printing process onto the alumina substrate PAC thick film

surface. Furthermore, the dielectric properties of the PAC mounted on the X-band sample holder were evaluated using a network vector analyzer system (Keysight, PNA 5227A) using the overlay technique.

Results and discussion

Thermal stability analysis

Figure 3 shows the TGA of a PAC paste with airflow, which consists of three decomposition stages: In the first stage, the decomposition of volatiles, which included m-xylene and alpha-terpineol, occurs at 420 °C, corresponding to a weight loss of 85%. In the second stage, with a broad weak peak around 480 °C, this is due to the 40 wt% of the PAC material; in the last stage the decomposition of non-volatile substances, i.e., linseed oil. The decomposition was stable at temperatures around 650 °C, with a weight loss of 0.7%, and ended to ash. This breaks the carbon bond through the air, which is why it turns into ash at 0.7% weight loss. The airflow causes more degradation, which uses more energy and heat. This is similar to the values reported for the TGA of multi-walled carbon nanotubes (MWCNT) [34]. Thermogravimetric analysis showed a steady weight loss accompanied by the absence of exothermic or endothermic reactions. PAC retained its structural integrity up to 650 °C when exposed to an air atmosphere, after which significant weight loss occurred above 700 °C [35]. Based on the DTA study conducted under air atmosphere, it was confirmed that PAC has increased stability in this specific environment, which led to the use of air atmosphere for the thick-film firing process. The TG curves indicated complete weight loss up to 650 °C, while DTA analysis revealed a peak at 420 °C, indicating the high purity of the PAC. The differential thermal analysis (DTA) plot showed a clear three-part heat loss pattern with a rapid rate of change between 420 and 480 °C, followed by a melting peak at 650–800 °C caused by an endothermic process characterized by a peak. Furthermore, the PAC samples were observed to exhibit similar decomposition patterns in the TGA curves, characterized by pronounced exothermic peaks (TGA) and endothermic peaks (DTA), which are inherently associated with the thermal degradation of organics. Furthermore, the similarity in the decomposition profiles of the PAC samples is evident as shown in the thermogravimetric analysis (TGA) curves, which are characterized by pronounced exothermic and endothermic peaks associated with the thermal degradation of organic components.

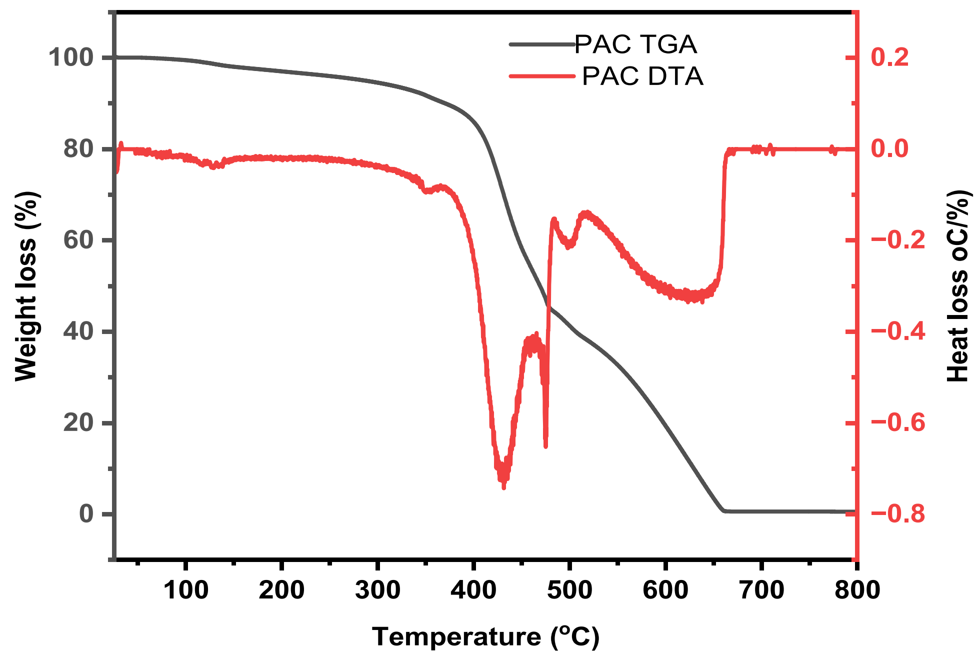

Fig. 3 The TGA/DTA curve of PAC paste in airflow atmosphere

The crystallinity analysis

As shown in Fig. 4, XRD diffraction patterns were obtained by scanning the 2θ values from 5° to 70°. XRD analysis is commonly used to identify and quantify the different crystalline phases and interlayer distances in PAC. The XRD patterns revealed the structure and crystallinity of the activated carbon and showed two intense peaks. The broad lines observed near the 2θ values of 25° and 44° correspond to crystallites of carbons, particularly the (002) and (011) planes for the PAC material, which is consistent with findings from related studies [34, 36]. In the graphitic structure, the refractions of these two peaks indicate an amorphous structure. The reference code 98–008-5678 for PAC matches the compound designation carbon.

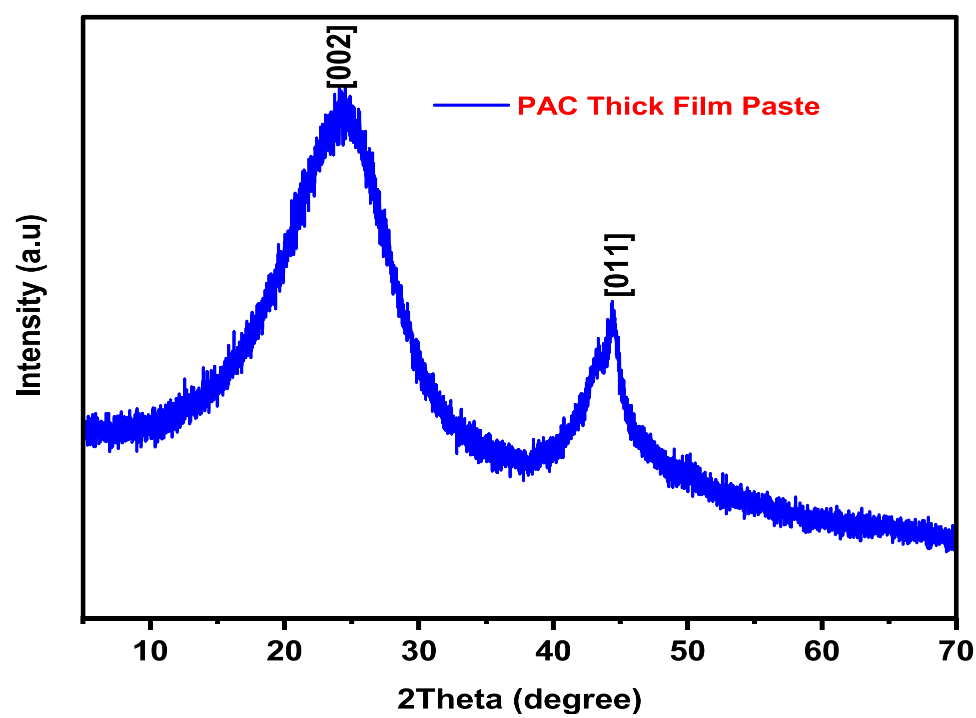

Fig. 4 The screen-printed thick PAC film with a pattern

Analysis of rheology properties of thick-film paste

Figure 5 shows the viscosity of PAC paste plotted against a fixed shear rate of 100/s. The ratios PAC were divided into four parts: 30, 35, 40, and 45 wt%. It was found that samples with a powder content of 40% by weight had good viscosity and printability on substrates. The measurement was carried out over a period of times to observe viscosity changes over time. The relationship between viscosity and shear rate was studied, while the shear rate increased from two points: (0.1–100)/s to (100–0.1)/s and the viscosity decreased. The study also examined the thixotropic behavior of the paste, an important parameter in the production of thick-film pastes, indicating good viscosity and high-quality rheology. The graph shows a decrease in viscosity with increasing shear rate, and shear-thinning behavior or pseudoplasticity is observed, which is beneficial for screen printing. This shear-thinning behavior ensured that the paste could be printed through a sieve mesh [26]. Rheological properties play an important role in thick paste films, especially when high shear stress is induced, as in the case of squeegee printing. The viscosity of the paste must be low so that it can pass through the screen during printing and return to a high viscosity after printing [37]. The viscosity of PAC pastes gradually decreased over the course of the measurement, starting with a higher viscosity, then slowly increasing to 30/s, and then rapidly declining towards 100/s. Then, to select the best among the four samples, PAC and organic binder powders were prepared. Based on this rheological behavior, pastes with a proportion of 40% by weight are recommended for thick-film production due to their favorable rheological behavior. A low viscosity aids seamless flow through the mesh during printing, allowing for the creation of a well-deposited thick film on the substrate. Following the printing process, the viscosity reverts to a higher level, serving as a protective measure against paste bleeding or smearing.

Surface morphology analysis

Field emission scanning electron microscopy (FESEM) is a powerful imaging technique for visualizing and analyzing fine details of surface structures at high magnification and resolution. As shown in Fig. 6a, nanoparticles became clearly visible on the surface after heating to 350 °C, removing the organic binder. Nanoparticles of the purpose material PAC were observed on the surfaces of the materials. Multiple recording points and different magnifications were used. Upon observation, the nanostructure of the samples showed flake-like shapes without noticeable changes, which may be due to nanographite reaching a stable state, making the diffusion process unlikely [37]. The nanoparticles were clearly visible, as was the dispersion of the PAC powders. Consequently, due to their small size, nanoparticles have a very large surface area, which leads to increased surface energy; this high energy contributes to particle agglomeration as particles aim to minimize their surface energy [32].

Moreover, Fig. 6b shows the cross-section of the PAC thick film on the substrate. The PAC thick film exhibited good uniformity, displaying minimal voids and a highly even surface, indicating a well-dispersed distribution of nanoparticles. Furthermore, the thick film displayed outstanding bonding with the alumina substrate, affirming its strong adherence. Remarkably, the thickness of the PAC thick film

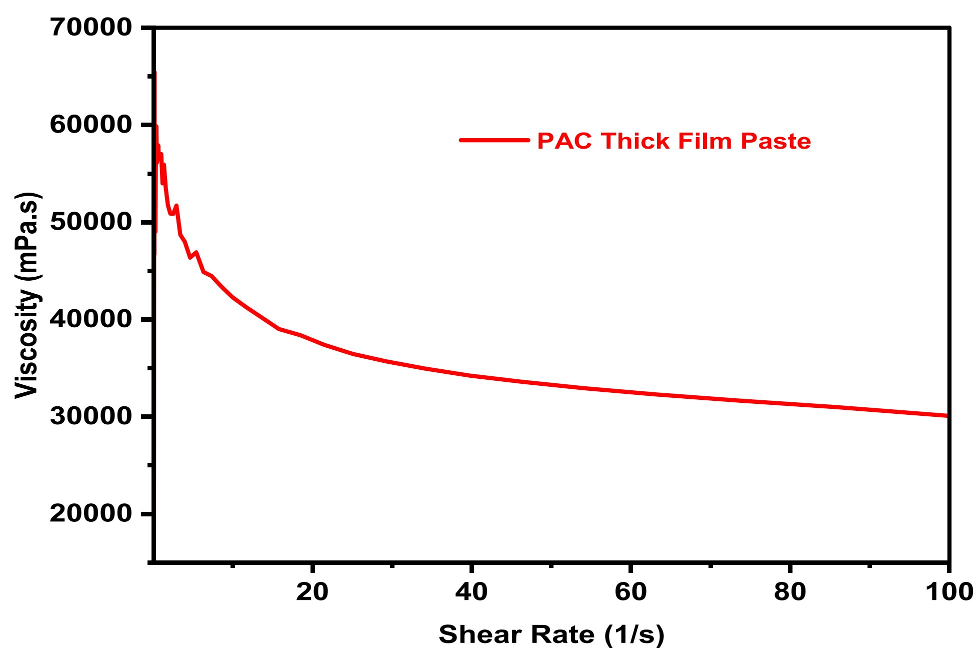

Fig. 5 The PAC flow behavior of shear rate vs viscosity

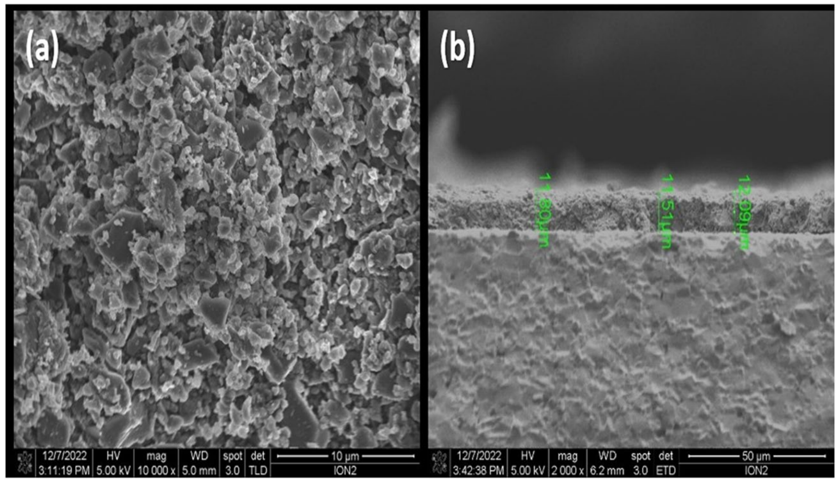

Fig. 6 **a** Surface morphology of thick PAC film. **b** Cross-sectional view of a PAC film deposited on the substrate

measures at 11.25 µm, which is the thickness is less than 20 µm. This shows that linseed oil is a good binder for the production of film-thick pastes, which enables the firing temperature to be reduced and eliminates the need for the use of glass frit as a binder [38].

Similarly, in Fig. 7, energy-dispersive X-ray (EDX) spectroscopy was also used to analyze the elemental composition of the samples. EDX is a valuable tool for determining the elemental composition of the new material PAC, where a higher C:O ratio means increased electrical conductivity [26]. Figure 7 and the inset table show the results of the EDX analysis, which gave the weight percentages of the components present in the samples. According to the analysis, both elements from the alumina substrate and those with high carbon content were found in the sample. Furthermore, a separate study showed that EDX analysis of graphite only showed the presence of two elements, namely carbon and oxygen [26] and carbon and silicon dioxide [39].

Dielectric properties

The dielectric constant and loss tangent are two terms used to describe the thick dielectric properties of the film. These properties can be measured using a vector network analyzer

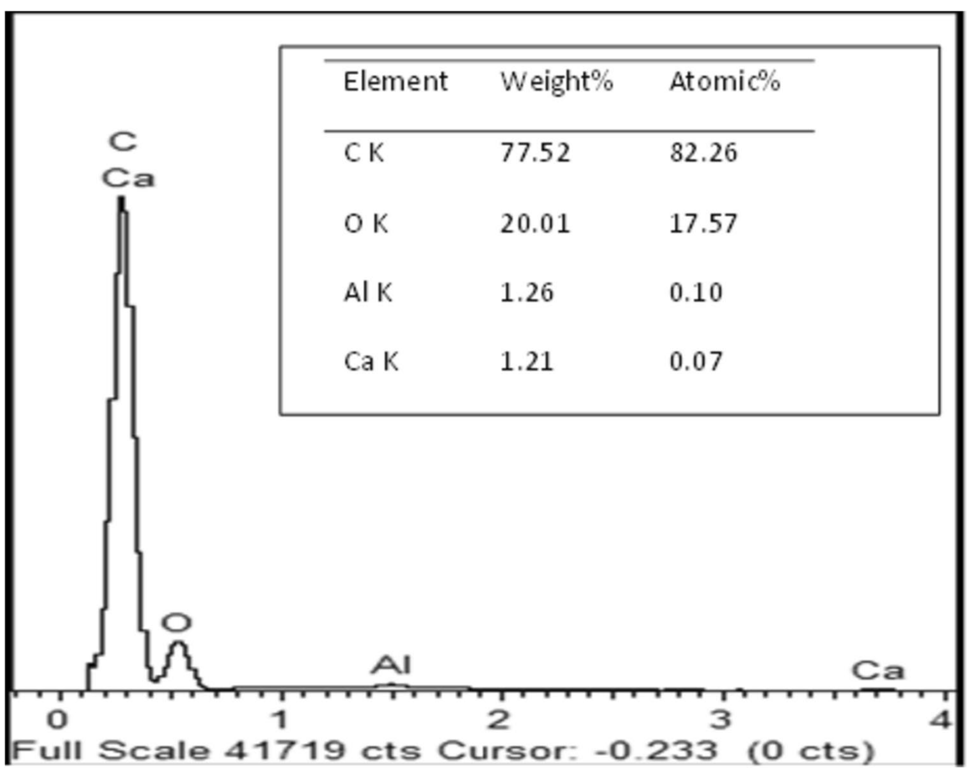

Fig. 7 The EDX of the PAC thick film

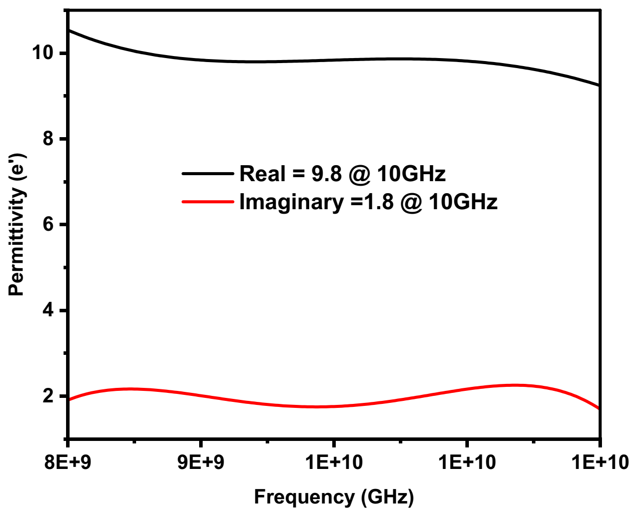

Fig. 8 The dielectric constant of Prosopis Africana Char (PAC)

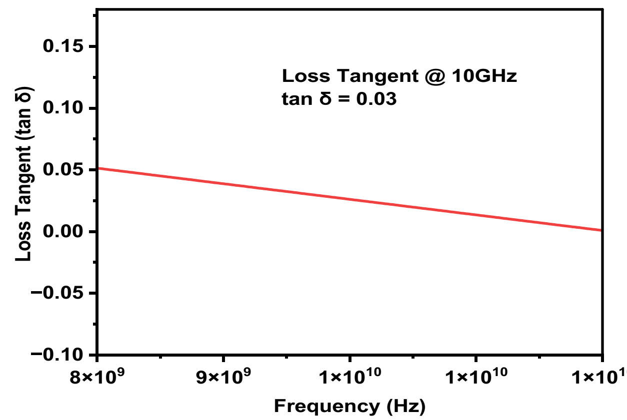

Fig. 9 The loss tangent of Prosopis Africana Char (PAC)

(VNA) in an X-band sample holder [40]. Both permittivity and loss factor values are important in antenna design and simulation because they help predict how antenna parameters might change when using a substrate with specific permittivity and loss factor values [32]. Figure 8 shows the imaginary and real permittivity of the PAC film in the frequency range from 8 to 12 GHz. Only the actual values were taken into account. At 10 GHz, the PAC thick film showed a higher permittivity ($\varepsilon'=9.8$), and this value remained constant across all measured frequencies, with a significant decrease from the initial permittivity.

These results are consistent with those of other researchers [41, 42]. The methods used to create materials in their core have an influence on the permittivity value [43, 44]. The obtained values of imaginary (ε'') and real (ε') permittivity of the PAC film were 1.8 and 9.8 at 10 GHz, respectively. The fact that the real value is higher than the imaginary value confirms that the PAC thick film has lossy material and finite conductivity. Figure 9 shows the loss factor values, also called loss factor (Df), for the PAC thick film at 10 GHz, which is 0.03. These values are in the range of the FR4 substrate, usually in the range of 0.03 to 0.04 [45]. The thick film falls into the category of low-loss materials and is therefore well suited for low-loss manufacturing, such as antennas. Furthermore, the graph shows that the loss factor values remained relatively constant at frequencies above 12 GHz and exhibited minimal fluctuations, which is consistent with the results of [41, 44].

Conclusion

In conclusion, this study successfully developed and characterized a screen-printed thick film of Prosopis Africana Char on an alumina substrate for antenna applications. The fabricated thick PAC film exhibited excellent thermal stability, desirable surface morphology, and promising microwave permittivity. Further research is warranted to explore its performance in practice with different systems and to optimize the fabrication process for enhanced performance. The results obtained for the X-ray diffraction assessment revealed distinctive peaks at around 25.0° and 44.7°. Field emission scanning electron microscopy (FESEM) showed a nonuniform surface morphology of the PAC. EDX spectroscopy investigation of the PAC detected elements both from the alumina substrate and those with a notably high carbon content of the PAC. Moreover, the PAC thick film exhibited a high permittivity (ε'), confirming its lossy behavior, and the dielectric properties were ascertained within X-band region. The computed values for the real and imaginary permittivity of the PAC thick film, at a frequency of 10 GHz, were found to be 9.8 and 1.8, respectively. Therefore, based on the result obtained, it can be concluded that the Prosopis Africana Char (PAC) can be used as a potential material for both antenna and sensor application.

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Author contribution Suleiman Babani led the project and conducted experiments, while Mohd Nizar Hamidon provided guidance. Other authors contributed to various aspects of the project, including experimental design, data analysis, manuscript preparation, and review. The research findings and manuscript were collectively reviewed and approved by all authors.

Data availability All data generated or analyzed during this study are included in this article.

Declarations

Conflict of interest The authors declare no competing interests.

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