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Development and Characterization of Turmeric Oil-Loaded Cassava Starch/Chitosan Composite Film Coatings for Sustainable Food Packaging

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Abstract

Conventional plastic packaging is widely used because of its durability, low cost, and effective barrier properties; however, its non-biodegradability raises substantial environmental and potential food-safety concerns that may undermine sustainable food systems and food-security efforts. This study aimed to develop and characterize a biodegradable composite film containing cassava starch, chitosan, carboxymethyl cellulose, glycerol, and turmeric oil as a coating for sustainable food-packaging paper. Uncoated paper (UP) and coated paper (CP) were characterized using scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), tensile-strength testing, antimicrobial-sensitivity testing, and contact-angle measurements. SEM revealed a porous surface with loosely packed fibers in UP, whereas CP exhibited a uniform, continuous layer, confirming effective coating formation. FTIR spectra of CP showed characteristic O–H (3200–3400 cm^{-1}) and C–H (2800–2900 cm^{-1}) stretching vibrations associated with cellulose and hemicellulose. Increased loading enhanced O–H, C–H, C=O, C–O, and

aromatic C=C signals, indicating improvements in hydrophobicity, mechanical integrity, barrier performance, and turmeric-oil-derived antioxidant activity. TGA demonstrated minimal initial mass loss, followed by a major degradation stage between 250 and 450 °C attributable to cellulose and hemicellulose decomposition; mass loss above 450 °C was negligible. CP1 exhibited greater tensile strength (44.28 MPa) than UP (37.86 MPa), while the coating solution displayed shear-thinning behavior and a pH of 5.6. UP produced no inhibition zone, whereas CP5 showed the largest inhibition zone (6.0 mm) and enhanced hydrophobicity, with water and oil contact angles of 95.4° and 101°, respectively. These findings demonstrate that the composite coating improves the mechanical, thermal, barrier, and antimicrobial properties of paper, supporting its potential application as a biodegradable material for sustainable food packaging.

Keywords: Biodegradable Composite Film; Cassava Starch; Chitosan; Sustainable Food Packaging; Turmeric Oil

INTRODUCTION

Due to growing consumer knowledge and environmental concerns, there is a greater demand for environmentally friendly and sustainable packaging solutions globally today (Hussani *et al.,* 2024). Developing packaging materials that are not only environmentally friendly but also capable of improving the safety and shelf life of packaged food products as an alternative to conventional plastics and non-biodegradable packaging materials is important (Dong *et al.,* 2023). The creation of green-composite materials, in which biodegradable polymers are mixed with natural additives to generate films with improved qualities is one of such promising direction in sustainable food packaging (Sid *et al.,* 2021; Raji *et al.,* 2025). These materials offer a variety of functional benefits, including enhanced barrier qualities and antibacterial activity, in addition to reducing the negative environmental effects of conventional plastics (Pinto *et al.,* 2021). Biopolymer as a constituent material enhanced the tensile strength and barrier properties in packaging that indicated their capacity to survive various loading and environmental conditions (Grzebieniarz *et al.,* 2023). According to Food and Agricultural Organisation (FAO), emphasis on ensuring food security and reducing food losses, effective barrier materials are essential for protecting food quality, safety and shelf life. However, the widespread use of petrochemical and metal-based packaging materials for household and street foods raises environmental and potential health

concerns, particularly during their production and disposal, highlighting the need for sustainable and environmentally friendly packaging alternatives (Rui *et al.,* 2023).

The incorporation of natural antimicrobial agents into green-composites presents an exciting opportunity to address the dual challenges of sustainability and food safety (Asgher *et al.,* 2020). Turmeric *(Curcuma longa)* is a widely recognized natural source of antimicrobial compounds, with curcumin being the primary bioactive constituent (Zhang *et al.,* 2023; Zhao *et al.,* 2023). Additionally, turmeric oil exhibits antioxidant and anti-inflammatory properties, further enhancing its potential as a valuable additive in food packaging (Tanpichai *et al.,* 2022).

Bio-based materials are widely used in different studies. Raji *et al.* (2025) developed turmeric oil-intercalated composite coating for food-paper packaging where the coating improved the paper's functional properties; tensile strength of 20.55 to 38.90 MPa, contact angle of 89.42 to 106° and antimicrobial activity against food microbes. Liu *et al.* (2023) showed that polyvinyl alcohol/quaternary chitosan composite films possessed enhanced hydrophobicity and mechanical properties (Young's modulus 344.99 MPa, tensile strength 39.12 MPa, elongation 507.09%). In another study conducted by Tanpichai *et al.* (2022) found that chitosan multilayer-coated paper achieved hydrophobicity (94.7 ± 2.8° water contact angle) with significant improvements in tensile strength and elongation at break. Earlier, Wang *et al.* (2021) reported that chitosan/montmorillonite-coated paper improved tearing resistance by 5.2% and 6.6% in the machine and cross directions, respectively; however, the study was limited to grease resistance evaluation. The study aims to develop and characterize turmeric oil-loaded cassava starch/ chitosan composite film coatings for sustainable food packaging with objective in investigating the effects of the formulation on uncoated paper (UP). Characterizations such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), thermal gravimetric analysis (TGA), tensile strength test on both uncoated paper (UP) and coated paper (CP) were carried out. The wettability and antimicrobial activity were equally conducted on both uncoated and coated food packaging paper for performance testing.

MATERIALS AND METHOD

Materials

Polysaccharide materials like cassava starch and carboxymethyl cellulose (CMC) were obtained from Muda Lawal market, Bauchi, Nigeria, were utilized in this study. Bauchi state,

located in northeastern Nigeria is an important agricultural region where the development of sustainable food packaging materials can contribute to food preservation, reducing post-harvest losses and nutritious food. Such innovations are relevant not only to the region but also to national efforts towards achieving sustainable food systems and food security in Nigeria. Chitosan was purchased from GHK, Mainland, China. Turmeric oil was supplied by Like Sun GmbH, Planck, Germany. Glycerol was purchased from Green Herbology, Puchong, Selangor, Malaysia. The brown kraft paper (substrate) was obtained from central market, Bauchi, Nigeria. *Bacillus cereus*, *Pseudomonas aeruginosa*, *Aspergillus niger* and *Penicillum expansum* were microbial strains for estimating the antimicrobial sensitivity activity of the paper samples which were obtained from the microbiological culture bank in the faculty of science, Gombe State University Nigeria. The selection of these bacterial and fungal strains was based on their potential application in enhancing the shelf life of food packaging, all materials were utilized.

Methods

The development of bio-composite film coating solution utilized sol-gel method, followed by the application of a thin-film coating solution to unbleached kraft paper (substrate). Finally, the coated papers underwent a post-treatment drying process using a desiccator at controlled temperature.

Preparation of bio-composite thin film coating solution

Figure 1 illustrate the development of a biopolymer coating film solution preparation that was used in coating UP. The gelatinous process was carried out with reference to the work conducted by Martins de Costa *et al.* (2020). The preparation of this biopolymer involves dissolving 2.5 g of cassava starch and 3.75 g of chitosan powder in 50 mL of distilled water at 75°C with stirring at 500 rpm for 20 minutes. Then, 5 mL of glycerol was added dropwise to the solution for plasticization. Next, 0.1 g of CMC powder was dispersed in 100mL of distilled water to form a viscous homogeneous solution on stirring; 2.5 mL of the viscous solution prepared was combined with the plasticize solution and continuously stirred (250 rpm) at 40°C for a period of 20 minutes to form a homogeneous biopolymer film solution. Finally, 1.25 mL of turmeric oil was added to the solution and stirred continuously for 20 minutes.

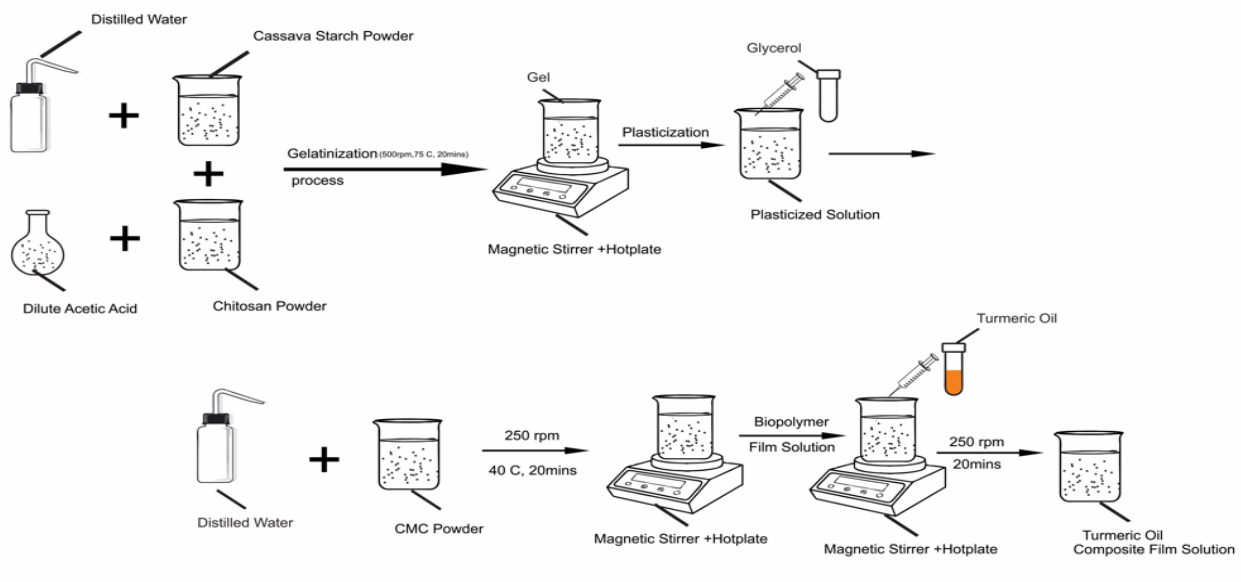

Figure 1: Turmeric Oil Composite Film Solution Preparation

Coating Process of Uncoated Paper (UP)

The substrate (uncoated paper: UP) with a size of 100 mm x 50 mm was coated with the formulated bio-polymer thin film coating solution using a cylindrical material (syringe) as a coating roller. Another syringe was used to dispense 1.5 mL of the solution onto the wire side of the paper. The coated paper was then rolled up and dried at 50°C for 30 minutes as indicated in Figure 2. This coating process was repeated on five different samples with varying loadings, yielding five differently coated paper samples: CP1, CP2, CP3, CP4 and CP5 as depicted in Figure 2.

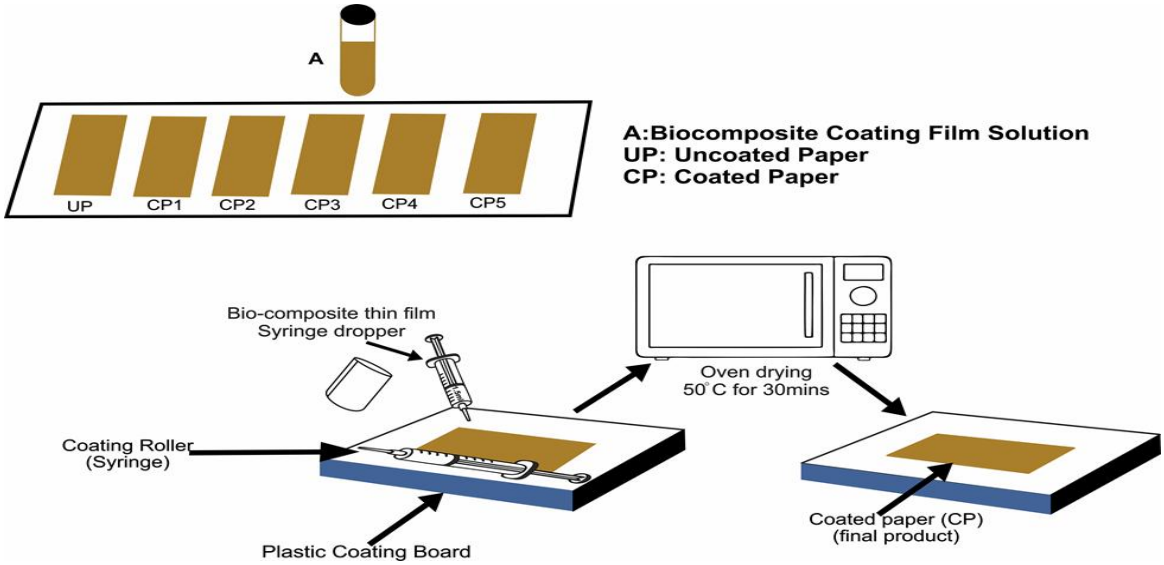

Figure 2: Coating Process on Uncoated Paper (UP) using Biopolymer Thin-film Solution and Coating Loadings (CP1-5)

Characterization

Physicochemical Characterization of bio-composite solution

pH Test

The pH of the sample was determined using a PHS-25 digital pH meter, prior to the pH test, the pH meter was placed on a stable surface and plugged into the power source. The meter was calibrated using standard buffer solutions of known pH values of 4.0 and 7.0. Fifty (50) mL portion of the bio-composite coating film solution, the bio-composite coating film solution was then poured into a clean beaker and the electrode immersed in the coating film solution; the pH reading was then taken and recorded by following a triplicate determination.

Viscosity Test

The viscosity of the coating film solution was measured using an NDJ-5S digital rotational viscometer. The instrument was placed on a stable, vibration-free surface and leveled by adjusting the tripod stand for a bubble in the spirit level was centered. The spindle number 4 was chosen and carefully attached to the viscometer shaft. An approximately 200 mL of the sample solution was prepared and poured into a clean 250 mL beaker. The sample was allowed to equilibrate before vertical immersion of spindle into the bio-composite coating film solution. The viscometer was then powered on with results recorded at a varying shear rate of 6, 12, 30 and 60 rpm, respectively at constant time of 30 seconds.

Physicochemical Characterization of Uncoated and Coated Paper

Tensile strength

The tensile strength test was carried out using tensile properties tester (Tensile Strength Test Machine TM 2101-T7) according to ASTM D638 with maximum force of 10 kN. The samples dimensions were 50 x 10 x 0.32 (mm) length, width and thickness respectively. A cross – head speed of 2 mm / min was used. The test specimens were held in the grips (upper and lower jaw) of the testing machine and tightened evenly and firmly to prevent any slippage as the test commenced. The resistance and elongation of the specimens were detected and recorded by load cell until a failure or rupture occurred. From the tensile test, tensile parameters (tensile strength (breaking point), elongation at break and tensile modulus) were determined and recorded.

Surface Morphological Analysis

SEM analysis (Hitachi TM3000) examined the uncoated and coated paper surface. Samples (1.0 cm) were gold/platinum-coated (5 min) before imaging. To prevent charging, the samples were coated with gold using an argon plasma metallizer (sputter coater K575X, Edwards Limited, UK). SEM imaging was conducted at an acceleration voltage of 15 kV and at different magnifications of 500x, 1000x and 2000x.

FTIR Analysis

Fourier transform infrared spectroscopy (FTIR) analysis was carried out using Perkin Elmer instrument with model (Cary 630 ZnSe) to identify and compare the functional groups present on the uncoated paper (UP) and coated paper (CP) samples. The adsorption spectra were recorded over a wavenumber range of 650-4000 cm^{-1} with a 16 cm^{-1} resolution in transmittance mode.

TGA Analysis

Thermogravimetric analysis (TGA) was carried out using a thermal analysis Instrument manufactured by Perkin Elmer to investigate the thermal properties of UP and CP samples. More so, a step-wise isothermal method was employed for the analysis, the samples were heated from 30°C to 950°C under airflow at a heating rate of 10°C/min. The data generated were then used for plotting of the TGA curve.

Contact Angle Analysis

The surface wettability of the uncoated paper (UP) and coated paper (CP) was determined using Sessile-drop method. Samples were ensured clean, a 5 μL droplet of distilled water and glycerol was gently dispensed onto the surface using a syringe and a high-resolution image of the droplet profile were captured immediately using a digital camera positioned at the horizontal level of the sample. The captured images were analyzed using ImageJ software with the Contact Angle Plugin. The baseline was set along the solid-liquid interface while the tangent angles on right and left were calculated automatically by the software (Lamour et al., 2010).

Thickness Measurement

The thicknesses of the uncoated paper (UP) and coated paper (CP) were measured using a digital micrometre (Model: Mitutoyo 293-831). Prior to measurement, the micrometre was calibrated to zero by gently closing the spindle for the anvils to made contact and pressing the zero-setting bottom. The uncoated and coated paper samples were placed between the anvil; spindle and the thimble were rotated for the spindle to approached the sample surface. The thickness was read directly from the digital display in millimetres on the contact made by the ratchet stop. Measurements were taken at three random points on each sample and the mean value was recorded as the representative thickness.

Antimicrobial Activity Evaluation

A modified agar diffusion method reported by Arezoo *et al.* (2020) and Alebooyeh *et al.* (2012) was employed to evaluate the antimicrobial sensitivity of UP and CP1, CP3 and CP5. The existing micro-organisms were sub cultured using the appropriate nutrients (media) namely nutrient agar for bacteria and potato dextrose agar for fungi. The composite- coated paper discs were prepared and placed on Mueller- Hinton agar inoculated with 0.2 mL of bacterial suspensions (approximately 105 to 106 CFU/mL). The plates were incubated at 37°C for 24 hours for bacterial strain and 72 hours for fungal strain. In addition, 6 mm diameter film disks were exposed to UV light for 30 minutes before being placed on the agar plates. Following incubation, the presence of zones of inhibition around the test discs of the UP and CP samples were recorded.

RESULTS AND DISCUSSION

Viscosity a rheological analysis plays a vital role in processing, stability, and performance characteristics particularly in applications such as coatings and film forming solutions. It was observed as depicted in Figure 3 that the non-linear pattern obtained in the plot of viscosity versus shear rate indicates that the rheological behaviour of the solution A5 formulated having a pH value of 5.6 followed non-Newtonian shear thinning, the results are consistent with those reported by (Lewandowski & Szulc, 2022). Viscosity values were observed and recorded with a decreasing value of 8333.32, 5459.34, 3424.21, 1985.83 milli-pascal seconds (mPa,s) with increase in shear rate of 6, 12, 30 and 60 rotation per minute (rpm) constant time of 30 Seconds.

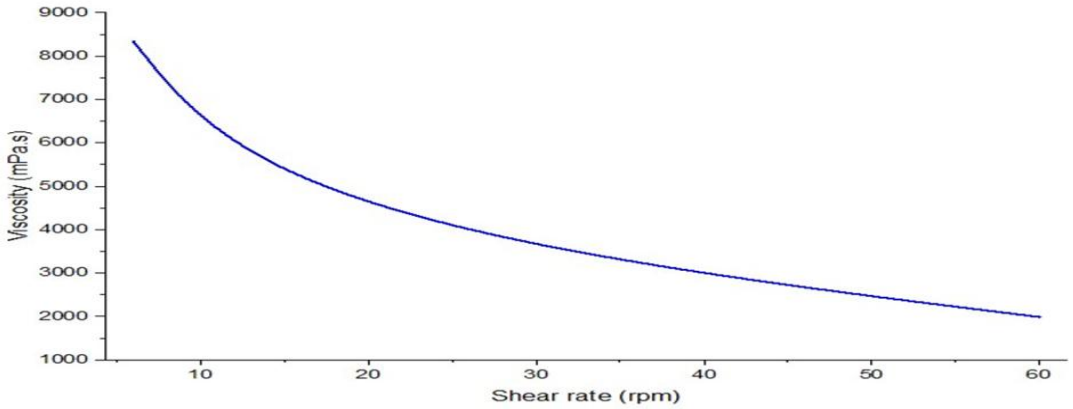

Figure 3: Rheological Behaviour of the Coating Film Solution

SEM analysis of uncoated paper (UP) as depicted in Plate I(a) reveals a smooth, porous surface with a random arrangement of fibres. The surface exhibits moderate roughness, with valleys and ridges distributed apart. It was observed that pores and voids were scattered throughout the surface. The fibre bundles are loosely packed, leaving noticeable gaps between them. Unlike the UP the analysis of the CP as depicted in Plate I(b) reveals a relatively uniform and thick coating layer. Similar trends were observed in comparison with previous studies reported by (Ruggero *et al.*, 2020; Raji *et al.*, 2025).

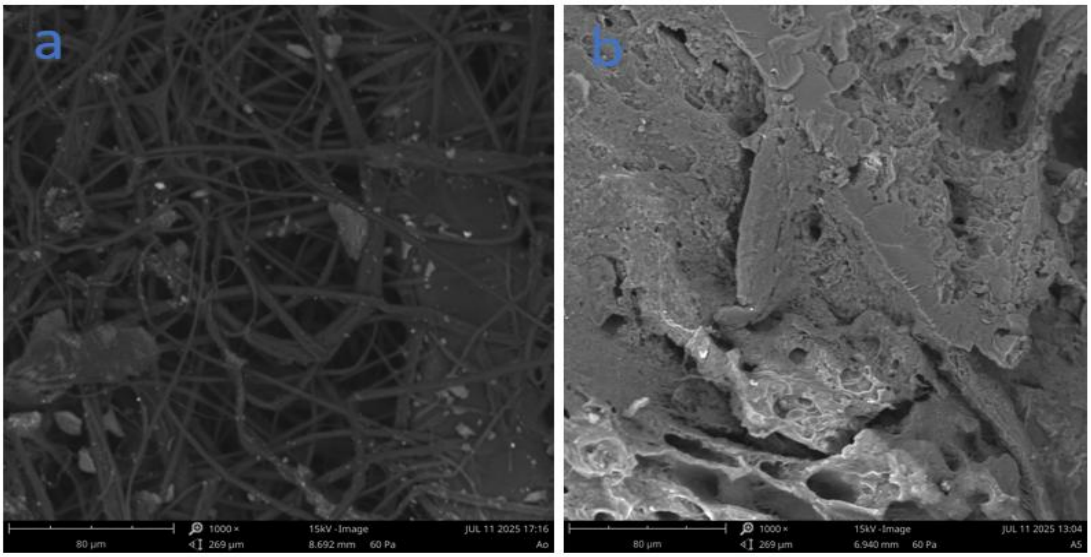

Plate I: SEM Morphology of Uncoated Paper(a) and Coated Paper (b)

FTIR characterization on the uncoated paper (UP) reveals characteristic absorption peaks which is an indication of its chemical composition. The O-H group was observed at the stretching vibrations (3200-3400 cm^{-1}) and C-H bond stretching vibrations (2800-2900 cm^{-1}) is observed hence, implies the presence of cellulose and hemicellulose in the material. In addition, aromatic rings (1630-1650 cm^{-1}) and carbonyl groups (1720-1740 cm^{-1}) implies

the presence of lignin content while ether groups (1200-1250 cm^{-1}) and alcohol groups (1000-1030 cm^{-1}) indicate cellulose and hemicellulose in the material as depicted in Figure 4 (UP). The identified functional groups imply hydrophilicity, oxidative degradation, and lignin presence which may influence paper properties such as durability, strength, and printability, the aforementioned results are consistent with those reported by (Ruggero *et al.*, 2020; Raji *et al.*, 2025). Furthermore, FTIR analysis of coated paper (CP) samples with bio-composites (CMC, cassava starch, glycerine, chitosan, and turmeric oil) at different loadings shows enhanced functional group absorption hence, indicating successful blending. The spectrum as depicted in Figures 4: (CP_1, CP_3, CP_5) revealed an increase O-H (3200-3400 cm^{-1}), C-H (2800-2900 cm^{-1}), C=O (1720-1740 cm^{-1}), and C-O (1200-1250 cm^{-1}) in stretching vibrations, and aromatic C=C (1630-1650 cm^{-1}) from turmeric oil, suggesting improved hydrophobicity, mechanical strength, barrier properties, and antioxidant activity. This improvement may be due to the hydroxyl groups from CMC, cassava starch, and glycerine, carbonyl groups from CMC and chitosan, and amide I/II bands from chitosan hence, revealing a potential relevance in enhanced paper products, the findings corroborate earlier reports by (Mustapha *et al.*, 2018; Hussaini *et al.*, 2024).

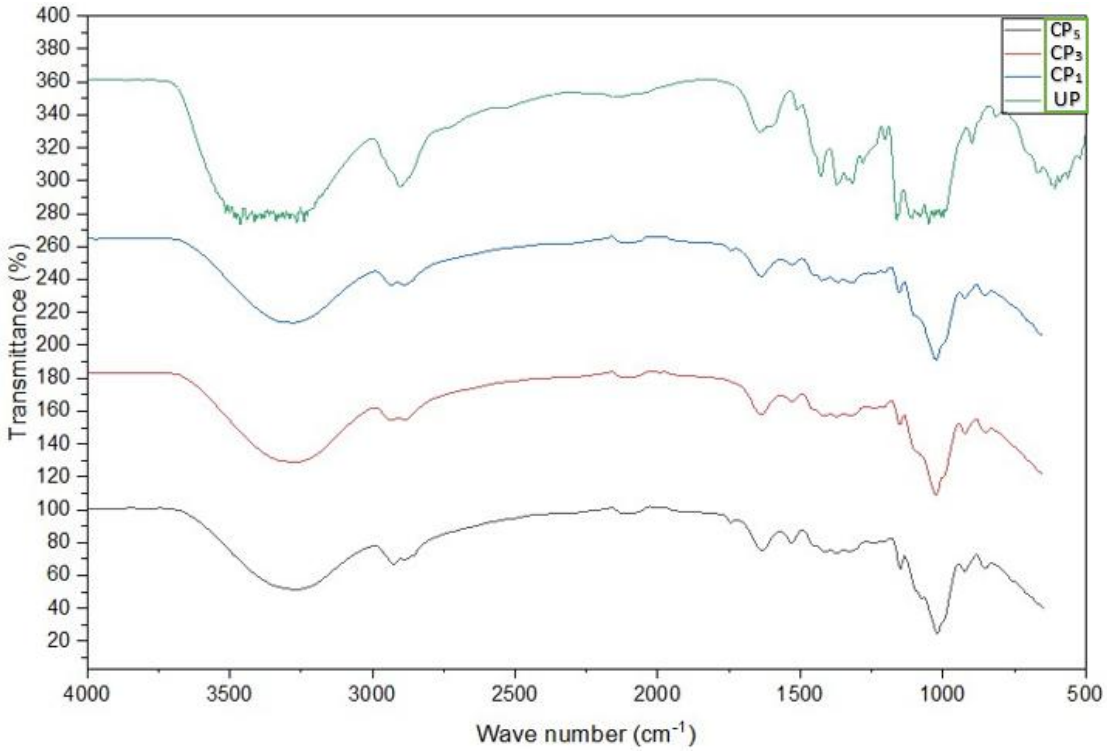

Figure 4: FTIR Analysis for Uncoated Paper (UP) and Coated Paper (CP) Samples

Thermogravimetric analysis (TGA) is an important technique for checking thermal stability and composition of a material, TGA gives an insight into processes such as oxidation, decomposition, volatile content and moisture content about material. It was observed as depicted in Figure 5 (a) from the onset of the heating process there was no appreciable change in mass of the material inform of weight loss but further increase in temperature between 250-450°C shows a single-stage degradation which may be attributed to cellulose and hemicellulose decomposition. Beyond 450°C temperature condition, it was observed that there was almost no significant change in weight loss of the material as depicted in Figure 5. Also, the TGA curves of UP and CP exhibit distinct thermal degradation patterns. However, unlike the uncoated paper (UP), the coated paper (CP) displays a multi-stage degradation profile as depicted in Figure 5 (b), (c) and (d) which may be due to moisture and glycerine evaporation, followed by degradation of cassava starch and carboxymethylcellulose (CMC), and finally, chitosan and cellulose decomposition (300-400°C). The turmeric oil present may be the reason for the slight shift in degradation temperature and residual weight. It was observed as shown in Figure 5 (b), (c) and (d) that from 500-950°C, there was almost no significant changes in weight loss of the coated paper at different loadings. The enhanced thermal stability of CP at first loading as depicted in Figure 5 (b), as indicated by the linear weight loss after 500°C as compared to UP suggests improved durability and resistance to thermal degradation, thereby making it a promising sustainable material. The aforementioned findings are in line with the previous studies by (Shah *et al.*, 2024; Raji *et al.*, 2025).

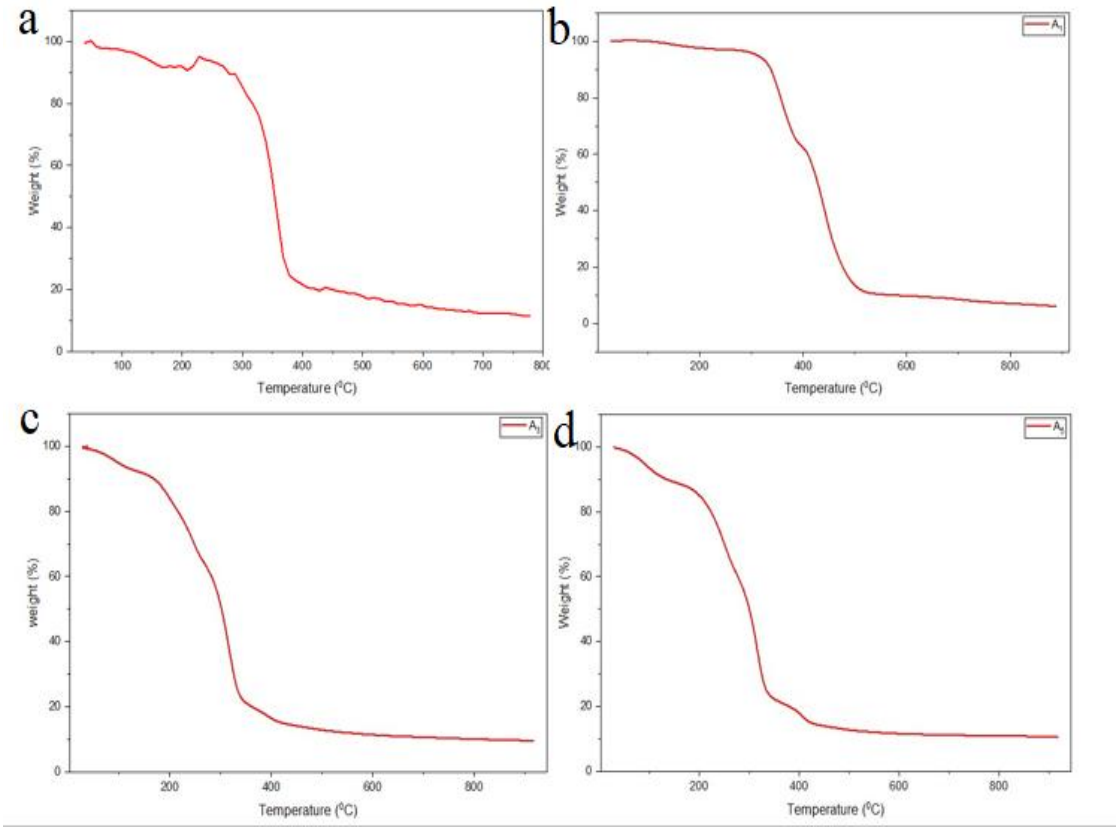

Figure 5: TGA of the Uncoated Paper (a) and Coated Paper Samples; CP1(b), CP3 (c) and CP$_5$ (d)

The tensile strength results of UP and CP with bio-composite materials shows variation in degrees of mechanical improvement. It was observed that CP_1 being the first loading revealed tensile strength of 44.28 MPa compared to uncoated paper (UP) having a tensile strength of 37.86 MPa hence, indicating that the bio-composite coating can improve paper durability. However, other coated papers with varying loading such as CP_3 and CP_5 revealed a significant decrease in tensile strength (32.86 and 12.91) respectively) hence, the findings indicate a variation in bio-composite. The aforementioned explanation shows the relevance of optimizing bio-composite formulation and coating processes in order to achieve desired mechanical properties in the material. The decreased tensile strength in $CP_{3\text{-}5}$ may be due to factors such as insufficient curing time, inadequate coating uniformity, quantity of antimicrobial agent or inadequate adhesion between coating and paper among others. The findings corroborate earlier reports by (Liu *et al.*, 2018; Raji *et al.*, 2025).

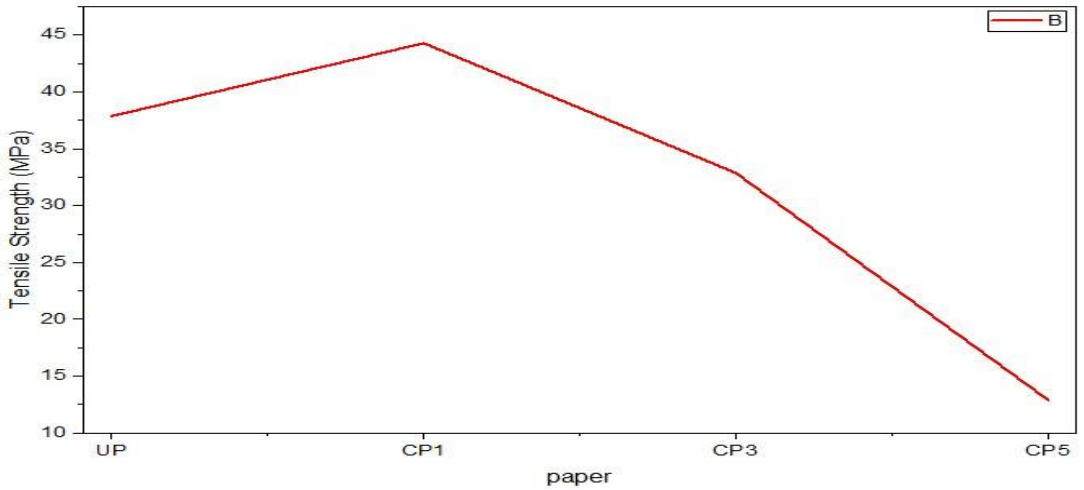

Figure 6: Tensile Strength of Uncoated Paper (UP) and Coated Paper (CP)

Thickness is an important property of films and coated papers as it affects their strength, flexibility and barrier performance. The measurements were used to assess how the different formulation steps influenced the uniformity and functional quality of the developed composite films and triplicates readings were obtained for each sample with an average recorded. The thickness measurement on uncoated paper (UP) recorded the lowest value of 0.07 mm, while the coated paper (CP) sample; CP_1, CP_3 and CP_5 showed a more thickness level of 0.15 mm, 0.22 mm and 0.31mm respectively. Therefore, the change in thickness level will improve the flexibility, strength and barrier performance of the material and with that there will be efficient protection to the package food.

The contact angle (CA) measurements were conducted using sessile droplet method where water and glycerol were utilized as solvents, revealing significant variations in hydrophobicity and oleophobicity between uncoated paper (UP) and coated paper (CP) samples. The uncoated paper (UP) exhibited a water contact angle (WCA) of 73.2° and OCA of 90.3°, indicating a hydrophilic nature of the packaging paper. Whereas the coated paper (CP) samples demonstrated enhanced hydrophobicity, with water contact angle (WCA) values ranging from 84.1° (CP1) to 95.4° (CP5), while CP3 displayed exhibited a water contact angle WCA value of 91.5°. The formulated bio-composite film showed effectiveness in improving hydrophobicity and oleophobicity particularly on the sample with the most loading; CP5. The oil contact angle (OCA) values remained relatively consistent across CP samples, indicating stable oleophobic properties with increased values of 92.7°, 98.4° and 101° respectively. These findings showed that the simultaneous use of cassava starch, chitosan, carboxy-methyl cellulose (CMC), glycerol and turmeric oil successfully enhanced

the water and oil repellences of CP samples. The variations in water contact angle (WCA) and oil contact angle (OCA) among CP samples may be attributed to loading ratio which resulted in differences in coating thickness, composition, or curing conditions. Further optimization of the bio-composite formulation and coating process could lead to even more significant improvements in hydrophobicity and oleophobicity. The aforementioned findings agree with the literature by (Raji *et al.,* 2025).

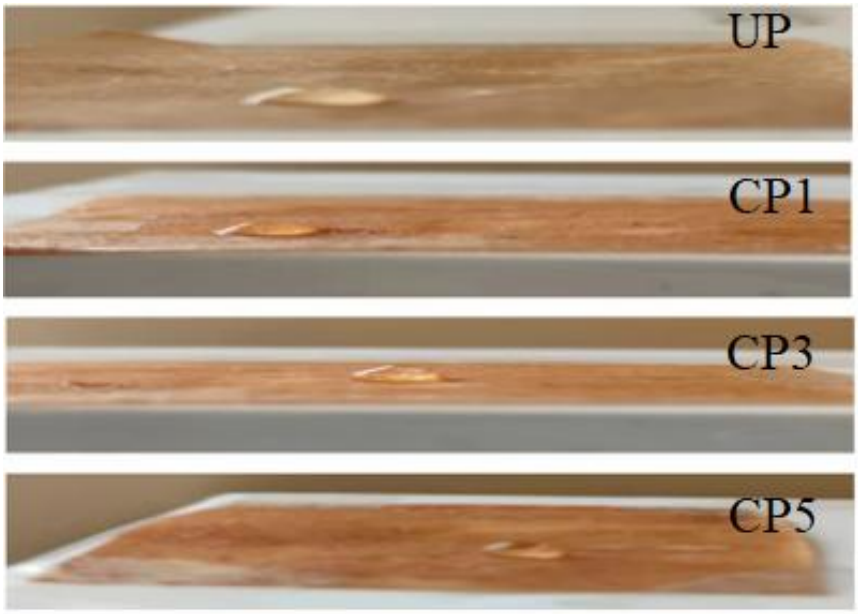

Plate II: Pictorial View of Water Droplet on Uncoated (UP) and Coated Paper (CP) Samples

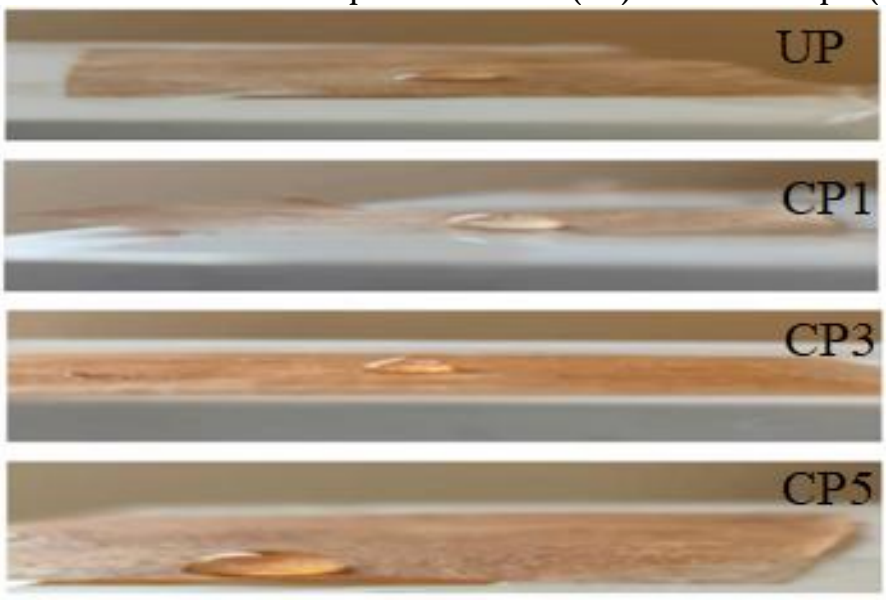

Plate III: Pictorial View of Glycerol Droplet on Uncoated (UP) and Coated Paper (CP) Samples

The antimicrobial activity of the uncoated and coated paper samples against *Bacillus cereus*, *Pseudomonas aeruginosa*, *Aspergillus niger* and *Penicillium expansum* was evaluated. It was observed that microorganisms used for the antimicrobial sensitivity test of the uncoated

paper revealed absence of inhibition as presented in plate IV. The aforementioned finding may be due to absence of anti-microbial agents (inhibitors) for microbial growth and proliferation. Also, for the coated paper, there was observed zone of inhibition among the coated papers, highest zone of inhibition of 6.0 mm was recorded by the most loaded paper (CP_5) as shown in plate V. The reason for the inhibition observed among the coated paper may be attributed to adequate concentration of anti-microbial agents (Turmeric oil), effective diffusion into the medium and sensitivity of the test organism among others. The application of the aforementioned organisms showed a similar trend that was observed in the previous study reported by (Raji *et al.,* 2025).

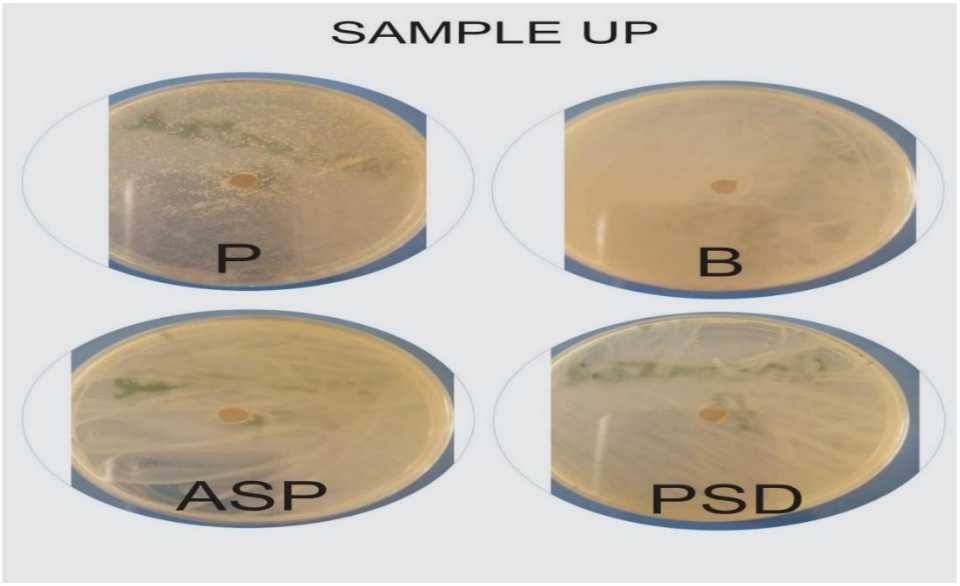

Plate IV: Morphological Antimicrobial Sensitivity Test for Uncoated Paper (UP)

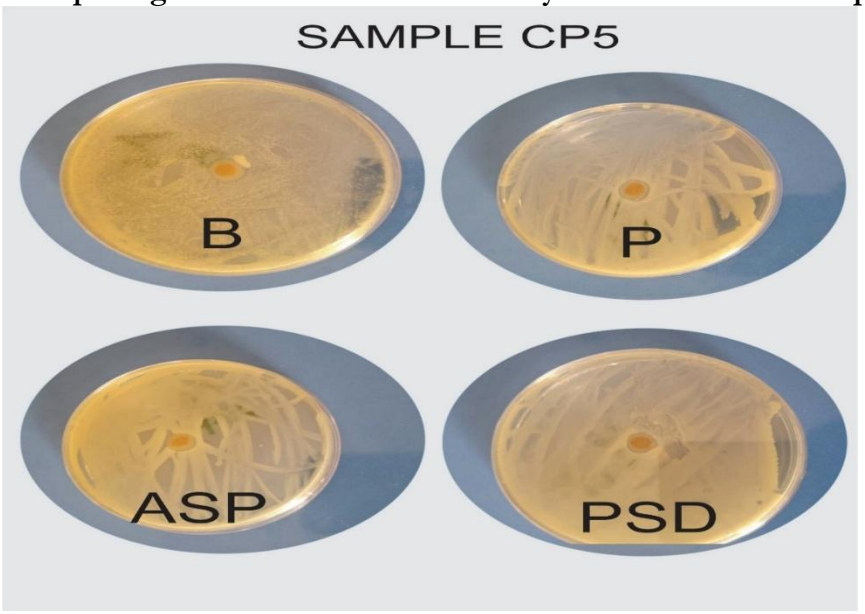

Plate V: Morphological Antimicrobial Sensitivity Test for Coated Paper (CP_5)

CONCLUSION

The bio-composite film that was prepared had a pH value of 5.6, exhibited non-Newtonian shear-thinning behaviour, which is best for coating food packaging paper having enhanced qualities like spread ability, transparency, adhesion and strong barrier strength.

SEM showed UP has a porous, rough surface with loosely packed fibres, while CP displayed a uniform, thick coating. FTIR confirmed cellulose, hemicellulose, and lignin presence in UP and increased O-H, C-H, C=O, C-O, and aromatic C=C in CP with bio-composites, indicating improved hydrophobicity, mechanical strength, barrier, and antioxidant properties. TGA revealed single-stage degradation in UP (250–450°C) due to cellulose and hemicellulose decomposition, while CP showed multi-stage degradation, with negligible weight loss beyond 450°C. Tensile strength improved in CP1 (44.28 MPa) compared to UP (37.86 MPa), though higher loadings reduced strength.

Antimicrobial tests showed no inhibition in UP, while CP5 recorded the highest inhibition (6.0 mm) and enhanced wettability (water and oil contact angles of 95.4° and 101°), confirming improved paper durability and functional properties

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