

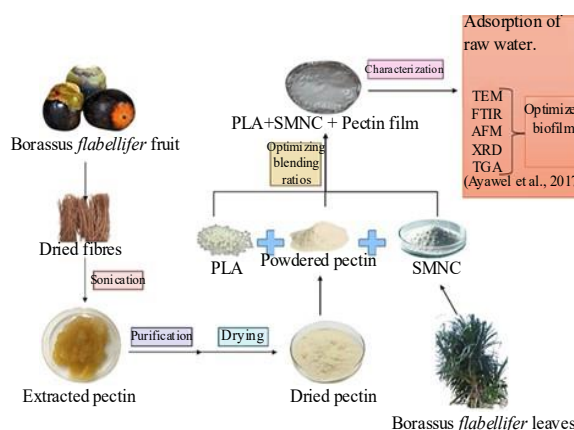
Exploring Polymer Biocomposite as a Sustainable Filter for Water Treatment

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Abstract

The present study explores the utilization of polylactic acid (PLA), a renewable polymer combined with surface-modified nanocellulose (SMNC), and pectin derived from *Borassus flabellifer* leaves and fruits respectively. Existing methods of filtration are synthetic and affect the environment and public health at an alarming rate thereby making biopolymer-based membranes a greener and effective approach for water treatment. PLA-SMNC-pectin biofilm was fabricated using 88.5 mg PLA, 3.5% (wt. % of PLA) of SMNC, and 8% (wt.% of PLA) of pectin. The optimization studies showed 65.89% and 54.8% reduction in calcium concentration and alkalinity respectively with an optimal contact time of 90 mins for a biocomposite weighing 0.5g. Bio composite's reusability was assessed for seven cycles, and it retained 97.36% of its adsorptive capacity which is superior in comparison to the conventional methods of filtration. Structural and morphological analyses confirmed the film's effectiveness. FTIR analysis showed a peak at 2031 cm^{-1} for adsorbed film entailing the interaction between calcium and other functional groups present in the bio-composite. XRD data confirms the increase in crystalline nature and decrement in halo peak up to 22.1° for the adsorbed film. TEM and AFM confirmed absorption by showing white patches and rough surface on the film respectively, and EDS showed a peak for calcium at 6.5 cps/eV thereby confirming the calcium absorption. TGA analysis exhibited 95% degradation for the adsorbed film whereas, the non-adsorbed film had only 50% degradation; both at 380°C which entails that adsorbed film is more susceptible to degradation.

Graphical Abstract



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INTRODUCTION

Water pollution is a global issue that affects ecosystems and human health. The release of untreated or inadequately treated wastewater into natural water bodies has led to the contamination of freshwater resources, threatening biodiversity and impairing water quality [5]. Key pollutants such as

heavy metals, excess nutrients, suspended solids, and harmful chemicals contribute to this crisis, necessitating the development of innovative treatment strategies that are both efficient and environmentally friendly. Biopolymer based technology has gained significant attention for such innovative treatment strategies and they are designed to optimize the removal efficiency of heavy metals and reducing alkalinity using adsorption phenomenon as studied by Tsaridou et al. [37]. These adsorption-based interactions between the pollutant and bio composite have been studied and influenced by adsorption isotherms, which can model bio bio-composite's capacity to adsorb contaminants depending on different environmental conditions and pollutant concentrations [4].

Transitioning to “green” materials is vital since conventional methods harm biodiversity and in order to implement this, dependence on traditional plastics needs to be decreased. Global annual plastic output has already surpassed three billion tonnes as of 2015 and 93% of these are discarded in landfills and water bodies according to Jimenez et al. [14]. However, these bio composites have several drawbacks too, some include susceptibility to environmental conditions, mechanical property limitations, thermal stability concerns, and chemical resistance issues, as stated by [30, 7, 31]. The term polymer bio composites refer to materials made from a natural or biodegradable polymer matrix in which natural fillers such as cellulose or plant fibers are incorporated. This approach mitigates the environmental impact of synthetic polymers [18]. These bio composites also exhibit useful properties, as they are effective adsorbents of heavy metals and dyes due to their lower toxicity and the functional groups within their polymer structure. In water treatment, they are superior to hydrophobic synthetic polymers because of their lower toxicity and greater permeability. Although bio composites have lower mechanical and chemical resistance compared to synthetics, their greater environmental sustainability and effective pollutant-binding make them highly valuable in eco-friendly water purification systems. Bio composite films are an economical alternative to conventional filtration since they are low-cost, and they help to minimize the use of costly chemical treatments due to their high adsorption capacity and hence, they are a more sustainable and cost-effective option. According to Palanisamy et al., [28], polymer bio composites have a smaller ecological footprint than conventional synthetic filter media as they can be made using renewable and biodegradable materials, which reduces the potential for long-term pollution and reliance on fossil resources. Additionally, bio composites will decompose in the right disposal environment, lowering the risk of microplastics, whereas synthetic materials like polypropylene or polyethylene will persist in the environment for hundreds of years. They may also be safely composted or incinerated without toxic byproducts and with a lower carbon footprint to production. Their manufacture is much cleaner by comparison. Products made synthetically use high amounts of energy, create landfill accumulation, and may have toxins emitted during disposal or degradation. Overall, bio composites are a cleaner, more sustainable choice for the use of filtration.

Drawbacks like mechanical properties, narrow processing windows, and inadequate antimicrobial and thermal properties can be overcome by using nanofillers along with composite [29]. In effect, the synergistic effects between the nanofiller and the biodegradable polymer matrix are incorporated through the polymer composites to enhance properties without departing from the dictates of environmental regulations [34]. As a stand-alone bio composite, PLA lacks the necessary properties for industrial application, hence the addition of SMNC and pectin has been introduced to enhance its utility.

Nanocellulose (NC) has garnered significant attention as a nanofiller due to its exceptional inherent properties, low cytotoxicity, high specific surface area, and distinct physical characteristics [21]. Chen et al. [8, 9] explained the contact between the surfaces among nanocellulose particles and PLA can be enhanced by surface modification. In non-polar polymeric materials, topochemical modification of NC particles, particularly through acetylation, is commonly used to reduce hygroscopicity and enhance dispersibility [12, 35]. Although SMNC has an ideal structure, it does not possess any inherent antibacterial properties. The incorporation of antibacterial properties prevents the growth and transmission of harmful microorganisms to ensure the efficiency and safety of filtration systems. Hence,

combining SMNC with biologically active compounds such as proteins, glycosides, cytokines, growth factors, local anaesthetics, other polysaccharides, nanoparticles, and even pectin enhances the durability of the biocomposite [7]. Pectin, a key non-starch polysaccharide (NSP) found in plant cell walls, is often extracted from agro-food by-products using various extraction techniques.

Krishnaveni et al. [19] showed that the Greek terms *Borassus* and *flabellifer*, which mean "the fruit containing a fibrous coating," are the origin of the botanical name *Borassus flabellifer*, also frequently known as the palmyrah palm. The species of plant is regional to southeastern Asia and the Indian subcontinent, and it's adaptable and persists in all sorts of harsh, semi-arid territories. India has the world's top palmyrah palm tree estimate with 85.9 million, with 51 million of those trees scattered across Tamil Nadu.

This study demonstrates PLA-SMNC-pectin bio composite adsorption efficiency depending on optimal contact time and biofilm weight. The pore size and shape of a PLA-SMNC-pectin bio composite filter is affected by its component's chemical and mechanical properties. PLA's rigidity and structural strength helps the pore withstand deformation during filtration which maintains its structural integrity. The SMNC not only helps increase surface area but improves the particulate capture via mechanical interception and electrostatic forces due to enhanced porosity. Pectin contributes to the increase of flexibility by providing polar functional groups capable of binding with water, thus, contaminants can be water soluble. PLA's hydrophobic characteristics guarantee there is no moisture blockage, while modified nanocellulose and pectin help with capturing the hooks and active components to lift within the multiple particle matrix improving blockage-free pectin filtration. All these factors work in conjunction to manufacture effective materials for water filtration [24]. Prolonged contact time might lead to effective adsorption, whereas weight helps in determining its adsorption capacity and surface area for interaction with pollutants. Additionally, SMNC's higher surface area and high aspect ratio, along with pectin's hydrophilic nature and bioactivity can further enhance the bio composite's ability to adsorb pollutants.

MATERIALS AND METHODOLOGY

Extraction of pectin from *B. flabellifer* fruits

B. flabellifer fruits, each weighing between two and four kilograms, were acquired from a nearby market. The pulp was separated from the kernel and skin after proper cleaning. The total weight of the fruit was 35 kg, and 15 fruits were randomly selected from it. These gave 10 kg of pulp, which was subsequently comminuted to fine sizes and dried in a laboratory hot air oven at 60°C for 48 h. The fibers were sun-dried and kept in sealed plastic bags at room temperature to store for further processing [3].

The dried fruit pulps were immersed in water at 100°C for 3 mins and cooled down in an ice bath. A solvent made with fruit fiber and 1.0 M HNO₃ in 1:30 (g/ml) ratio was used for further processing. This mixture was ultrasonicated with a frequency of 20kHz and a power input of 750 W for 30 mins with an amplitude of 30%. It was pulsed for 10 seconds repeatedly. Ultrasonicated samples were centrifuged at a speed of 5000 rpm for 15 mins and the resultant supernatant was filtered and pellet was refrigerated at 4°C for approximately 30 mins. The samples were filtered once again and further immersed in a solution of ethanol and water in a ratio of 7:3 for the removal of impurities and later dried at a temperature of 40 °C for 12 h in a hot air oven (Sun et al., 2020).

Groundwater Analysis

Ground water was procured from a local site, and it was tested for total alkalinity and calcium concentration.

Total alkalinity (as CaCO₃)

Procured groundwater was tested for total alkalinity in terms of CaCO₃ by titration method [17]. For this method, phenolphthalein was used as an indicator where 0.5g of phenolphthalein was dissolved in

50% ethanol. A few drops of the resulting solution were added to the 10 ml of groundwater and were titrated against concentrated sulphuric acid (H_2SO_4) till the solution turned colourless from pink colour indicating the removal of hydroxyl ions from the solution as stated by Sharma et al. [36]. Alkalinity was calculated using the following formula in eqn 1 and similarly, in eqn 2 alkalinity estimation as $CaCO_3$ is denoted (2):

$$\text{Phenolphthalein alkalinity (mg/L)} = \frac{\text{Volume of sulphuric acid (V1)} \times \text{Normality} \times 50 \times 1000}{\text{Volume of sample taken}} \dots \quad (1)$$

$$\text{Alkalinity as } CaCO_3 \text{ equivalent (mg/L)} = \frac{V1 \times 0.02N \times 50 \times 1000}{100} \dots \quad (2)$$

Calcium Concentration Estimation

Estimation of calcium concentration was done using titration method, where EDTA was used as a titrant and Eriochrome Black T as an indicator as studied by Ward [39].

For this experiment, 0.37% of 0.1M EDTA was prepared in distilled water 5 ml of NH_4Cl/NH_4OH buffer of pH 8 was added to every 20 ml of groundwater sample and resulting solution was titrated against prepared EDTA solution after adding few drops of indicator [38]. EDTA was added until pink colored solution turned clear blue indicating adsorption of calcium in the solution. Concentration of adsorbed calcium was calculated using formula denoted in eqn (3) according to Ferreira et al. [10]:

$$\text{Calcium concentration (mg/L)} = \frac{\text{Titrant volume (V1)} \times 400.5 \times 1.05}{\text{Volume of sample taken}} \quad (3)$$

Optimization of Adsorption Factors

Contact time

In order to find the optimal contact time for calcium adsorption onto the biocomposite, the sample was incubated with the biocomposite at varying time intervals. For every 100 ml sample 0.5g of biocomposite was added with incubation time ranging from 15 to 165 minutes with 15-minute time interval. After respective time intervals, the adsorbed film was removed from the sample and weighed to observe weight change if any, whereas adsorbate was filtered using Whatman filter paper No. 42 and resultant filtrate was checked for post-adsorption analyses of alkalinity, pH and calcium concentration.

Experiments were performed in triplicates and the mean value having the lowest calcium concentration and total alkalinity at a particular time was chosen as the optimal contact time.

Weight of Biocomposite

Optimization of biofilm weight was done after finding optimal contact time. 100 ml of groundwater sample was taken in each beaker and a biocomposite of weight varying from 0.1g to 1g was added to the same. On completing the incubation period according to optimized time, biocomposite was removed, and weight change was noted. Adsorbate was filtered using Whatman filter paper No. 42 and the resultant filtrate was checked for post-adsorption analyses of alkalinity, pH and calcium concentration. Experiments were performed in triplicates and mean value having the lowest calcium concentration and total alkalinity at a particular weight was chosen as the optimal weight of biocomposite.

Recyclability of the PLA-SMNC-Pectin biofilm

Recyclability of a bio composite refers to the number of cycles a biofilm can perform adsorption without losing its ability to adsorb efficiently. Previously adsorbed bio composite of optimal weight was incubated with 100 ml of groundwater sample for time interval optimized earlier and calcium concentration in adsorbate was calculated after filtration. The process was repeated with the same bio

composite until it showed decreased calcium adsorption efficiency thereby indicating its recyclability (Lu et al., 2023).

Characterization of the Adsorbed Biofilm

Fourier Transform Infrared Spectroscopy (FTIR)

The functional groups present in adsorbed bio composite were detected through FTIR analysis using Agilent Technologies Cary 600 Series FTIR spectrophotometer. The recorded spectrum of the powdered sample was examined using the KBr pellet method over a broad wavelength range (400-4000 cm^{-1}), which identifies and differentiates between various molecules based on their unique molecular structures (Subash et al,2023).

X-ray Diffraction (XRD) Analysis

The crystalline or amorphous nature of the membrane was ascertained by X-ray diffraction performed at room temperature using a Cu-K α source and a generator set at 40kV and 15mA. The X-ray diffractogram (BRUKER USA D8 Advance) was used to examine the bio composite before and after adsorption [32]. The crystalline size (D) of the bio composite was estimated using the Debye–Scherrer formula shown below eqn (4) [40]:

$$D = \frac{k\lambda}{\beta \cos \theta} \dots \quad (4)$$

where λ is the 1.5419 Å X-ray wavelength, k (value 0.9) is the dimensionless form factor, θ represents the Bragg angle in radians, while β is the radian full width at half maximum (FWHM).

Atomic Force Microscopy (AFM)

The roughness of the bio composite was studied using Atomic Force Microscopy (Park Systems Corporation, XE7). Film with dimensions of 2*2 cm was cut and analyzed for their surface morphology [26].

Transmission Electron Microscopy (TEM)

To find out the smallest structures of the elements present on the surface of the bio composite, TEM analysis was performed for non-adsorbed and adsorbed films at various magnifications. The presence of elements was further proved by the energy-dispersive X-ray spectroscopy (EDS) [13].

Thermogravimetric Analysis (TGA)

Using a thermogravimetric analyzer, TGA was carried out. Utilizing the differential scanning calorimetry method, the PLA-SMNC-pectin bio composite's thermal characteristics before and after adsorption were examined. The heating process was conducted in the presence of nitrogen, with temperature starting from 30°C and gradually increasing to 600°C at a rate of 10°C/min [11].

RESULTS AND DISCUSSION

The casting of PLA-SMNC-pectin bio composite with optimized ratios

The optimization of the blending ratios of the PLA-SMNC-pectin biocomposite was performed along with other functional and structural analyses as noted by Maitra et al. [25]. The optimized ratios were found to be 88.5% PLA, 3.5% of SMNC and 8% pectin. Using this ratio a film was cast.

Groundwater Analysis

Groundwater analysis was performed to find total alkalinity and calcium concentration. It was found that the water was slightly alkaline with a reported alkalinity of 448mg/l and calcium content was relatively higher with a concentration of 210.26mg/l.

Optimization of the parameters for adsorption

Contact time

Experiments were performed in triplicates for adsorption using biocomposite. In these experiments at first, the weight was fixed at 0.5g and the time was varied with intervals of 15 mins and the mean

value of calcium concentration and total alkalinity in the three batches was taken to choose the optimal time. Error bars in Figure 1 represent the standard deviation ($n=3$), with statistical significance ($p<0.05$) confirming optimal adsorption at 90 mins. The data aligns closely with the Langmuir isotherm model, indicating monolayer coverage of calcium ions on the surface of the biocomposite.

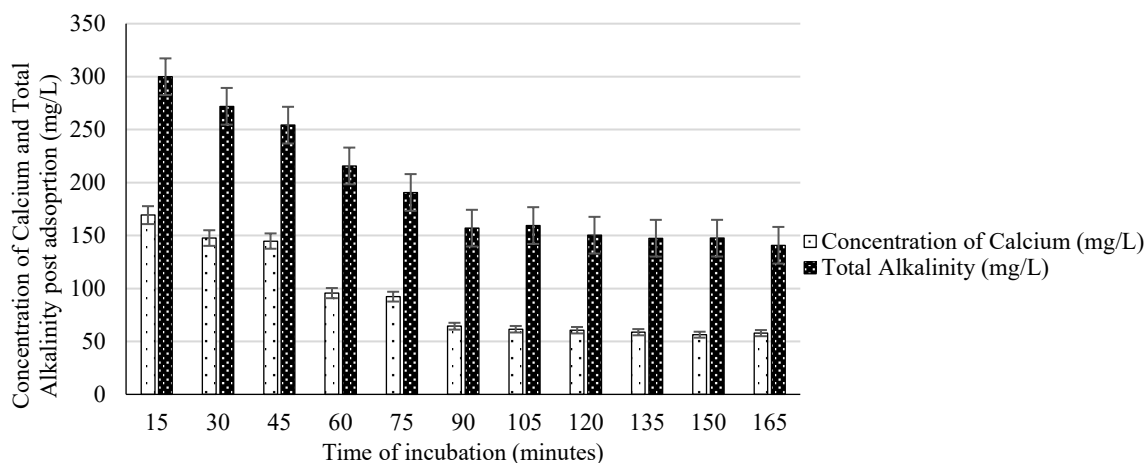


Figure 1. Optimization of incubation time for total alkalinity and calcium adsorption.

Optimal contact time was found to be 90 mins since alkalinity and calcium concentration showed a drastic decrease in values after that. Possibly, a plateau effect was observed beyond 90 mins due to surface saturation of binding sites onto the biocomposite and thereby limiting further removal of calcium. The biocomposite showed promising results in water treatment applications by significantly lowering the levels of calcium and alkalinity in groundwater samples by 53.125% and 65.89% respectively at an optimized time of 90 mins [1-2].

Weight of biocomposite

Experiments were performed in triplicates for adsorption using biofilm and the period of incubation was chosen to be 90 mins since it was found to be the optimal contact time. The weight of the biocomposite varied from 0.1g to 1g and the mean value of calcium concentration and total alkalinity in the three batches was taken to choose the optimal weight. Error bars in Figure 2 represent the standard deviation ($n=3$), with statistical significance ($p<0.05$) confirming optimal adsorption with 0.5g of the PLA-SMNC-Pectin biocomposite. Biocomposite weighing 0.5 g was found to have reduced the alkalinity in the treated groundwater by 54.87% and all weight ranges further had similar alkalinity levels indicating saturation. Similarly, 0.5g of biocomposite showed lower concentrations of calcium in the treated samples by 65.5%.

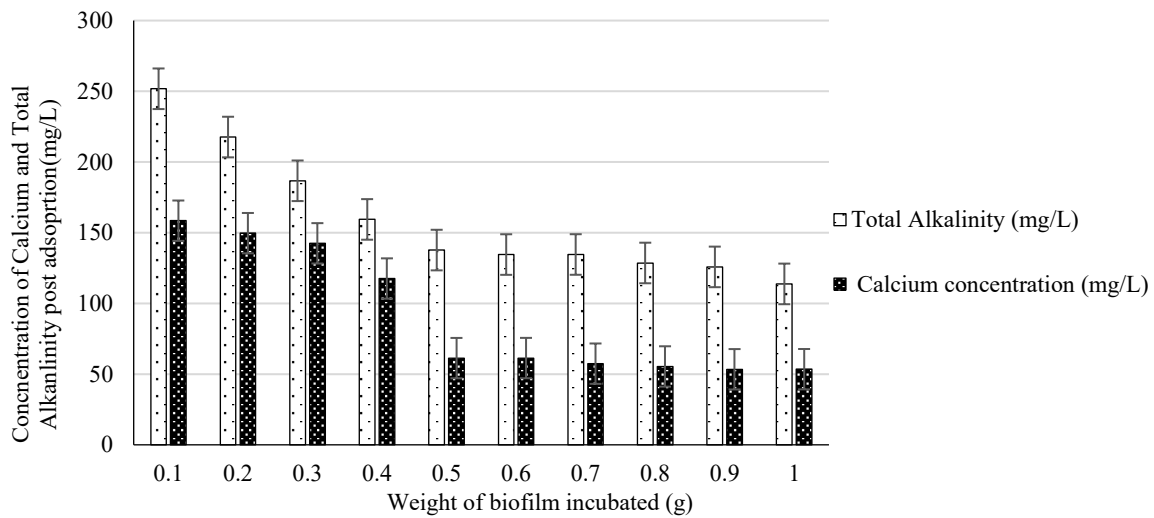


Figure 2. Optimization of film weight for total alkalinity and calcium adsorption.

Therefore, the PLA-SMNC-Pectin biofilm has potential use in water treatment applications since it significantly lowers the levels of calcium and alkalinity in groundwater samples. These results establish the PLA-SMNC-Pectin biofilm as a competitive substitute for other biofilms documented in the literature that have shown sulfate reduction methods to reduce alkalinity by up to 62% [23]. Furthermore, under ideal conditions of pH 8.0 and a hydraulic retention time of 12 h, the biofilm approaches the calcium reduction effectiveness of 67.2% observed in reactor-based biofilm systems [9].

Recyclability of the PLA-SMNC-Pectin biofilm

The recyclability test was performed on film with optimized time and weight of up to 7 cycles. It was observed that the calcium content in each of the cycles remained relatively the same with a slight decrease over the cycles as represented in Figure 3. Despite multiple reuses, the biofilm exhibited minimal structural degradation, as evidenced by the maintained surface integrity and it retained approximately 97.36% of its adsorptive capacity unlike chitosan-based biofilms, which lose 20-30% efficiency within five cycles as studied by Liu et al. [23]. Therefore, PLA-SMNC-Pectin bio composite demonstrates superior stability and a high retention rate further underscoring its suitability for repeated applications in water treatment thereby making it an environmentally friendly and sustainable approach for water purification.

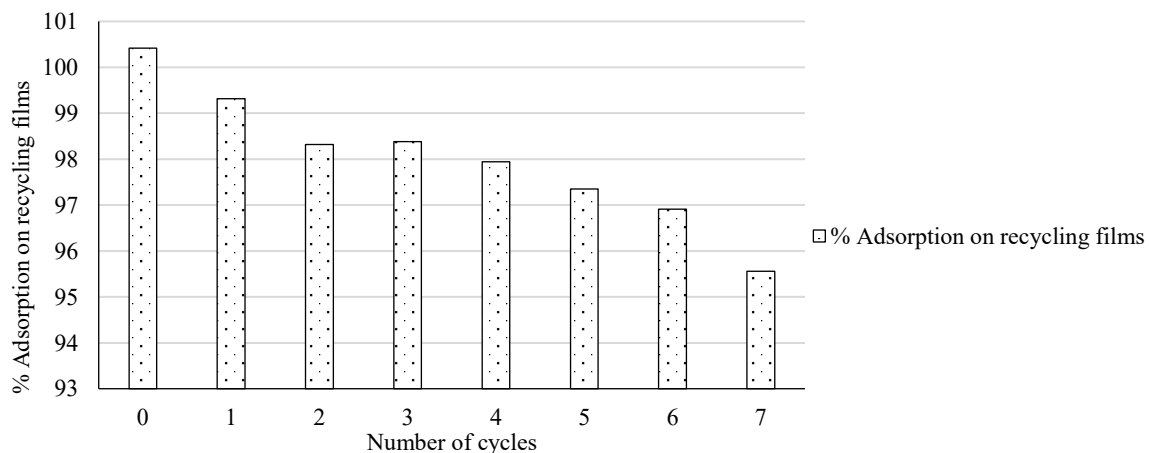


Figure 3. Recyclability of biopolymer films via adsorption efficiency.

Characterization of the Adsorbed Biocomposite FTIR Analysis

From the FTIR graph, the presence of various functional groups was studied as shown in Figure 4. The strength of the carbonyl group peak was reduced in the PLA-SMNC-Pectin film. This is believed to be due to hydrogen bond formation between the PLA matrix's carbonyl groups and the SMNC's hydroxyl groups. The PLA-SMNC composite exhibited identical peaks to the pure PLA spectra but at differing intensities which implies that the presence of SMNC influences the features of these peaks. Similar shifts have been reported in bio-based adsorbents interacting with divalent metal ions [25]. FTIR spectrum of PLA-SMNC-Pectin bio composite before and after Ca^{2+} adsorption shows drastic structural change, which is a characteristic of efficient Ca^{2+} binding. Prior to adsorption, the FTIR spectrum detects a broad band at 3298 cm^{-1} , which is an O–H and N–H stretching vibrations band which has disappeared upon adsorption, indicating the presence of hydroxyl groups in interaction with Ca^{2+} . The bands due to C–H stretching of aliphatic groups at 2995 cm^{-1} and 2941 cm^{-1} do not change, showing that the interaction with calcium ions is negligible [27]. The band for the ester carbonyl C=O at 1749 cm^{-1} is still seen in both spectra with minimal variations in intensity based on adsorption. A peak at 2031 cm^{-1} was formed on adsorption, which is because of the formation of coordination bonds between Ca^{2+} and functional groups such as carboxyl or hydroxyl was studied by [33]. The change in the spectrum ensures that PLA-SMNC-Pectin bio composite can effectively chelate calcium ions and thus can be used for the adsorption of calcium absorption.

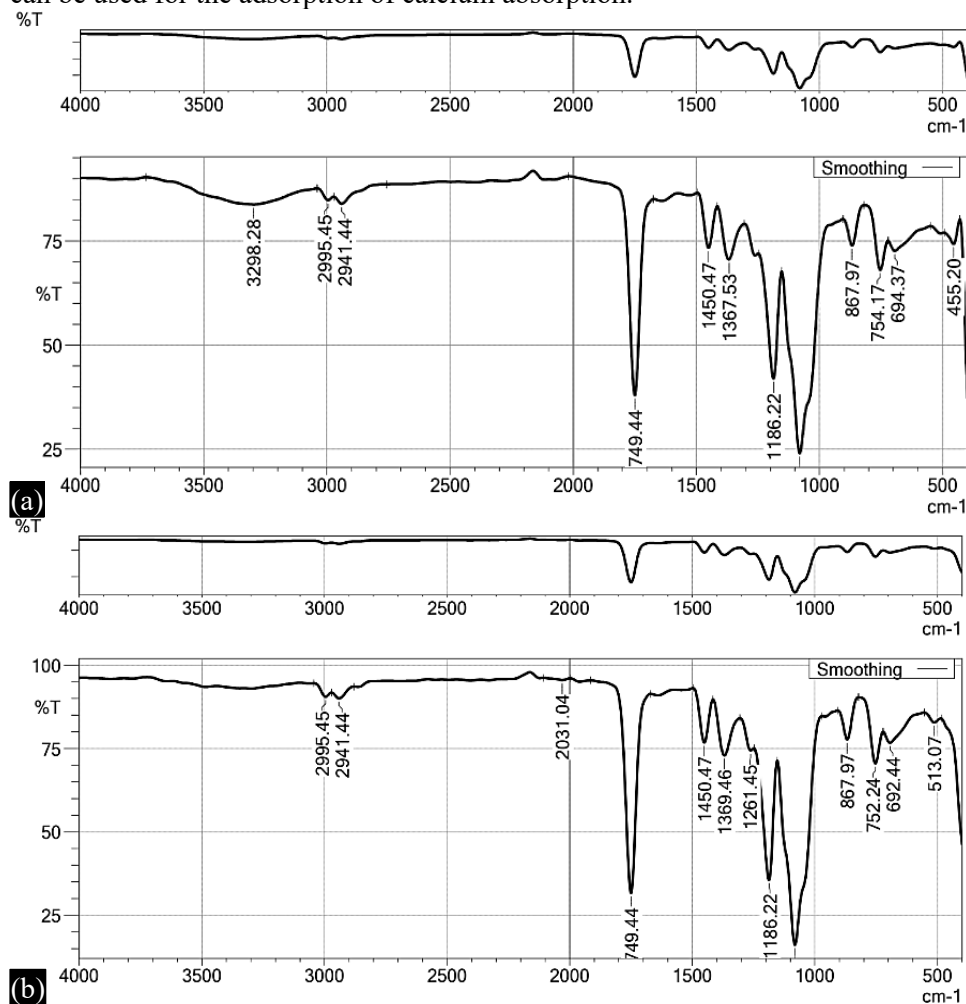


Figure 4. FTIR analysis for PLA-SMNC-Pectin biofilm (a) before adsorption; (b) after adsorption

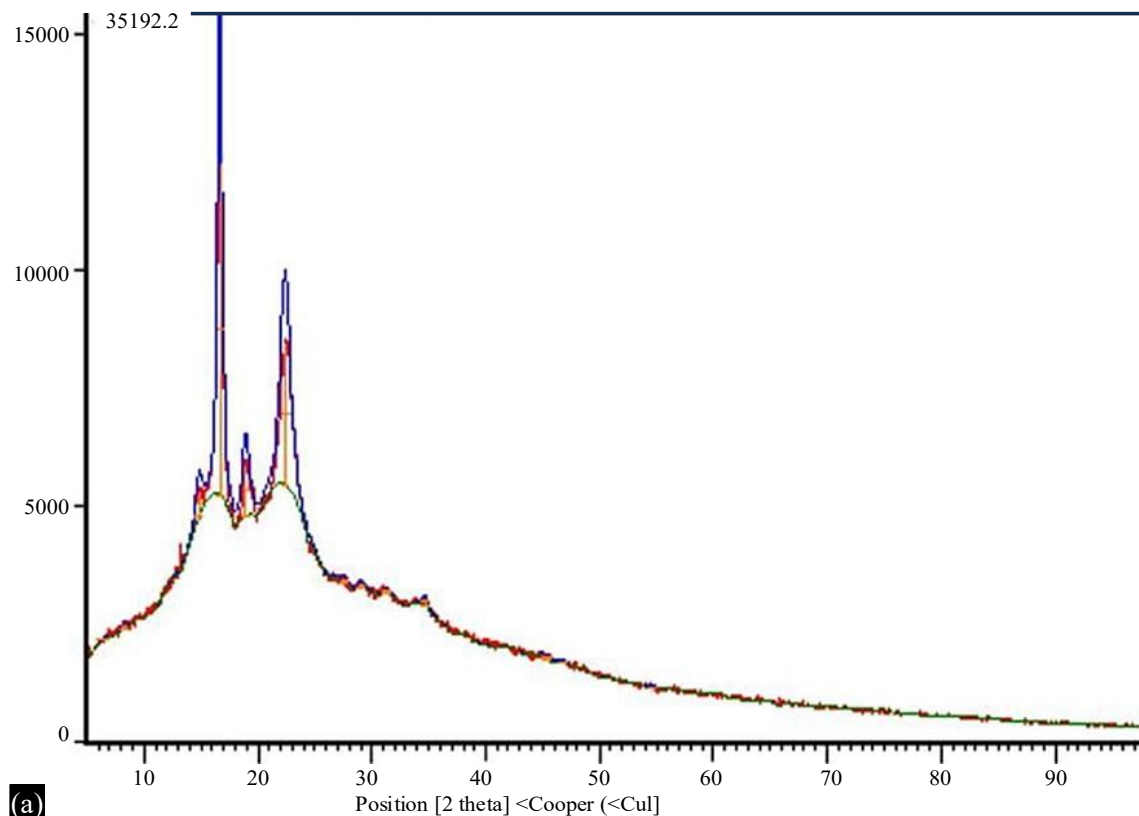
XRD Analysis

The crystallographic characteristics of PLA-SMNC-Pectin biofilm before and after adsorption were investigated using XRD as shown in Figure 5. In the non-adsorbed biocomposite, the graph displayed 2 broad peaks at $2\theta = 16.80^\circ$ and 23.4° which showed that the structure of the film was highly amorphous.

Referring to the diffractograms, the biofilm possesses a semi-crystalline formation assembled of a combination of crystal and amorphous features as noted by [25]. In the adsorbed bio composite, a decrease in the halo peak was noted at 22.1. From the XRD results, it can be inferred that the adsorption of calcium ions may lead to the localized ordering of polymer chains, reducing amorphous regions and increasing crystallinity [15]. Thus, by the adsorption of calcium onto the surface of the film, the crystallinity index has increased from 56.75% to 94.41% thereby decreasing the amorphosity; supporting the hypothesis that calcium adsorption induces structural reorganization.

AFM Analysis

AFM analysis is a highly advanced imaging technique used to scan and measure minuscule features on surfaces. For the film, non-contact AFM was used and the surface morphology and roughness before and after absorption was inspected. The 3D mapping AFM images captured for the two films, as shown in Figure 6, showcase unique surface qualities. AFM results display that the biocomposite used before adsorption was rough and had peaks on its surface (Figure 6a), while Figure 6b having an image of post-adsorption bio composite depicts a smoother surface with no peaks detected which entails the incorporation of calcium on the surface of the biocomposite, leading to the filling up of the pores on the surface. A reduction in average roughness (Ra) from 1.7464 μm to 0.4873 μm suggests that calcium ions filled surface voids, creating a smoother structure conducive to further adsorption cycles. A Previous study has demonstrated that surfaces with higher levels of roughness can enhance the hydrophobic properties of the material since air is trapped by these surfaces [15]. The non-adsorbed film was more hydrophobic due to the presence of pectin, but this hydrophobicity decreased when the calcium was adsorbed.



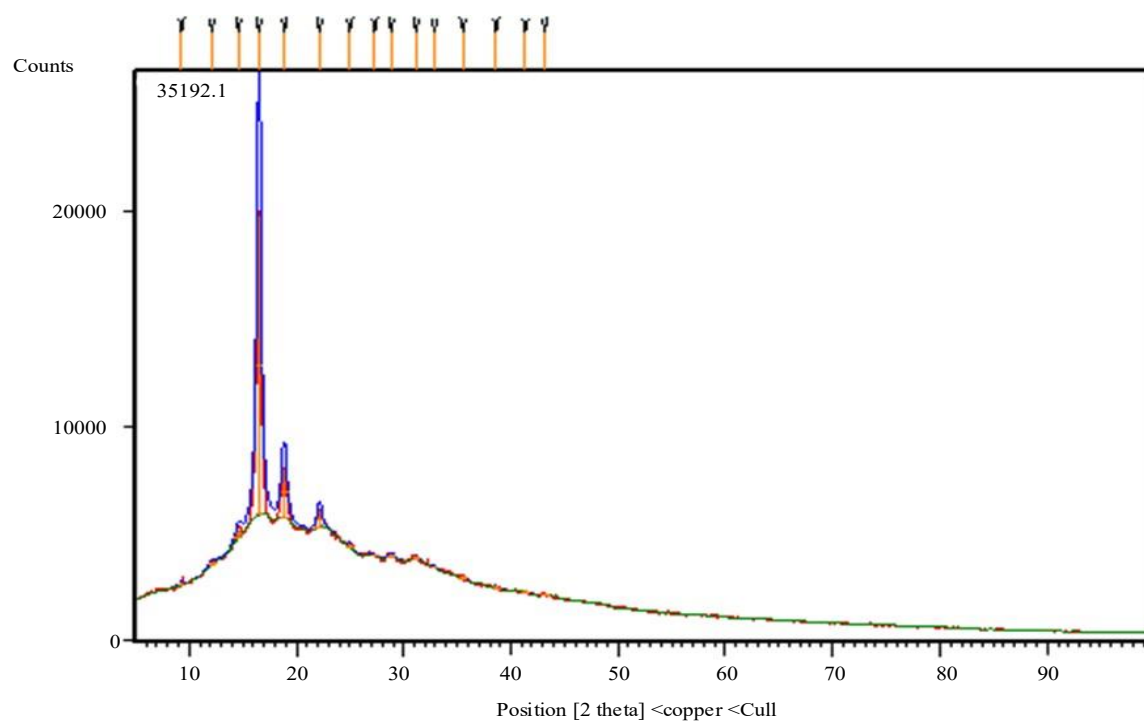


Figure 5. XRD analysis for PLA-SMNC-Pectin biofilm (a) before adsorption; (b) after adsorption

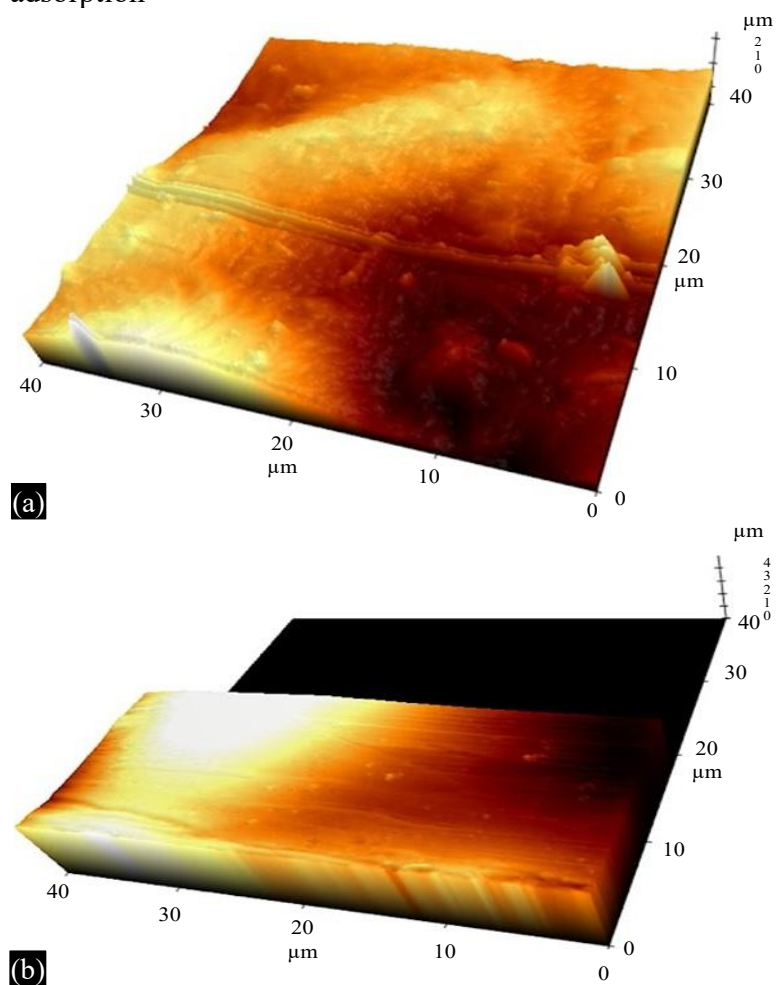


Figure 6. AFM analysis for PLA-SMNC-Pectin biofilm (a) before adsorption;(b) after adsorption.

TEM analysis

TEM analysis was performed to detect various elements present in the biocomposite. Figure 7 shows that there is the presence of some patches on the surface of the PLA-SMNC-Pectin biofilm after adsorption whereas non-adsorbed bio composite is fairly uniform. This difference is observed due to the occurrence of adsorption onto the film. EDS analysis further confirmed the presence of calcium with peaks up to 6.5 cps/eV in the adsorbed bio composite and the non-adsorbed film showed no traces of calcium as seen in Figure 8. This proves that PLA-SMNC-Pectin bio composite can actively incorporate calcium on its surface [13].

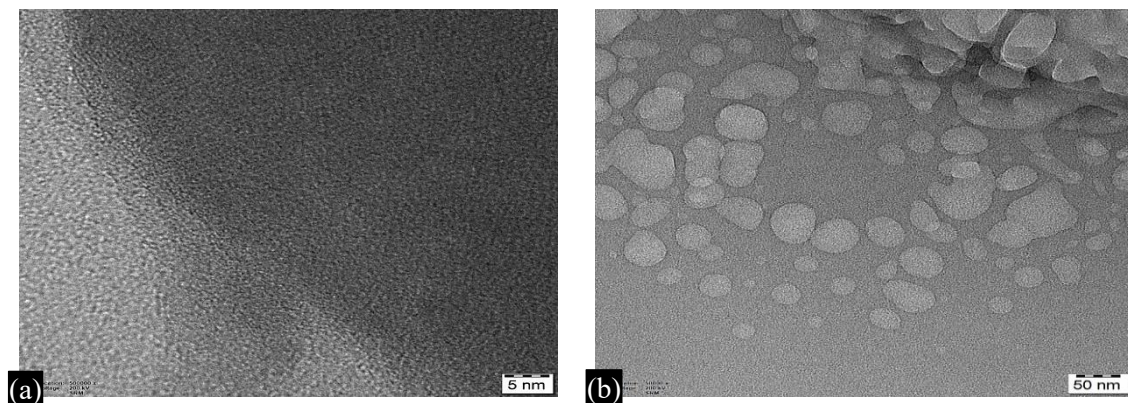


Figure 7. TEM analysis for PLA-SMNC-Pectin biofilm (a) before adsorption;(b) after adsorption

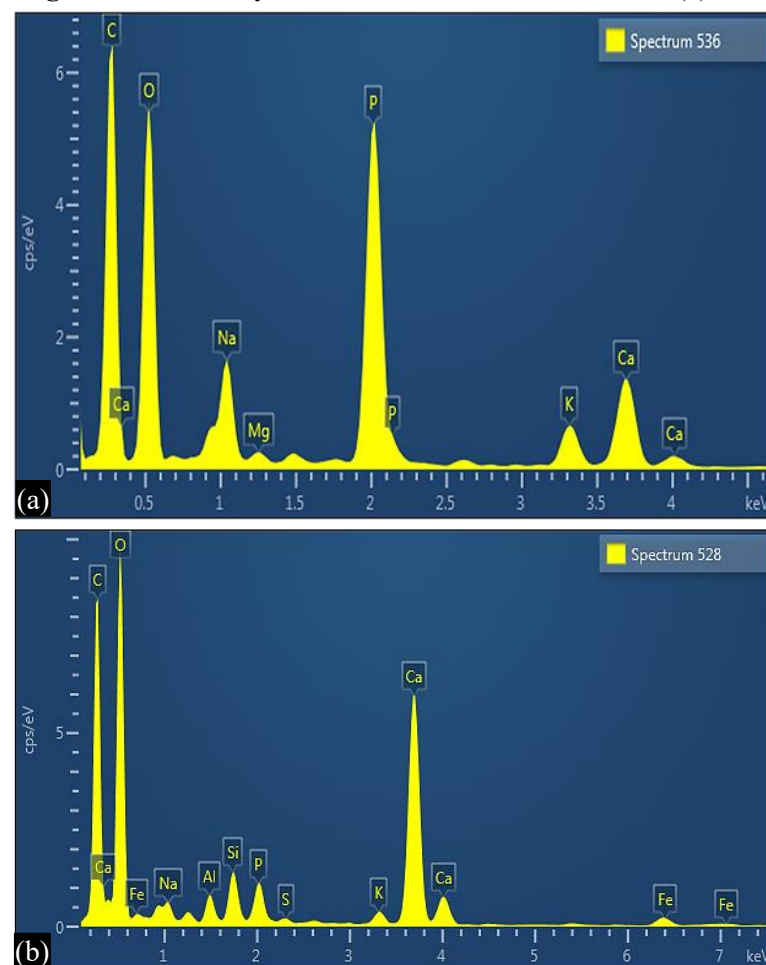
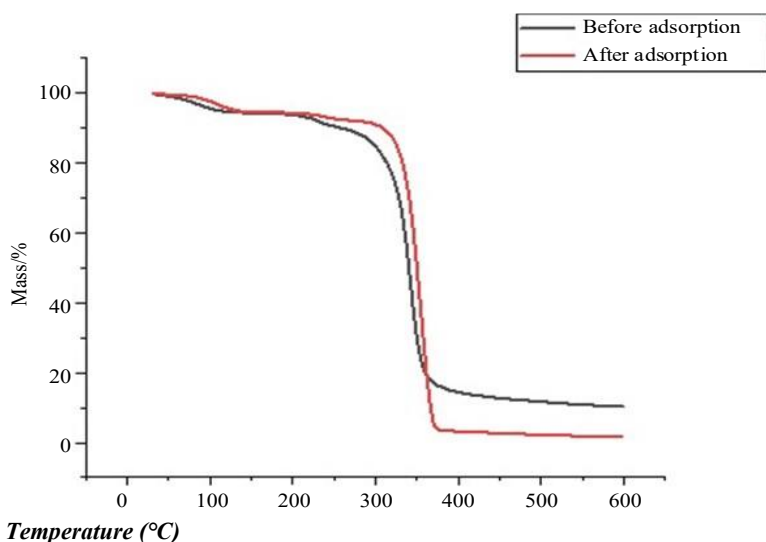


Figure 8. EDS analysis for PLA-SMNC-Pectin biofilm (a) before adsorption;(b) after adsorption**TGA Analysis**

The evaluation of the thermal stability of PLA-SMNC- Pectin bio composites before and after subjecting to adsorption was conducted using TGA. TGA analysis showed that initially, both films showed no decrease in the mass percentage. The initial value at 50°C was 100% for both the samples



Temperature (°C)

Figure 9. TGA analysis for PLA-SMNC-Pectin biofilm before and after adsorption.

and a similar trend was followed till 380°C, beyond that there was a drastic decrease in the mass percentage of the biofilm. PLA tends to hydrolyze easily when in the presence of bound water molecules and the decrease in thermal stability after adsorption suggests that calcium ions promote hydrolytic degradation of PLA, as evidenced by a faster onset of mass loss at 380°C. Compared to untreated PLA-SMNC-Pectin biofilm, which degrades at 400°C, the film after adsorption exhibited a lower onset degradation temperature (380°C), suggesting potential long-term structural instability. The line representing the post-adsorption bio composite fell up to 5% whereas the non-absorbed line showed a mass of 50% observed in Figure 9. Thus, at this temperature, the adsorbed film (red line) has a lower thermal stability compared to the non-adsorbed one indicating that there is more degradation by microorganisms in the adsorbed film due to its lower thermal stability. This also leads to a reduction in the weight percentage of the biofilm. The non-adsorbed bio composite had more thermal stability thus it is less likely to degrade unlike the treated adsorbed one [16].

CONCLUSION

Adsorption studies of PLA-based biocomposite blended with, SMNC and pectin derived from *B. flabellifer* prove the significance of film and its PLA- SMNC enriched characteristics in water treatment procedures [6]. Incorporating this bio-composite may bring about the onset of a systemic change in the manufacturing and consumption of plastic and eco-friendly materials. Testing the scalability and feasibility of pectin extraction and consumption derived from *B. flabellifer* fruits may provide insight into their wide applications in sustainable packaging and waste reduction due to biodegradable plastics, thereby finding their applications in industries that consume non-degrading materials and adversely affect the environment at an alarming rate [3,20,22]. Exploring other potential biotic sources of pectin along with other potential suitable natural derivatives with a PLA amalgamation is a greener, sustainable and economically wiser decision compared to the filtration membrane and techniques being used currently. The PLA-SMNC-pectin biocomposite was highly effective for raw groundwater purification. Minimal structural deformation was observed post-adsorption, thereby increasing its durability. AFM analysis of the treated film showed a smoother surface in comparison to the untreated film which was rougher on the surface. An XRD analysis indicated an increase in the crystallinity index

of the film and TGA analysis showed increased degradability after adsorption and thus, increased susceptibility to microbial decomposition. TEM and EDS of the adsorbed film at 50,000 times magnification showed calcium adsorption; however, the peak intensities were lower compared to the untreated sample. Further research on this bio-composite can enable the creation of sustainable bio-membrane technology for industrial and domestic applications and being biopolymer-based biocomposites, costs of production, maintenance and disposal are much lesser than that of the synthetic polymer-based membranes. Further pilot-scale studies are required to assess the feasibility of large-scale production and implementation in water treatment facilities. Unlike the conventional RO filters, which degrade with time and leach out contaminants into the water, the biodegradable nature of PLA-SMNC-pectin biofilms mitigates the risks of chemical leaching and unlike RO filters they do not require high energy inputs and are not easily prone to fouling. This calls for a very serious need for shifting from conventional membranes, which are scalable and foul-prone, to sustainable bio-membranes that assure both functional and environmental advantages.

Abbreviations

- B.flabellifer* : *Borassus flabellifer*
PLA: Poly(lactic) acid
SMNC: Surface-Modified Nanocellulose
TDS: Total Dissolved Solids
FTIR: Fourier Transform Infrared Spectroscopy
TGA: Thermogravimetric Analysis
XRD: X-Ray Diffraction
AFM: Atomic Force Microscopy
TEM: Transmission Electron Microscopy
EDS: Energy Dispersive X Ray Spectroscopy
EDTA: Ethylenediamine tetra acetic acid
NH₄Cl: Ammonium Chloride
NH₄OH: Ammonia
H₂SO₄: Sulphuric acid

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