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Research Article

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Sustainable Hemodialysis Membranes Based on Palm Waste Cellulose and Polypyrrole with Enhanced Mechanical and Filtration Properties

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Abstract

With more patients experiencing end-stage renal disease, there is a need for effective and low-cost dialysis membranes. Polypyrrole/palm-cellulose membranes were developed in and studied for dialysis applications in this work. The waste palm trunks of Iraq were used for extraction of cellulose to be used as support material. In-situ polymerization of polypyrrole was done to enhance mechanical properties and control membrane pore size. Membranes containing 25 to 100 wt% PPy were prepared to assess their performance in simulated dialysis. We used a diaphragm pump that would give us a dynamic flow and non-blood flow as blood would not flow in dialysis but it would have pressure changes. Evaluation of the membrane performance through solute removal, albumin retention, pore size, burst pressure. The membrane composed of 100 wt% PPy exhibited pore sizes ranging from 9.5 nm to 21.5 nm. It also recorded the highest removal efficiencies of 75% for urea, 70% for creatinine. In addition, it removed 63% potassium and 59% sodium while retaining 93% albumin. According to mechanical tests, the burst pressure rises with increasing PPy content, with a maximum value of 150 psi. The obtained results illustrate that palm-cellulose/PPy composite membranes exhibit good selectivity, high mechanical stability, and low price of material. Hence, they can be promising candidates for hemodialyser based on simulated results. In the future, we will conduct a study on blood compatibility, whole blood testing, and membrane reuse and electro-assisted transport.

Keywords: Palm-Derived Cellulose, Polypyrrole (PPy), Uremic Toxins, Burst Pressure, Hemodialysis Membranes

1 Introduction

Worldwide, chronic kidney disease is on the rise, resulting in a growing demand for dialysis that is effective and cost-effective [1]. Hemodialysis is the most commonly used treatment in patients with end-stage kidney disease. This procedure depends on semi-permeable membranes that eliminate metabolic waste from blood like urea and creatinine, while retaining useful biomolecules like albumin [2]. The dialysis membranes' performance and safety are highly dependent on their mechanical strength, permeability and biocompatibility [3].

In present time, most of the dialysis membranes are manufactured with synthetic polymers like polysulfone (PSF), polyethersulfone (PES), polyvinylpyrrolidone, and polyacrylonitrile (PAN) [4]. These materials are expensive and require a manufacturing process of an advanced nature but give good filtration efficiency. As a result, their accessibility in developing countries is limited. Consequently, it is evident that affordable, sustainable and local sourcing of membrane materials along with use of simpler technologies are much needed to yield good dialysis performance [5].

Natural biopolymers, particularly cellulose, are promising materials for membrane fabrication due to their abundance, biodegradability and biocompatibility [6]. Nonetheless,

pure cellulose does not contain enough mechanical strength for future dialysis [7]. The advances in nanomaterials have given birth to composite membranes in which functional nanoscale materials are incorporated with improved mechanical and chemical properties [8,9]. Fibers from palm plants comprising date-palm trunk fibers have beneficial mechanical properties including a high tensile-strength and flexibility that enables membranes to endure dialysis operational stresses [10]. Furthermore, the fibrous structure of cellulose from palm can be manipulated to adjust pore size and pore size distribution that is vital for toxin removal while retaining macromolecules [11,12].

In a bid to enhance the cellulose-based membranes, polypyrrole (PPy) conductive polymer was incorporated. PPy has many benefits, such as strengthening mechanical properties, providing good chemical stability, and tuning surface properties with better adsorption behavior. Its conductivity That could allow for future applications for electro-assisted dialysis. Crucially, incorporation of PPy into porous cellulose matrices can be achievedwithout losing overall biocompatibility [13,14].

Earlier research on PPy–cellulose membrane blood purification, such as Ferraz et al. [15], focused on their static in-vitro behavior using bacterial nanocellulose and its ion-exchange properties. In proceeding research, we propose to investigate important aspects which are currently underexploited. These include (i) the use of alternative, native or local cellulose made from palm waste; (ii) a systematic evaluation of the loading of PPy (25–100 wt%) and effect of such a loading on the nanoscale structure, solute transport, and mechanical strength; and (iii) testing of membranes under dynamic flow as in dialysis conditions along with burst-pressure testing.

This study addresses these gaps by synthesizing palm-derived cellulose/PPy composite membranes with different PPy content. The membranes are consistently assessed for their structural, mechanical and filtration properties. The membranes are subjected to dynamic circulation tests using a diaphragm pump to mimic dialysis conditions to be able to evaluate uremic toxin removal and mechanical stability. The goal of this work is to illustrate a membrane platform that is sustainable and of high-performance potential for dialysis applications, particularly in under-resourced settings.

2 MATERIALS AND METHODS

2.1 Materials

We prepared polypyrrole (PPy)/palm-cellulose nanocomposite membranes using the following materials. pyrrole monomer (Fluka AG) has been purified by double distillation and stored in an ice bath before use to prevent premature polymerization and preserve its reactivity. We used ferric chloride ($FeCl_3$) (Central Drug House, India) as the oxidizing agent for pyrrole polymerization without further purification.

cellulose acetate is extracted from locally available Iraqi palm tree trunks and used it as the main biopolymeric matrix for membrane fabrication. This palm-derived cellulose provides a sustainable and low-cost material source while remaining well suited for composite membrane processing.

2.2 Cellulose extraction from Palm trunk

Cellulose was extracted from palm tree trunks following the method reported by Szymańska-Chargot et al. [16], using a sequence of chemical treatments designed to remove soluble impurities, hemicellulose, and lignin (Figure 1). To start, 500 g of palm trunk

material was immersed in 1.2 L of hot water for 30 min. Sugar and other compounds were eliminated through this step. After filtering the mixture, I collected the solid residue for further treatment.

The solid was then treated with 1.2 L of 1.0 M HCl at 85 °C for 60 min with continuous stirring. The acid treatment was repeated once, this time using 0.5 M HCl, keeping the conditions the same so it is termed as two acid cycles. Following every acid step, the residue was washed with deionized water until neutral pH of the filtrate was achieved. Subsequently, alkaline treatment was done by 1.2 L of 1.0 M sodium hydroxide (NaOH) at 85 °C for 30 min to remove hemicellulose. This alkaline step continued on three occasions. Washing with distilled water was performed after every cycle, until neutral pH was attained. To remove residual lignin, bleaching was done in two (2) stages using NaClO. Following each bleaching step, the precipitate was washed with distilled water until the filtrate became neutral.

The extraction route in Fig. 1 was accordingly developed to minimize possible non-cellulosic components while not hampering the long and tangled architecture of palm fiber. It is important to keep this fibrous structure intact. It enables uniform in-situ PPy deposition and provides continuous transport pathways in the membrane.

On a dry-mass basis, about 25% cellulose was extracted (25 g dried cellulose from 100 g dry-corrected palm trunk). Cellulose purity was qualitatively assessed using process indicators. After performing successive acid, alkaline, and bleaching treatments, the solid developed an off-white colour, the rinsing solutions attained neutral pH, and the final filtrate appeared clear and colourless. Extraction of soluble impurities, hemicellulose and most lignin seem to be effective.

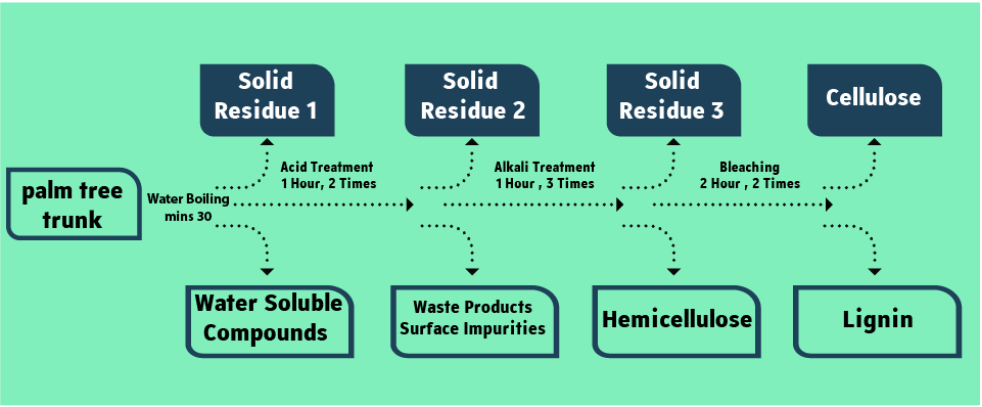


Fig. 1: Scheme of the Cellulose extraction from Palm trunk

2.3 Synthesis of Palm/Polypyrrole Composites

Polypyrrole composites were made from in-situ oxidative polymerization Initially, 1.34 mL pyrrole monomer was added to 50 mL distilled water to get a 1 M solution. We transferred the solution into a 3-neck round bottom flask and stirred in ice bath for about 15 min at 3 °C in order to stabilize reaction conditions. Simultaneously, a solution of oxidizing agent was prepared by dissolving 8.33 g of the ferric chloride ($FeCl_3$) in 50 mL distilled water which is a 1 M aqueous solution.

The proportion of PPy in the composites was based on the dry weight of palm cellulose. For this reason, composite formulations with the PPy-to-cellulose weight ratios of 1:4 (25 wt% PPy), 1:2 (50 wt% PPy), 3:4 (75 wt% PPy), and 1:1 (100 wt% PPy) were prepared. All material weighing procedures were all performed using a four-digit analytical balance in a

nitrogen glove box to prevent moisture and oxygen from entering the box.

After that, the solution of pyrrole, solution of $FeCl_3$ and palm cellulose was added in the reaction flask while stirring at a temperature maintained at about 3 °C. The color changed from clear to dark black with a grainy texture, indicating the start of polymerization. Through 5 h of stirring and a 20 h delay, polymer growth and composite formation were completed.

Upon completion of the polymerization, the product was collected under vacuum filtration, washed thoroughly with distilled water to remove any leftover oxidant and by-products and dried. Ultimately, the composite that had dried was carefully ground to a fine powder and stored for membrane fabrication and characterization later.

2.4 Dialysis Process Using Cylindrical Membranes

A specially designed dialysis system was fabricated using two cylindrical membrane modules of 2.5 cm diameter and 1 cm thickness. Figure 2 illustrates the scheme of setup. The system was designed to mimic essential aspects of clinical hemodialysis, allowing for the selective removal of metabolic waste products and excess electrolytes under controlled dynamic conditions.

A motoroperated diaphragm pump driven the flow of both the dialysate and the simulated blood solution through the membrane modules. The operation of the system was at a constant flow rate, at 125 $mL \cdot min^{-1}$, in a closed-loop mode and 60 s transfer cycle. The membrane module and a fixed return line connected container A and container B so that the circulation was continuous. During each pumping cycle, nearly 125 mL solution will be taken from Container A through the membrane module into Container B while the return pipe was taking the fluid back to Container A. Thus, there was no need to change the containers manually and the system was continuous.

The measurements of sampling and concentration were done at cumulative operating times of 20, 40, 60, 80, 100 and 120 min. During the working of the membrane module the inlet pressure was maintained between 120–150 mmHg and monitored continuously. The diaphragm pump and the inline pressure wage were calibrated against a reference manometer using water, at room temperature, before each experimental run. The system was calibrated after removing all air. The pressure gauge was installed before the membrane module, and the connection was checked for leaks at all points.

The solution of artificial blood is designed to have a concentration of solutes higher than that of end-stage renal disease. The solution was found to contain urea (214 $mg \cdot dL^{-1}$), creatinine (12 $mg \cdot dL^{-1}$), potassium (6.0 $mg \cdot dL^{-1}$), sodium (145 $mg \cdot dL^{-1}$). The tubes acted as semi-permeable membranes to allow the diffusion of low-molecular-weight toxins such as urea and creatinine into the dialysate while retaining high-molecular-weight ones such as albumin (target concentration >350 $mg \cdot dL^{-1}$) in the blood compartment [17].

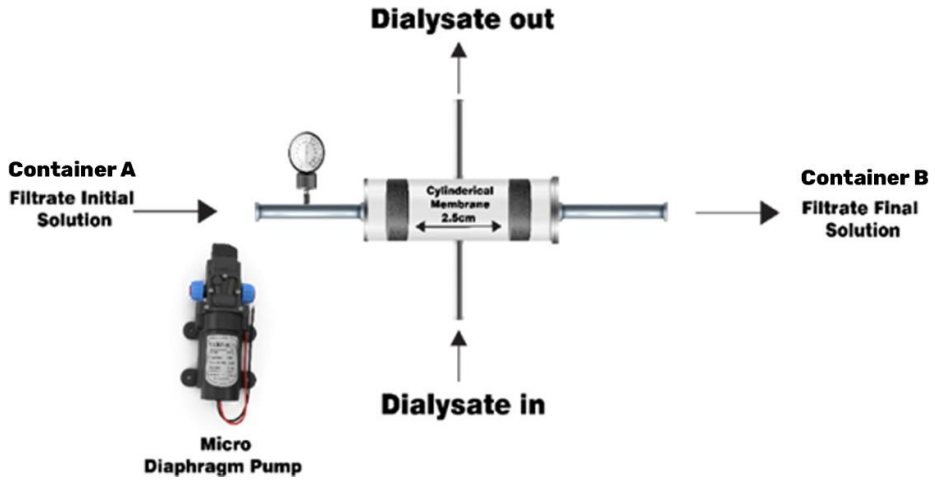


Fig.2: Schematic diagram of the experimental setup of the dialysis process.

2.5 Burst Pressure Measurement

The mechanical performance of cylindrical membrane materials is assessed using the burst-pressure measurement system illustrated in Figure 3. For the test, a membrane having diameter 2.5 cm and thickness 1 cm was subjected to internal pressure to observe mechanical failure. A motor-operated diaphragm pump created pressure control to ensure loading conditions were reproducible.

Throughout the testing process, a calibrated psi/MPa gauge was used to monitor the applied pressure in the system. The term burst pressure refers to the highest pressure just before the membrane ruptures. This measure allows assessing the membrane reliability and mechanical stability under useful operating conditions.

Under the environmental stresses acting on it, the membrane ultimately ruptured. A digital microscope camera was used to visually display the rupture event to validate the failure. Membrane samples tested (n = 1 per composition) for every composition mode of PPy (25%, 50%, 75% and 100%). Since burst testing is destructive in nature, a single membrane was pressurized till failure once using constant pressure. The module inlet pressure values were measured and the burst pressures quoted are for single measurements for a given composition.

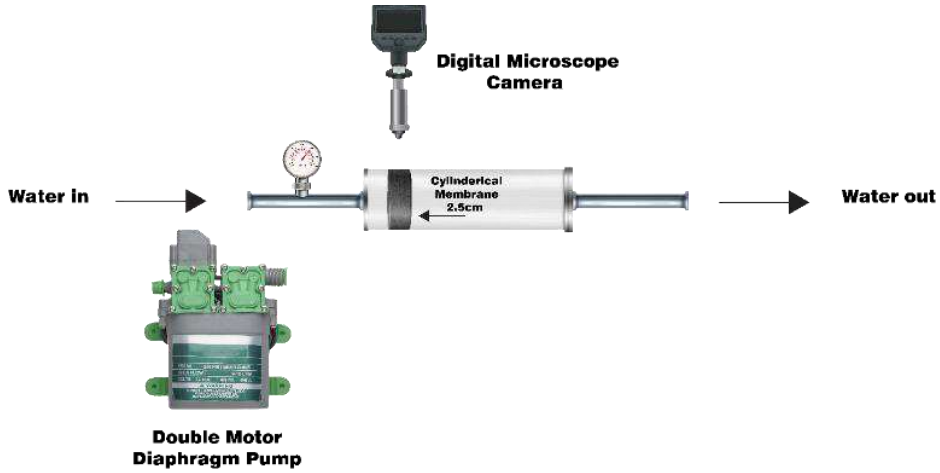


Fig. 3: Schematic diagram of the burst pressure measurement setup.

2.6 Characterization Instruments

The synthesized membranes were analyzed to outline their structural, chemical, and surface characteristics through various analysis techniques. We used the field-emission scanning electron microscope (FESEM, MIRA III, Tescan) along with energy-dispersive X-ray spectroscopy (EDX) to analyze the elemental composition and surface morphology. This study allowed us to observe not only the surface texture but also the distribution of elements on the membrane surface.

The chemical interactions of palm cellulose and polypyrrole were identified and confirmed by Fourier transform infrared spectroscopy (FTIR 1800, Shimadzu), which provided the information of the vibration and bonding characteristics of the molecule. To investigate surface topography and nano pore-hole size, atomic force microscopy was used (Nanosurf, Switzerland, 2023). This analysis is essential for determining surface roughness, pore uniformity and overall nanoscale membrane morphology.

2.7 Surface Wettability

The contact angle with deionized water was measured under static conditions at room temperature. For all membrane samples the droplet deposited was absorbed within less than one second, resulting in no stable contact angle formation.

3 RESULTS

3.1 IR Spectroscopy

The chemical structure of the pure palm-derived cellulose and palm-derived cellulose/polypyrrole (Palm/PPy) composite membranes was investigated by FTIR spectroscopy as presented in Figure 4. As it can be seen in the FTIR spectrum of pure cellulose, a broad absorption band centered at 3373 cm^{-1} show up which attributed to O–H stretching vibrations. This band suggests strong hydrogen bonding within the cellulose network, including intermolecular hydrogen bonds. According to Alam et al. [18] and Kim et al. [19], the identity of the cellulose was noticed in AgNO3 cellulose complex formed.

The peak of absorption was detected at 2914 cm^{-1} which corresponded to the C–H stretching vibrations of the aliphatic CH_2 groups. It shows that the cellulose which agrees with the structure of cellulose [20]. Furthermore, the clearly visible peak at 1639 cm^{-1} is due to O–H bending vibrations of water, which is absorbed within hemicellulose of the cellulose, as reported by Hospodarova et al. [21]. The other signatures cellulose peaks which are at 1428 cm^{-1} (CH_2 bending);1334 cm^{-1} (C–H and O–H bending);1027 cm^{-1} (C–O stretching of polysaccharide back bone) and 896 cm^{-1}, which is due to β-glycosidic linkages. All these features confirm that it has a polymeric cellulose structure.

After polymerization of polypyrrole, a distinct spectral change is observed, indicating Palm/PPy composite formation. The broad O–H stretching band is reduced due to PPy incorporation that partially disrupts the hydrogen bonding. Two new absorption bands appear at 1546 cm^{-1} and 1460 cm^{-1} which are attributed to C=C stretching in the pyrrole ring and C–N

stretching vibrations respectively. The features of polypyrrole in these bands were consistent with those stated by Rahman et al [22]. Additional PPy-related peaks appear at 1306 cm^{-1} (C–N bending), 1186 cm^{-1} (C–N stretching), and 1042 cm^{-1} (C–H in-plane deformation), further confirming the presence of PPy within the cellulose matrix. Moreover, a new band observed at 780 cm^{-1} corresponds to C–H out-of-plane bending and is commonly associated with polypyrrole polymerization in PPy-based materials [22].

Overall, these spectral changes demonstrate that, compared with pure cellulose, the Palm/PPy composite exhibits new chemical interactions and modifications in the polymer backbone, confirming successful incorporation of polypyrrole into the palm-derived cellulose structure.

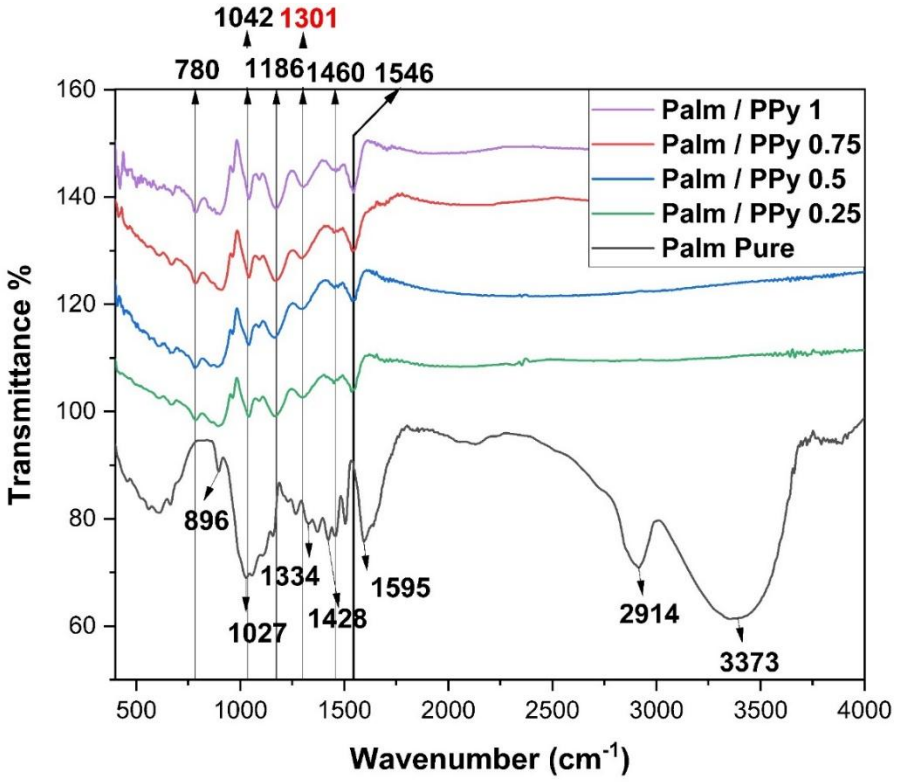


Fig. 4: shows the FTIR spectra of palm/PPy composites in the ratio of (palm/PPy 1, 0.75, 0.5, 0.25) and pure palm.

3.2 Energy Dispersive X-ray Spectroscopy

Elemental analysis of palm-derived cellulose composites containing 25% and 100% polypyrrole (PPy) was carried out using energy-dispersive X-ray spectroscopy (EDX), as shown in Figures 5a and 5b. Both composite membranes exhibit a high carbon content, with carbon accounting for approximately 70% of mass. This observation is expected and can be attributed to the carbon-rich nature of both the cellulose fibers and the polypyrrole phase [23]. The EDX spectra show nitrogen peaks which indicates the successful incorporation of PPy into the cellulose matrix. These nitrogen peaks are obtained from the polymerization of pyrrole [24]. Moreover, both samples were detected with chlorine. It is due to the use of chloride-based dopants (such as ferric chloride), which are generally used for PPy synthesis and are known to enhance the electrical conductivity of PPy-based composites [25]. Importantly, no residues of iron (Fe) were observed indicating complete removal of oxidant by washing after synthesis.

Si signals were only present in the 25% PPy composite, which potentially arises from residual silica-based impurities related to the cellulose source or sample handling. In both

samples, the peaks of gold (Au) are due to the sputter-coating process. They do not reflect the genuine composition of the membranes. The comparatively higher nitrogen signal observed in the 25% PPy composite relative to the 100% PPy sample can be explained by the surface-sensitive nature of EDX analysis. Variations in gold coating thickness and local surface morphology can attenuate the detected nitrogen signal, particularly for higher PPy loadings. For this reason, EDX results are interpreted qualitatively to confirm the presence of nitrogen from PPy and chlorine dopants. Quantitative composition trends are instead based on the defined formulation ratios and are further supported by FTIR analysis.

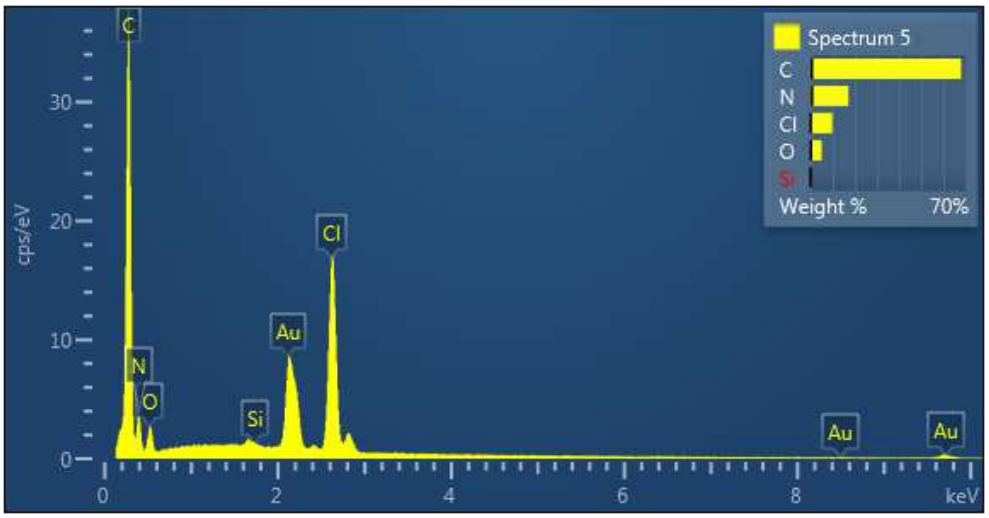


Fig. 5a: : EDX spectrum showing the elemental analysis of Palm / PPy 25%

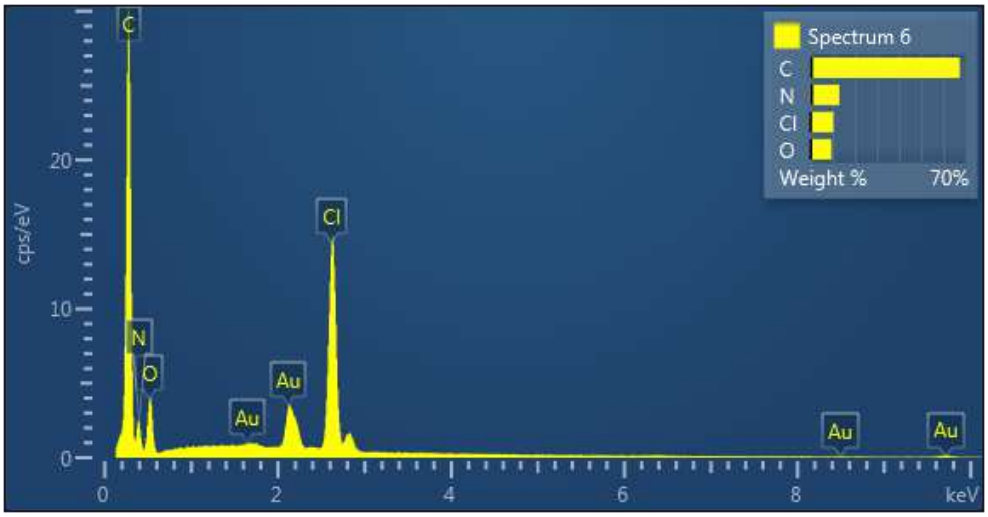


Fig. 5b: : EDX spectrum showing the elemental analysis of Palm / PPy 100%

3.3 FE-SEM Analysis

The surface morphology of palm-derived cellulose/polypyrrole (PPy) composite membranes

with 25% and 100% PPy loadings was examined using field-emission scanning electron microscopy (FESEM), as shown in Figure 6. Structural differences are clearly seen in micrographs as PPy content increases.

The surface of the composite with 25% PPy is marked by larger particles and has an average particle size of 46 nm. Unlike the other membrane, the membrane containing 100% PPy has a finer and compact morphology with smaller particles of size 25 nm. The reduction of particle size is due to the greater PPy deposition which increased the density of nucleation sites which restricts the growth of the particle owing to physical spatial limitation during the polymerization process.

Similar trends were reported on similar cellulose-based polypyrrole composites. The increase in PPy or polypyrrole concentration results in the deposition of more uniform surface structures or nanoparticles. In addition, it also reduces the spacing between the particles. A certain kind of morphological refinement which is the case here is known to help improve mechanical strength and electrical conductivity in such composites containing PPy [26–29].

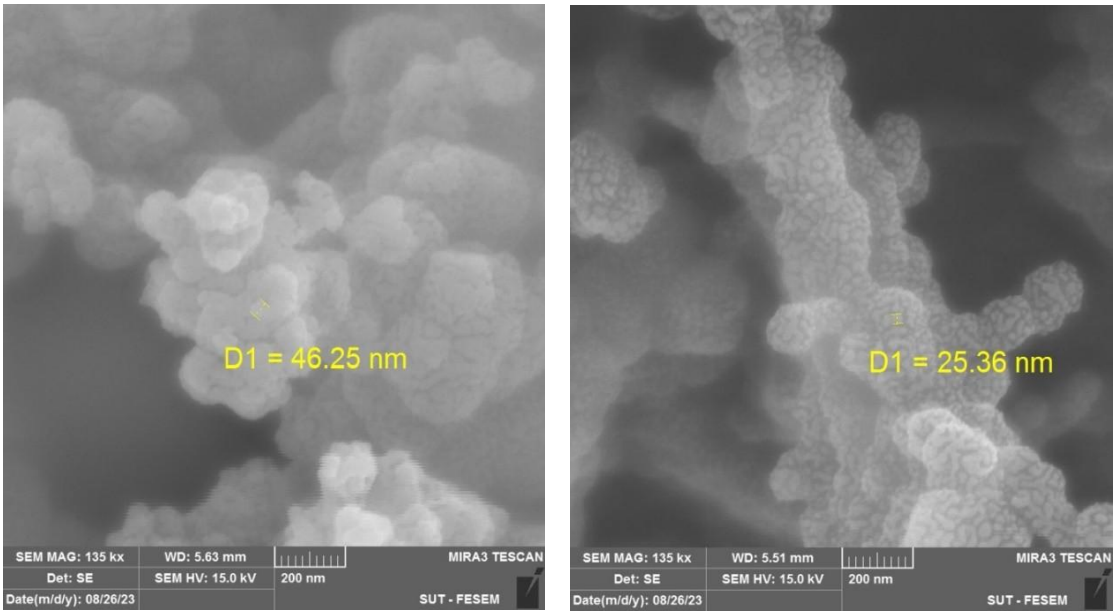


Fig. 6: SEM images of Palm-Derived Cellulose / PPy nanocomposites: (1) Palm / PPy 25% (2) Palm / PPy 100%

3.4 AFM Analysis

Atomic force microscopy (AFM) was performed on polypropylene/polypyrrole (PPy) composite membranes to characterize their surface morphology and pore structure. In figure 7 you can see a 3D surface and a 2D height map obtained from the same scan. The nanoscale surface features are highlighted through the AFM images; with the image, one can get direct information about the pore distribution and the depth of the pores on the membrane surface.

The analysis of the AFM data shows that the pores diameter of the composite membranes ranges from 9.5 nm to 21.5 nm with an average value of ~16.0 nm. The mean pore depth was found to be 12.4 nm with pore depth distribution in the range of 7.5 to 18.0 nm. The values of indicate the pore structure is well developed on a nanoscale. As presented in Table 1 and Table 2, the detailed quantitative descriptors, such as void volume, pore coverage and particle density. The observed pore morphology presents a more or less uniform distribution of nanoscale pores on the membrane. A structure of this type is in agreement with the low-flux dialysis operation where the selective transport of small solutes is favoured but larger

macromolecules passage is effectively barred [32].

Through suitable choice of substrate and synthesis condition, palm-derived cellulose/PPy composite membrane's surface morphology and porosity can be tailored effectively as demonstrated. It is important to tailor the membrane for unique performance needs for dialysis.Overall, these results demonstrate that the surface morphology and porosity of palm-derived cellulose/PPy composite membranes can be effectively tailored through appropriate substrate selection and synthesis conditions. This tunability is essential for meeting specific performance requirements in dialysis membrane applications.

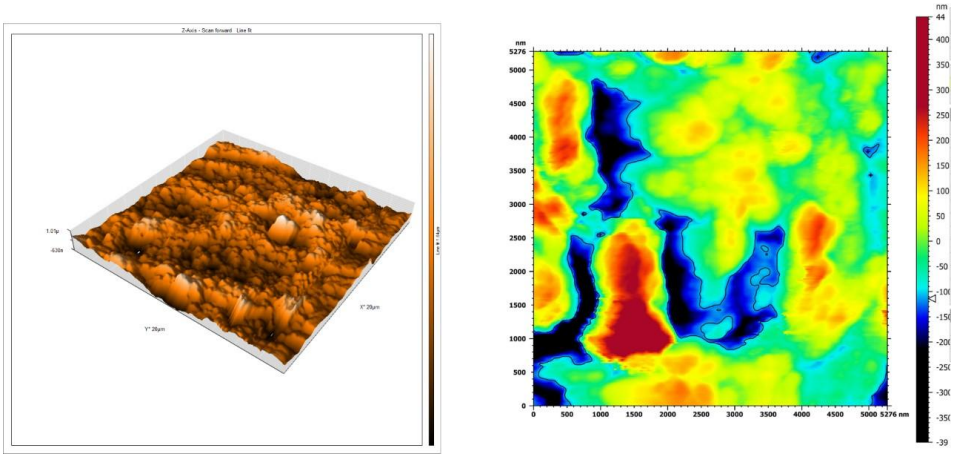


Fig. 7: AFM topography of the palm-cellulose/PPy membrane which contains 3D surface rendering of the scanned area and corresponding 2D height map with color bar innanometres.

Table 1: Individual pore measurements from the AFM map in Figure 7: mean diameter, void volume, and depth for each detected pore.

Pore ID	Mean diameter (nm)	Void volume (nm^3)	Mean depth (nm)
1	14.5	1600.2	11.5
2	18.5	3331.7	14.5
3	9.5	449.9	7.5
4	20.0	4188.8	16.0
5	12.5	1022.6	9.0
6	10.0	523.6	8.0
7	21.5	5594.8	18.0
8	16.5	2350.2	13.0
9	19.0	3435.6	15.0
10	13.0	1150.3	10.0
11	15.5	1954.8	12.0
12	17.5	2811.2	14.0

Table 2: Global pore statistics from the same AFM map: mean, minimum, and maximum values for diameter, void volume, and depth.

Metric	Mean	Min	Max	Units
Pore diameter	16.0	9.5	21.5	nm
Void volume	2851.5	449.9	5594.8	nm^3
Pore depth	12.4	7.5	18.0	nm

3.4 Uremic Toxins Filtration Rate

Palm Palm-derived cellulose–polypyrrole (PPy) composite membranes containing 25%, 75%, and 100% PPy were evaluated for uremic-toxin removal under simulated dialysis conditions. Concentrations of albumin, sodium, potassium, creatinine, and urea were monitored at cumulative operation times of 20, 40, 60, 80, 100, and 120 min. The experiments were conducted under dynamic, non-blood circulation using five consecutive 60-s pumping cycles. The reservoir volume was maintained at 125 mL, and the inlet pressure of the membrane module was controlled within the range of 120–150 mmHg. The concentration profiles are shown in Figure 8a (25% PPy), Figure 8b (75% PPy) and Figure 8c (100% PPy).

A consistent clearance trend was observed at all sampling times. The highest removal efficiencies of urea, creatinine, potassium, and sodium were obtained with the membrane containing 100% PPy. The second-best removal performances were obtained with the membrane composed of 75% PPy. Finally, the membrane possessing 25% PPy had the lowest removal efficiencies for these solutes. Narrow but big sodium and potassium were the quickest to drop off followed closely by creatinine and urea. This behavior is consistent with size-selective transport mechanisms operating under the condition of flow and pressure applied. On the other hand, albumin concentrations did not change significantly for all membranes. So, the macromolecule was effectively retained.

The 100% PPy membrane performed superiorly it is an advantageous feature in composites for diverse application purposes. The palm-fiber network contains polypyrrole to produce pores of 9.5 – 21.5 nm size. Moreover, a rapid uptake of water was observed, and no stable static contact angle could be measured, confirming the highly hydrophilic and porous nature of the membrane. In combination, these features allow small solutes to be transported efficiently, while bigger proteins cannot pass through under dialysis like flow conditions.

The findings have also been reported by earlier studies such as Azhar et al. [31], which discussed how polymer-modified membranes, like polyvinyl alcohol composites, improved the removal of uremic toxins while retaining proteins by optimizing porosity and permeability. The present study shown a similar trend as the PPy content increases from 25% to 100%. A higher PPy loading increases the capacity for adsorption and transport pathways and facilitates faster removal of toxin. Thus, the best overall performance is found in the 100% PPy membrane while the 75% PPy membrane improves significantly over the 25% PPy membrane. The 25% PPy membrane shows poor performance due to less PPy content.

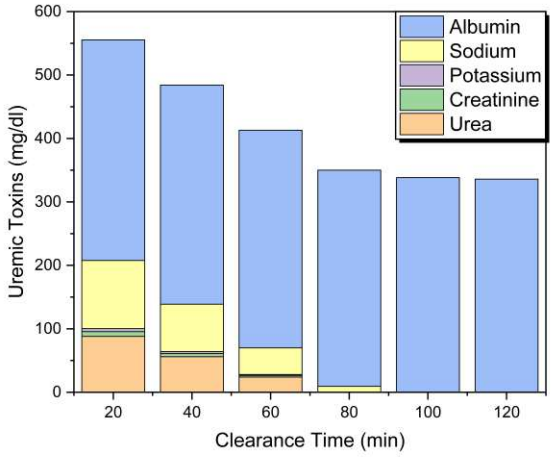


Fig. 8a: Uremic toxin concentrations (mg/dL) from 20 to 120 minutes for Palm-Derived Cellulose / PPy 25% nanocomposites

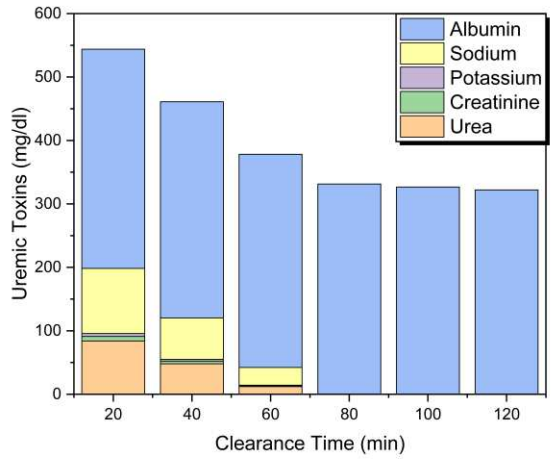


Fig. 8b: Uremic toxin concentrations (mg/dL) from 20 to 120 minutes for Palm-Derived Cellulose / PPy 75% nanocomposites

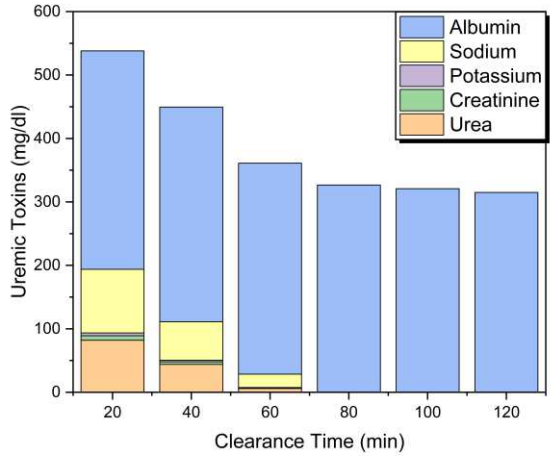


Fig. 8c: Uremic toxin concentrations (mg/dL) from 20 to 120 minutes for Palm-Derived Cellulose / PPy 100% nanocomposites

3.5 Burst Pressure Measurement

The link between the polypyrrole (PPy) content and the burst pressure of palm cellulose/PPy composite membranes is illustrated in Figure 9. The more PPy was loaded, the better the resistance to failure due to pressure. Increasing the PPy content from 25% to 100% improves the membrane mechanical strength in a progressive manner.

Out of all the membrane containing 25% PPy has the lowest burst pressure which indicates that low PPy loading is not properly stabilized structuarally. When the PPy content is raised to 50% and subsequently to 75%, it can be seen that the burst strength increases steadily. It is suggested that the reinforcing effect of PPy laid down into the cellulose fibre network is responsible for the increase in burst strength. The composite membrane made of 100% PPy has the greatest burst pressure of 150 psi. This indicates that PPy is essential to mechanical stability.

Burst pressure determinations were done using one independent membrane specimen per composition (n=1). As the test is destructive in nature, each membrane was pressurized only once to failure with pressure continuously recorded at the module inlet. Thus, measured values correspond to a single measurement of each PPy loading.

Membranes for dialysis application should sustain the continuous pressure of a fluid without changing its selective permeability. As the PPy content increased, the burst pressure increased suggesting enhanced structural integrity, which implies that the membrane will not fail mechanically under the operating conditions making them suitable for hemodialysis. By modulating the loading of PPy, the mechanical strength composite membranes ensures a good balance of flexibility, porosity and filtration performance. According to Alexander et al. [32], similar strength under pressure at 160 psi has been recorded, corresponding to the performance in the study.

The transmembrane operating pressures of clinical hemodialysis are up to approximately 300 mmHg and bench-scale assessments are up to 500 mmHg [1]. The burst pressure of the 100% PPy membrane (around 7,760 mmHg, or 150 psi) exceeds both of those figures, meaning that there is a large mechanical safety margin present under laboratory conditions. As a reference, burst pressure is reported to be 69 psi for polysulfone dialyzers and 91 psi for optimized PVDF hollow-fiber membranes [2,3]. Thus, comparing with these values, the developed palm cellulose/PPy composite membranes have good mechanical robustness.

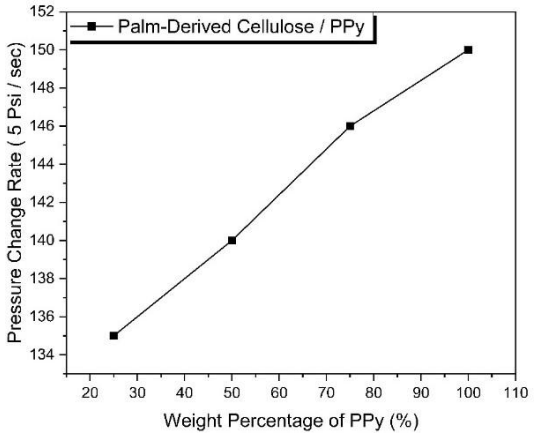


Fig. 9: Relationship between polypyrrole (PPy) content and burst pressure of palm-derived cellulose/PPy composite membranes.

4 CONCLUSIONS

This research centers on palm cellulose/polypyrrole (PPy) composite membranes for hemodialysis applications. Composite membranes were made from cellulose sourced from waste Iraqi date-palm trunks containing different levels of PPy. The evaluation of the filtration performance was done using a diaphragm pump under dynamic flow conditions to simulate the pressure conditions of the dialysis circuit.

A limitation of this study is that the performance of the membranes was assessed using simulated dialysate solutions rather than whole blood. Furthermore, the lack of investigation into long-term stability and biocompatibility limits direct translation into clinical settings. It needs further investigation before becoming useful in medicine.

In spite of these limitations, this study conclusively shows that palm cellulose/PPy composites have the potential to be used as a dialysis membrane material. For the first time, it has been systematically demonstrated the effect of PPy content on both filtration efficiency and mechanical strength. The use of diaphragm pump to mimick dialysis-like pressure conditions enhances the practical relevance of the experimental approach.

The findings reveal that higher PPy content considerably improves membrane mechanical stability. The membrane that was 100% PPy was able to achieve a burst pressure of 150 psi while simultaneously maintaining high efficiencies for the removal of uremic toxins and albumin retention. The membranes were confirmed to feature nanoscale porosity that is applicable for size-selective filtration, or dialysis.

Overall, cellulose/PPy composite membranes derived from palm had a great potential as dialysis membranes. There are plenty of raw materials that are locally available in Iraq to manufacture membrane materials instead of importing them. Future work will concentrate on optimizing the PPy content, enhancing the biocompatibility, and assessing the membrane performance in long-term and clinical scenario evaluations.

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Contribution of Authors Statement.

The research design study was conceived by M. A. S. who performed the experimental work, collected data, performed the analysis, prepared results, and wrote the main manuscript text as part of his PhD research project. S. M. H. provided the academic supervision, enhancement of study design, guidance on data interpretation and critical revision of the manuscript for important intellectual content.

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