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Cellulose Acetate Membranes from Agricultural Waste: Synthesis, Properties, and Sustainable Applications

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Abstract

Cellulose acetate membranes made from agricultural waste are being researched as a sustainable and adaptable filtering and separation option. This review paper gives a thorough examination of cellulose acetate membranes, with a particular emphasis on their manufacturing from agricultural waste sources such as sugarcane bagasse, coconut fibres, rice husk, cotton waste, wheat straw, and pineapple leaf. Utilising these waste products has several advantages, including waste valorization, decreased environmental impact, and cost-effectiveness. The review discusses the extraction methods, chemical changes, and characterisation procedures used in the conversion of agricultural waste to cellulose acetate. The unique features and benefits of cellulose acetate membranes made from agricultural waste sources are investigated, as well as the most recent advances in membrane technology. The paper goes on to examine the filtration and separation methods used by cellulose acetate membranes. This detailed research gives significant insights into the use of agricultural waste in the development of sustainable cellulose acetate membranes, promoting innovation and proposing possible applications in a variety of sectors.

Keywords: Cellulose acetate membrane, agricultural waste, synthesis parameter, extraction

1. Introduction

Due to their outstanding qualities and wide uses in different separation and filtering processes, cellulose acetate membranes have received a lot of attention in recent years. They have various advantages, such as being renewable and sustainable, having great biocompatibility, having high mechanical strength, chemical stability, and thermal resistance. [1] These membranes are simple to make and modify [2] in order to acquire desired qualities such as pore size, surface characteristics, and selectivity. [3] Cellulose acetate membranes are well-suited for a wide range of separation and filtering applications due to their flexibility and environmental friendliness. [4][5]

Add to this the advantage that cellulose acetate has in sustainability, as the cellulose required to synthesise the membrane can be obtained from a variety of agricultural wastes and discarded biomass material, often rich in cellulose. Saiful et. al. [6] used Palm Oil Empty Fruit Bunch waste due to its high cellulose content of 65%. Shbib et. al. [7] used cotton wastes from spinning. We also see other waste materials being converted into cellulose for cellulose acetate membrane synthesis in work from Widyaningsih et. al. [8] (coconut sap), Suhartini et. al. [9] (rice husk), Amaral et. al. [10] (coconut shells), Thi To Nu et. al. [11] (sugarcane bagasse) etc.

This review paper seeks to offer an overview of the synthesis techniques, characteristics, and uses of agricultural waste-derived cellulose acetate membranes, highlighting current advances and future prospects in this interesting topic.

Agricultural waste created by farming operations and agro-industrial processes presents disposal and environmental issues. However, the utilisation of agricultural waste as a feedstock for the manufacturing of cellulose acetate gives a potential for sustainable resource utilisation. Sugarcane bagasse [12][13][14], rice straw [15][16][17], wheat straw [18][19][20], coconut fibres [21][22], and maize husks [23], for example, are plentiful and renewable sources of cellulose.

To get high-purity cellulose fibres, cellulose must be extracted and modified from agricultural waste in a number of stages. Pretreatment, delignification, and purification procedures are used to eliminate non-cellulosic components and increase cellulose accessibility. [25] Alkalization, bleaching, and acetylation can be used to adjust the characteristics of cellulose generated from agricultural waste for cellulose acetate synthesis. [26]

The acetylation technique is used to create cellulose acetate from agricultural waste-derived cellulose. Acetyl groups are placed into the hydroxyl groups of cellulose. To generate cellulose acetate membranes with desirable qualities, many acetylation procedures, including solution, suspension, and heterogeneous processes, have been investigated. These synthesis processes' compatibility with agricultural waste-derived cellulose, as well as their influence on the final membrane characteristics, are critical concerns. [27]

Cellulose acetate membranes made from agricultural waste have distinct features due to the source material. Mechanical strength, thermal stability, hydrophilicity, permeability, and separation performance are among these qualities. The peculiarities of agricultural waste-derived cellulose impact the structural, morphological, and transport aspects of cellulose acetate membranes. [28]

The use of agricultural waste-derived cellulose acetate membranes provides long-term applications in a variety of sectors. These membranes may be used efficiently in water treatment, wastewater treatment [29, 30], gas separation [31], and biomedical applications [32]. In each application area, the benefits and drawbacks of employing agricultural waste-derived cellulose acetate membranes will be highlighted.

2. Cellulose Acetate Membrane Materials

Agricultural waste has emerged as a significant and plentiful feedstock for the production of cellulose acetate membranes, providing a sustainable alternative to typical cellulose sources. Various agricultural leftovers, each with its own composition and features that impact the properties of the resultant membranes, can be used. [33]

Several typical procedures are involved in the conversion of agricultural waste products into cellulose acetate. First, the waste material is collected and processed to eliminate contaminants, such as sugarcane bagasse [12], coconut fibre [21], or maize husk [23]. The material is then subjected to a series of chemical treatments in order to extract the cellulose component and eliminate non-cellulosic components such as lignin and hemicellulose. This procedure frequently comprises processes such as alkaline extraction, bleaching, and purification. [15]

After obtaining the cellulose-rich material, it is acetylated via esterification processes. Acetic anhydride or acetic acid are commonly employed, coupled with a catalyst such as sulfuric acid, to introduce acetyl groups into the cellulose structure. [34] During the acetylation process, cellulose is converted into cellulose acetate, which is soluble in organic solvents and may be cast into membranes.

Here are some of the commonly used agricultural waste materials used as raw material for synthesis of cellulose acetate membranes.

2.1 Sugarcane Bagasse

Sugarcane bagasse is a fibrous byproduct produced during the sugarcane crushing process. It's made up of cellulose (40-45%), hemicellulose (20-25%), lignin (20-25%) [35], and other minor ingredients. To make cellulose acetate for membrane manufacture, the cellulose component is removed and processed. Sugarcane bagasse's high cellulose content adds to the superior mechanical strength and thermal stability of the resultant cellulose acetate membranes. [13, 14, 36] Bagasse-derived membranes' hydrophilicity and surface properties are influenced by the presence of lignin and hemicellulose, making them appropriate for applications such as water purification, ultrafiltration, and reverse osmosis. Furthermore, because sugarcane bagasse is a plentiful agricultural waste material, it is an appealing and cost-effective feedstock for cellulose acetate membrane production. [36]

2.2 Cotton Spinning Fibres

Cotton fibres are a commonly accessible and sustainable agricultural waste material obtained from the cotton plant. Because they are mostly cellulose, they are appropriate for cellulose extraction and subsequent acetylation to generate cellulose acetate. [37] Cotton fibre-based cellulose acetate membranes are very strong, thermally stable, and chemically resistant. [38] These membranes have a high porosity and have demonstrated potential performance in water treatment applications such as filtration and desalination. [39] Cotton fibres may be used as a source material for cellulose acetate membranes since they are a commonly available and sustainable waste resource. [40] Cotton stalk may also be used as a source material, making cotton overall a solid option for membrane synthesis. [41]

2.3 Rice Straw

Rice straw is a byproduct of rice production that contains cellulose (35-45%), hemicellulose (25-35%), lignin (15-25%), and silica (10-20%). [33, 42] For membrane manufacture, the cellulose component recovered from rice straw can be chemically converted into cellulose acetate. [15, 25, 43] Rice straw-based cellulose acetate membranes are mechanically strong, chemically resistant, and thermally stable. [16, 17, 44] The inclusion of silica in rice straw can provide the membranes special features such as increased hydrophilicity and fouling resistance. [17, 45] Because of their outstanding separation performance and low cost, rice straw-derived membranes have shown promise in applications such as wastewater treatment, gas separation, and desalination. [46]

2.4 Wheat Straw

Wheat straw is a type of agricultural debris that is produced after the harvesting of wheat crops. [33] It is made up of cellulose (35-45%), hemicellulose (20-30%), lignin (15-25%), and other ingredients. [47] Cellulose acetate membranes may be made by acetylating cellulose taken from wheat straw. Wheat straw-based membranes have good mechanical qualities, are thermally stable, and are chemically resistant. [48, 49] Hemicellulose in wheat straw can affect the pore structure and hydrophilicity of the resultant membranes. [50] Wheat straw-derived cellulose acetate membranes have been used in a variety of applications, including water purification, organic chemical separation, and gas separation. [51] Because of their low cost and wide availability, they are a viable alternative to synthetic membranes.

2.5 Coconut Fibres and Water

Coconut husks and fibres are agricultural byproducts of coconut flesh and oil extraction. They are made up of cellulose (30-45%), hemicellulose (15-25%), lignin (35-45%), and other ingredients. [21, 52, 53] Acetylation of the cellulose component taken from coconut husks and fibres results in cellulose acetate membranes. [22] These membranes are very porous, have exceptional mechanical strength, are thermally stable, and are chemically resistant. Lignin content in coconut-based membranes contributes to their hydrophobicity and selectivity during separation operations. [54] Because of their unique features and sustainability, coconut husk-based cellulose acetate membranes have been effectively used in applications such as wastewater treatment, desalination, and gas separation. [55] Other parts of the coconut fruit can be used in membrane synthesis, like coconut water, which was converted into nata de coco and then into cellulose acetate membranes by means of a bacterium *Acetobacter xylinium* by Khamwichit et. al. [56]. Nata de coco is also a popular choice for membrane synthesis. [57, 58, 59] It is a product of fermenting coconut water, which results in the production of bacterial cellulose. [60, 61]

2.6 Corn Husk

Corn cobs are the cylindrical middle component of the corn ear that is left over after the corn kernels have been harvested. They are made up of cellulose (35-45%), hemicellulose (20-30%), lignin (20-30%), and other substances. [23] Cellulose acetate may be made by acetylating cellulose taken from maize cobs. [62, 63] Corn cob-based cellulose acetate membranes are mechanically strong, thermally stable, and chemically resistant. [64] Because of their biocompatibility and selective separation characteristics, these membranes have proved uses in the water treatment [65], food processing [63, 66], and pharmaceutical sectors. [67, 68, 69]

2.7 Pineapple Leaf Fibres

Pineapple leaf fibres are agricultural waste materials derived from the pineapple plant after the fruit has been extracted. They are made up of cellulose (50-70%), hemicellulose (10-20%), lignin (10-20%), and other ingredients. [70] The cellulose component recovered from pineapple leaf fibres may be acetylated to form cellulose acetate, which can be used to make membranes. The cellulose acetate membranes made from pineapple leaf fibres have high mechanical qualities, chemical resistance, and biocompatibility. These membranes have demonstrated promise in a variety of applications, including water filtration, wastewater treatment, and biomedical engineering. Membranes made from pineapple leaf fibres have been used to remove heavy metal ions via adsorption in research by Daochalermwong et. al. [71]

Table 2.1 discusses the differences in properties and unique features of each waste material in synthesising cellulose as well as cellulose acetate.

Table 2.1: Cellulose and Cellulose Acetate Properties of various agricultural waste source materials.

Source Material	**Cellulose Properties**	**Cellulose Acetate Properties**
Sugarcane Bagasse	High cellulose content (40-50%)	Improved solubility in organic solvents
	High crystallinity	Reduced crystallinity
	High tensile strength	Decreased tensile strength
	Insoluble in most common solvents	Soluble in common organic solvents
	High thermal stability	Lower thermal stability
	Hydrophilic surface	Hydrophobic surface
Coconut Fibres	Moderate cellulose content (30-40%)	Enhanced solubility in organic solvents
	Lower crystallinity	Decreased crystallinity
	Good tensile strength	Reduced tensile strength
	Partial solubility in common solvents	Improved solubility in organic solvents
	Moderate thermal stability	Reduced thermal stability
	Hydrophilic surface	Hydrophobic surface
Rice Husk	Moderate cellulose content (30-40%)	Enhanced solubility in organic solvents
	Lower crystallinity	Decreased crystallinity
	Good tensile strength	Reduced tensile strength
	Partial solubility in common solvents	Improved solubility in organic solvents
	Moderate thermal stability	Reduced thermal stability
	Hydrophilic surface	Hydrophobic surface
Cotton Waste	High cellulose content (80-90%)	Improved solubility in organic solvents
	High crystallinity	Reduced crystallinity
	High tensile strength	Decreased tensile strength
	Insoluble in most common solvents	Soluble in common organic solvents

	High thermal stability	Lower thermal stability
	Hydrophilic surface	Hydrophobic surface
Wheat Straw	Moderate cellulose content (35-45%)	Enhanced solubility in organic solvents
	Lower crystallinity	Decreased crystallinity
	Good tensile strength	Reduced tensile strength
	Partial solubility in common solvents	Improved solubility in organic solvents
	Moderate thermal stability	Reduced thermal stability
	Hydrophilic surface	Hydrophobic surface
Pineapple Leaf	Moderate cellulose content (50-70%)	Enhanced solubility in organic solvents
	Lower crystallinity	Decreased crystallinity
	Good tensile strength	Reduced tensile strength
	Partial solubility in common solvents	Improved solubility in organic solvents
	Moderate thermal stability	Reduced thermal stability
	Hydrophilic surface	Hydrophobic surface

3. Fabrication of Membrane Setup

Several important procedures are involved in the production of cellulose acetate membranes to ensure their best performance and appropriateness for diverse applications in various domains and industries. The steps of the procedure are generally as follows:

1. Material Selection and Preparation: The principal material is cellulose acetate, which is generated from cellulose obtained through agricultural waste. The cellulose acetate flakes or pellets are next treated and purified to create high-quality cellulose acetate flakes or pellets. [33]
2. Preparation of Polymer Solutions: Cellulose acetate is dissolved in a suitable solvent, which is often a combination of acetone and a non-solvent such as water or ethanol. The concentration and viscosity of the solution are carefully controlled to attain the appropriate membrane characteristics. [1, 2, 72]

3. Membrane Casting: Using different processes such as phase inversion, spin coating, or knife coating, the cellulose acetate solution is cast onto a support material or substrate. The casting process entails uniformly spreading the solution across the substrate to generate a thin layer. [4, 5]
4. Solvent Evaporation: After casting, the solvent is allowed to slowly evaporate, allowing a porous structure to develop within the membrane. To guarantee optimum pore creation and distribution, the evaporation rate, temperature, and humidity are all regulated. [4, 5]
5. Membrane Treatment and Modification: A fabricated cellulose acetate membrane may be subjected to further treatments in order to improve performance and adjust its characteristics to specific applications. Surface modifications such as cross-linking, grafting, or functionalization can be used to increase stability, selectivity, or environmental compatibility. [2, 3, 4, 5]
6. Membrane Characterization: Various procedures are used to examine the pore size, thickness, morphology, porosity, mechanical strength, and surface characteristics of the manufactured membranes. These characterization procedures assure the membranes' quality and uniformity for their intended uses. [1, 2]

Based on the required qualities and application requirements, the cellulose acetate membrane production process may be further customised and optimised. Because of this versatility, membranes with precise pore sizes, surface functions, and mechanical characteristics suited for filtration, separation, biomedical engineering, sensing, and other sectors may be produced.

Some of the areas and fields where cellulose acetate membranes can be used are:

3.1 Filtration and Separation

Cellulose acetate membranes have received much praise for their superior filtering and separation properties. Controlling membrane production parameters precisely enables for customisation of pore size and distribution, resulting in membranes with particular filtering capabilities. These membranes are frequently employed in water treatment techniques such as microfiltration, ultrafiltration, desalination, and reverse osmosis to remove suspended particles, colloids, bacteria, and viruses. [2, 5, 27, 30, 31, 73, 74, 75, 76]

To remove suspended particles and particulate matter from liquids in microfiltration applications, cellulose acetate membranes with higher pore sizes (usually >0.1µm) are used. These membranes are used in sectors like food and beverage, pharmaceuticals, and biotechnology to clarify liquids and remove macromolecules. [77, 78, 79]

Narrower particles, macromolecules, and proteins can be separated using ultrafiltration, which operates at a narrower pore size range (0.001-0.1µm). In protein concentration, fractionation, and purification operations, cellulose acetate membranes with proper pore diameters are used. They are also used to remove organic chemicals, heavy metals, and other contaminants from wastewater. [71, 80, 81, 82, 83, 84]

RO membranes with even lower hole diameters (<0.001µm) allow the separation of dissolved solutes and salts from water. Cellulose acetate membranes modified with thin-film composite layers reject salts with great efficiency and produce efficient desalination solutions. RO membranes are used in both industrial and home saltwater desalination, brackish water treatment, and water purification. [6, 8, 85, 86, 87, 88, 89]

3.2 Biomedical Engineering

Cellulose acetate membranes have several uses in biomedical engineering due to their unique features that make them appropriate for a wide range of applications. Because of their biocompatibility, porosity, and adjustable properties, they can be used in drug delivery systems, tissue engineering scaffolds, and wound healing applications. [25, 32, 90, 91, 92, 93, 94]

Cellulose acetate membranes are used in medication delivery systems as carriers for regulated and sustained drug release. The release rate and duration of medications may be precisely regulated by changing membrane parameters such as pore size, thickness, and surface functionalization. These membranes allow for localised medication distribution, which improves treatment efficacy and decreases potential negative effects. [69, 95, 96, 97]

Tissue engineering also makes use of cellulose acetate membranes as scaffolds. Their porosity and mechanical characteristics are similar to that of the extracellular matrix, making them an ideal habitat for cell adhesion, proliferation, and differentiation. These membranes enhance tissue regeneration and integration by changing the surface chemistry and adding bioactive molecules such as growth factors or peptides. [91, 92, 98, 99]

Wound healing treatments use cellulose acetate membranes as dressings to produce a moist environment that speeds up healing. The membranes protect the wound site, prevent infection, and allow for the exchange of gases and moisture. Their water vapour permeability supports appropriate wound hydration, facilitating cell migration, angiogenesis, and granulation tissue development. [25, 93, 94, 100, 101]

3.3 Membrane-Based Sensors and Biosensors

Membranes made of cellulose acetate are adaptable substrates for the creation of membrane-based sensors and biosensors. These instruments are capable of detecting and quantifying a wide range of analytes, including biological molecules, gases, ions, and contaminants, with excellent sensitivity and selectivity. [102, 103]

Specific receptors, enzymes, antibodies, or nanoparticles can be added to the surface of cellulose acetate membranes to provide functionalized interfaces for target analyte detection. Interactions between the analyte and the changed membrane surface provide detectable signals such as changes in electrical conductivity, optical characteristics, or mass. [104, 105]

Environmental monitoring, food safety, and medical diagnostics all benefit from cellulose acetate-based biosensors. They are used in environmental monitoring to identify contaminants, heavy metals, and hazardous chemicals in water or air samples. These biosensors enable the quick and sensitive detection of pollutants, allergies, and foodborne pathogens in the food business. In medical diagnostics, cellulose acetate-based biosensors allow for the detection of biomarkers, illnesses, or infections while also allowing for point-of-care testing and real-time monitoring. [106, 107]

Because of the flexibility of cellulose acetate membranes, numerous transduction mechanisms, such as electrochemical, optical, and piezoelectric, may be included, allowing for multiplexed sensing, miniaturisation, and integration into portable devices. [108, 109]

The use of cellulose acetate membranes as platforms for membrane-based sensors and biosensors has important benefits such as simplicity, adaptability, and cost-effectiveness, making them viable solutions in a variety of disciplines that need sensitive and selective detection capabilities.

Advancements in Cellulose Acetate Membranes

Significant advances in the field of cellulose acetate membranes have been made in recent years, propelling research towards higher performance, improved characteristics, and broader applications. Researchers are concentrating their efforts in many important areas in order to better investigate and develop cellulose acetate membranes.

One area of progress is the alteration of cellulose acetate membranes to improve selectivity and permeability. Tong Li et al. [110] synthesised MIL-53(Fe)@γ-Al_2O_3 nanocomposites and merged them with a cellulose acetate membrane. This was used in forward osmosis applications in order to improve desalination performance. By modifying cellulose acetate membranes with clay and titania nanoparticles, Refaat et. al. [111] was able to achieve much more efficient removal of bovine serum albumin from water.

Wound healing solutions and accelerated healing techniques are a great field for cellulose acetate membranes to be utilised. Graça et. al [112] combined chitosan and reduced graphene oxide with hydrogel into polycaprolactone/cellulose acetate membrane to create an asymmetrical, antibacterial wound dressing. Altharti et. al. [113] modified the membranes with Ag_2O and ZnS nanocomposites, to reduce inflammation and heal skin wounds as a wound dressing.

Techniques such as polymer mixing, nanoparticle inclusion, and surface modification are being researched to increase separation efficiency and meet particular separation difficulties in sectors such as water treatment, gas separation, and food processing. Koriem et. al. [114] carried out polymer mixing further blended with nano sized metal organic framework (UiO-66 MOF) in their experiment, using cellulose acetate membranes integrated with polyvinylidene fluoride for reverse osmosis. Wibisono et. al. [115] mixed nanosolids from the *Olea europaea* plant into cellulose acetate membranes which aided to anti-biofoiling, utilisable for ultrafiltration.

Furthermore, researchers are investigating novel approaches for producing cellulose acetate membranes with customised structures and morphologies. Kramar et. al. [116] used solution blow spinning method which made cellulose acetate membranes with a hydrophobic and hydrophilic surface. Attari and Hausler [117] reinforced cellulose acetate with cellulose nanofibrils and cellulose nanocrystals. The modified membranes showed improved mechanical properties, with nanofibrils being the better choice of the two.

Thus, controlling the pore size, thickness, and surface features of the membrane is being investigated using techniques such as electrospinning, phase inversion, and layer-by-layer construction. These methods are intended to improve membrane performance in terms of flow, rejection [114], fouling resistance [115], and mechanical strength. [117] Orlando et. al. [118] helped remove toluene from air by using carbon electrospun composite cellulose acetate-TiO_2 membranes. Their experiment resulted in 45.5% removal of toluene from air, with a starting concentration of 22.5ppm. Dye removal is also turning out to be a popular field to employ cellulose acetate. Eltaweil et. al. [119] incorporated graphene oxide into cellulose acetate beads in order to remove methylene blue dye from water, preventing water pollution.

Future Scope

The future scope of cellulose acetate membranes has enormous potential for progress and innovation. The most recent studies and rising trends point to a number of fascinating areas for inquiry and development.

One important avenue for future study is to improve membrane performance using improved materials and production processes. To increase selectivity, permeability, and fouling resistance, nanomaterials such as carbon nanotubes, graphene, and metal-organic frameworks are being used. [3, 31, 59, 83, 85, 108, 110, 114, 119] Additionally, the development of innovative membrane architectures, such as mixed matrix membranes [4, 31, 88, 114] and thin-film composite membranes, offers potential for improving separation performance. Douna et. al. [120] blended ZnO nanorods in a cellulose acetate based mixed matrix membrane, which resulted in improved CO_2 permeability and reduced H_2 permeability.

Another area of interest is the development of sustainable and environmentally friendly cellulose acetate membranes. To improve membrane sustainability and decrease environmental effect, researchers are studying the use of renewable resources [88], biodegradable polymers [121], and bio-based additives. [115]

Furthermore, the creation of multifunctional cellulose acetate membranes is gaining popularity. These membranes may also include antibacterial capabilities [81, 83, 99], self-cleaning surfaces [122], and stimuli-responsive behaviour [123], allowing for novel applications in domains such as water purification [87, 110], biomedical engineering [112,123], and drug delivery systems. [69, 97, 124]

The combination of developing technologies with cellulose acetate membranes, such as membrane distillation [125], forward osmosis [6, 85, 86, 88, 89, 110] and membrane bioreactors [126, 127], opens up interesting possibilities for sophisticated separation processes with better efficiency and energy savings.

Moreover, the integration of computer modelling and experimental techniques will remain critical in the design and optimisation of cellulose acetate membranes. Predictive modelling and simulation approaches provide useful insights into the structure-property correlations of membranes, assisting in the creation of membranes with customised attributes and performance. [128, 129]

In general, the research of cutting-edge materials, environmentally friendly practises, multifunctionality, and integration with developing technologies are key to the future of cellulose acetate membranes. To fully utilise cellulose acetate membranes and open up new avenues for effective separation and filtration processes in a variety of industries, researchers, engineers, and industry stakeholders must continue to work together.

Conclusion

In conclusion, agricultural waste-derived cellulose acetate membranes provide a viable and promising option for filtration and separation operations. Utilising waste materials including sugarcane bagasse, coconut fibres, rice husk, cotton waste, wheat straw, and pineapple leaves demonstrates the possibility of waste valorization and the creation of environmentally friendly membranes.

These membranes exhibit advantageous qualities such mechanical toughness, thermal stability, chemical resistance, and the capacity for selective separation. The most recent developments emphasise inventive manufacturing methods, useful additives, and environmentally friendly production strategies.

The investigation of cutting-edge materials, multifunctionality, and integration with developing technologies are key to the future of cellulose acetate membranes. Overall, this review demonstrates the substantial advancements in cellulose acetate membrane research that have opened the door to cost-effective and sustainable solutions in a variety of fields and applications.

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