Cellulose Nanostructure-Based Membranes: Structure, Synthesis, and Applications

Amy Jose Kollannoor
Christ University
Varsha Lisa John
Christ University
Joshua Jose
Christ University
Rinu Thresia P. X.
Mahatma Gandhi University
Vinod T. P. (vinod.tp@christuniversity.in)
Christ University https://orcid.org/0000-0001-5815-5230

Research Article

Keywords: membrane, nanocellulose, regenerated nanocellulose, desalination

Posted Date: March 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1300095/v1

Abstract

Cellulose nanostructures and composite membranes incorporating nanoscale cellulose have gained attention due to their promising utility in various applications. Cellulose nanocomposites in the forms of aerogels, thin films, and nanopapers have been studied extensively. This review focuses on nanocomposite membranes of cellulose which find uses in desalination, sensing, electrical, and biomedical applications. The presence of abundant hydrogen bonds and easily functionalizable surfaces makes cellulose an appropriate material for the fabrication of membranes that can be leveraged for their adsorptive capabilities applicable to water treatment. Membranes of nanocellulose, their modifications by various reinforcements, augmentation of thermal stabilities, selectivity as sensors etc., are discussed in detail here along with pertinent physicochemical aspects. Regenerated cellulose which has different characteristics compared to natural cellulose, is also being discussed.

1. Introduction

Cellulose is an inexhaustible form of polymer suitable for potential applications in important areas such as healthcare, electronics, and photovoltaics (Trache et al. 2017; Eichhorn 2018; Raghav et al. 2021). Cellulose, when broken down into the nanometer dimensions, forms cellulose nanocrystals (CNCs), a highly crystalline form of nanocellulose (NC) (Trache et al. 2017). There has been a recent surge in research for sustainable and cost-efficient technology in the fields like water decontamination. Polymeric membranes dominate the current market, and these membranes are generally composed of inorganic and inorganic-organic hybrid materials (Tan et al. 2020). Incorporating cellulose either fully or partially into membranes enables membrane reinforcement due to the extraordinary mechanical and chemical properties of nanocellulose. Other non-cellulosic biomaterials like collagen and chitosan are also being studied for their use in membrane technology (Galiano et al. 2018). There has been an increasing demand for clean and efficient energy sources and fuel cells with polymer electrolyte membranes, where incorporation of cellulose has become significant (Muhmed et al. 2020).

Membranes and the study of osmotic phenomenon dates back to the 18th century. Nollet is credited with discovering the relation between osmotic phenomenon and semipermeable membranes (Lonsdale 1982). Graham performed more systematic studies to understand the diffusion of gases (Graham 1833). Earlier studies were primarily based on membranes derived from natural sources. Traube and coworkers first synthesized an artificial semipermeable membrane by using porous porcelain, which has cupric ferrocyanide precipitated on it (Mason 1991). Pfeffer (Liu 2019), Fick (Fick 1855), Van’t Hoff (van’t Hoff 1888), Nernst and Planck gave substantial contributions to developing various theories which accelerated the development of membrane and membrane technology (Strathmann 2006). The advent of the twentieth century saw a sudden shift in membrane technology in terms of synthesis methods and materials being used. The successful development of a working hemodialyzer in the mid-1900s paved the way for membranes to be used extensively in biomedical applications (Kolff et al. 2009). If membranes were initially developed for laboratory uses, they were soon adapted for industrial purposes. Studies incorporating nanocellulose into membrane material started in the early 1990’s (Mautner 2020).

Later, two approaches evolved for using nanocellulose in membranes,; (i) using a structure wholly made out of NC and (ii) a hybrid system in which NCs are integrated to a porous substrate. These membranes were used for water treatment, biomedical, and energy storage applications.

Cellulose nanostructures and membranes from cellulose nanostructures are a rapidly growing research area. An upward trend has been observed in the publication of research articles in the past 20 years (Fig. 1).

2. Structure, Classification, And Characterization Of Cellulose Nanostructures.

Cellulose is a biopolymer composed of D-glucopyranose ring units linked together by beta-1,4-glycosidic bonds (Heinze 2015). These units have a chair conformation. Glucose residues are the repeating unit of cellulose (French 2017). Each of the units have three reactive hydroxyl groups; one primary and two secondary groups (Kargarzadeh et al. 2017, Klemm et al. 2005) (Fig. 2). Cellulose contains both intramolecular and intermolecular hydrogen bonds, which influences its solubility. The cellulose chain has a reducing (a D-glucopyranose ring in equilibrium with the aldehyde group) and a non-reducing end (anomeric carbon linked by glycosidic bonds) (Heinze 2015). The degree of polymerization and polymeric chain length determines the cellulosic characteristics (Trache et al. 2020). The degree of polymerization (DP) can be up to 20,000 depending on the cellulose source (Klemm et al. 2018). There are mainly four types of cellulose crystals: Cellulose I, Cellulose II, Cellulose III, and Cellulose IV. The varying unit cell dimensions and the methods for synthesis also are different. The types, synthesis methods and unit cell dimensions are tabulated in Table 1.

Table 1
Cellulose crystal types, synthesis methods and their unit cell dimensions

Crystal type	Synthesis method	Unit cell and dimensions	ref.
Cellulose □	Natural sources like wood, straw, cotton, plant extracts	Triclinic P1 (a = 0.672 nm, b = 0.596 nm, c = 1.040 nm, α = 118.1°, β = 114.8°, γ = 80.4°) Monoclinic $P2_1$ (a = 0.778 nm, b = 0.820 nm, c = 1.038 nm, γ = 96.5°)	(Nishiyama et al. 2002, 2003)
Cellulose □	Chemical regeneration and mercerisation of natural cellulose	Monoclinic $P2_1$ (a = 0.810 nm, b = 0.903 nm, c = 1.031 nm, γ = 117.1°)	(Langan et al. 2001; Gong et al. 2017)
Cellulose □	Liquid ammonia treatment of cellulose □ and □	Monoclinic $P2_1$ (a = 0.445 nm, b = 0.764 nm, c = 1.036 nm, α = β = 90^0, γ = 106.96°)	(Wada et al. 2004; Wada et al. 2009)
Cellulose □	Heating cellulose □ with glycerol	Orthogonal (a = 0.803 nm, b = 0.813 nm, c = 1.034 nm)	(Gardiner and Sarko 1985)

2.1 Sources of Cellulose

Cellulose is found in plants, animals, algae, fungi and bacteria. It is the major structural component in plants, primarily found in combination with lignin, hemicellulose, pectin, and other substances. Various methods can be employed for the extraction of cellulose from different sources. Pretreatment, mechanical processing, and chemical hydrolysis are identified as critical steps for extracting cellulose (Khui et al. 2021). Once isolated, they can be modified and used for various applications (Table 2).

Table 2
Sources of cellulose with applications

Source	Species	Application	ref.
Wood	Teak	Removal of cationic dyes like methylene blue and malachite green	(Olivera et al. 2018)
	Acacia	-	(Taflick et al. 2017)
	Rubber	Polylactic acid (PLA) based composite films	(Ou et al. 2021)
	Pine	Production of polymer composites	(Ditzel et al. 2017)
Cane	Bamboo	Biodegradable composites	(Guimaraes et al. 2015)
	Sugarcane bagasse	Bio-nanocomposite films, tissue engineering scaffold synthesis, Polyvinyl alcohol (PVA) based films	(El Achaby et al. 2017; Lam et al. 2017; Pavalaydon et al. 2021)
Seed/ fruit	Cotton	Wound dressing, composite film fabrication	(Bhowmik et al. 2017), (Jiang et al. 2021)
	Coir	Polyvinyl alcohol (PVA) based films	(Pavalaydon et al. 2021)
	Banana peel	Bio-adsorbent for enhancing bio-sorption of dyes	(Abdelghaffar 2021)
	Oil palm	Cellulose membrane for dye waste water treatment	(Teow et al. 2020)
Straw **Leaf**	Rice	Supercapacitor, bioplastics	(Agustin et al. 2014; Gao et al. 2018; Kim et al. 2020)
	Wheat	Catalytic conversion to valuable products like Syringaldehyde and Vanillin	(Yu et al. 2021)
	Pineapple leaf	Biomedical applications	(Cherian et al. 2010)
	Carex meyeriana Kunth	Methylene blue adsorption	(Yang et al. 2017)
Bast	Flax	CNC films	(Csiszár and Nagy 2017)
	Coconut husk	Poly-vinyl alcohol based hydrogels	(Thinkohkaew et al. 2020)
	Kenaf	Drug delivery excipient for curcumin	(Zainuddin et al. 2017)
	Pistachio shells	Pickering agent	(Kasiri and Fathi 2018)

Source	Species	Application	ref.
Trunk/stem	Banana stem	Biodegradable cellulose films	(Ai et al. 2021)
	Okra	Removal and recovery of Cd and Pb ions	(I. A. Okoro and O. K. Amadi 2012)
	Cassava stem	Dye removal from water	(Obele et al. 2021)
Bacteria	*Komagataeibacter xylinus*	Wound dressings, food packaging	(Sampaio et al. 2016; dos Santos et al. 2018)
Algae	*Valonia ventricosa*	-	(Bourret et al. 1972)
	Valonia macrophysa	-	(Chanzy and Henrissat 1985)

Plant cellulose is elementary crystallites organized parallel to each other, joined into fibres by hydrogen bonding. The elementary fibril, which is the basic fibrillar unit of the cellulose chains, are about 100 nm in length. Microfibrils, which are elementary fibrils assembled as fibrillar bundles, have 10–30 nm widths. Fibers vary in their structure and morphology according to their source. Plant sources that are extensively studied include wood (Rashad et al. 2017; Sullivan et al. 2018; Keplinger et al. 2021), rice husk (Kalita et al. 2015; Basu et al. 2019; Shahi et al. 2021), flax (Tang et al. 2019), coconut husk (Chua et al. 2020), hemp (Padinjakkara et al. 2020), sisal (Mondragon et al. 2018) and kenaf (Oyekanmi et al. 2021). Cotton fibers are about 99% of cellulose, making them a rich source of cellulose.

Algae are good cellulosic sources. Among the wide range of algae, green algae are mostly preferred for cellulose extraction. Some examples of cellulose producing algae include *Valonia* (Zanchetta et al. 2021), *Micrasterias denticulate* (Hanley et al. 1997), *Micrasterias rotate* (Kim et al. 1996), *Cladophora* (Zhou et al. 2019), *Boerogesenia* (Kargarzadeh et al. 2017). Cellulose derived from algae are highly crystalline, especially those derived from *Valonia* or *Cladophora* (Ferraz et al. 2013).

Bacterial cellulose is a promising biopolymer source which, due to its highly crystalline nature, containing no lignin, pectin, hemicellulose, provide for a very pure material. Its diameter ranges from 20–100 nm and is a three-dimensional network of ultrafine cellulose fibrils (Manoukian et al. 2019). Some bacterial cellulose sources include *Komagataeibacter xylinus* (Ho Jin et al. 2019), one of the most prominent bacterial nanocellulose (BC) producers, belonging to the group of acetic acid bacteria (AAB) (dos Santos et al. 2018). The AAB group is an essential class as these are food-grade bacteria and are generally considered safe. Other group species include *Komagataeibacter hansenii* (Güzel and Akpınar 2020), *Komagataeibacter medellinensis* (Molina-Ramírez et al. 2020), *Komagataeibacter uvaceti* (Nascimento et al. 2021), *Komagataeibacter oboediens* (Taweecheep et al. 2019), *Komagataeibacter rhaeticus* (Semjonovs et al. 2017), *Komagataeibacter saccharivorans* (Gayathri and Srinikethan 2019) *and Komagataeibacter pomaceti* (Gorgieva and Trček 2019). The bacterial cellulose has a better water retention capacity when compared to plant cellulose, thereby allowing it to be used as a structural component in biomedical applications. Also, they are highly crystalline while retaining their moldability and flexibility. BNC does not exhibit antimicrobial activity on its own but, when integrated with other functional materials, can inhibit microbial growth (dos Santos et al. 2018). Tunicates, a kind of marine invertebrate sea animal, also produce cellulose in large quantities. The structure and properties of cellulose so created will differ depending on the species (George and Sabapathi 2015).

2.2 Regenerated cellulose

Regenerated cellulose is a type of material produced by converting natural cellulose to a soluble cellulosic derivative and then restoring it, usually into a fiber (e.g., rayon) or a film (e.g., cellophane) (Niaounakis 2017). High-purity cellulose is a requisite for the production of regenerated cellulose and cellulosic derivatives (Bajpai 2018). Regenerated cellulose is distinct from natural cellulose in its molecular weight, crystallinity and polymerization degree. The tensile strength and Young's modulus of regenerated cellulose nanofiber film is less than the usual CNF film. Therefore, using the latter is better for preparing nanocomposites (Zhai et al. 2021). Low thermal stability of the regenerated cellulose membrane (RCM) to treated cellulose microfibers (t-CMF) was observed, and was attributed to the low crystallinity of RCM (Mohamed et al. 2015). The RCM extracted from recycled newspapers is an excellent alternative to paper recycling. This was demonstrated by comparing the changes in electrical, mechanical, diffusive parameters of a highly swollen RCM modified with a dendritic molecule (thiol DAB dendrimer of generation 3) to the original regenerated cellulose (RC/4) membrane (Vázquez et al. 2015). Studies at different concentration levels for other electrolytes (NaCl, $CdCl_2$, $PbCl_2$) establish the use of these modified membranes for heavy metal wastewater treatment. Amine functionalized RCM exhibited good catalytic activity, indicating a favourable material for industrial catalysis (Wang et al. 2017).

2.3 Classification of various cellulose nanostructures

Cellulose nanomaterials are classified into two classes: i) nanostructured materials, which includes cellulose microcrystals and cellulose microfibrils, and ii) nanofibers, which consists of cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs) and bacterial nanocellulose (BNC) (Islam et al. 2014; Trache et al. 2020) (Fig. 3). The characteristics of each nanocellulose class depend on the origin of the cellulose, the isolation and preparation methods.

2.3.1 Cellulose nanofibrils (CNFs)

CNCs are usually rod-shaped or needle-like and have dimensions of 1–50 nm in width, and can be up to a few 100 nm in length (Fig. 4A). CNCs are highly crystalline, have a large surface area, and have excellent thermal stability and strength. There are several methods for isolating CNFs from the lignocellulosic material of plants. Lignin and hemicellulose are removed during the pre-treatment process. CNFs have a higher aspect ratio when compared to CNCs due to its large surface area and a considerable amount of hydroxyl groups on the surface, enabling modification. CNFs are much more useful in the production of thin films when compared to other cellulose derivatives as they possess high viscosity and yield stress. The three-dimensional framework enables its modification for various applications using nanoparticles like CQD's (Melvin Ng et al. 2020).

2.3.2 Bacterial nanocellulose (BNC)

BC has a twisted ribbon-like shape with a diameter ranging between 20 nm and 100 nm. BNC is similar to other kinds of nanocellulose, exhibiting higher purity, crystallinity and water holding capacity, resulting in enhanced thermal and mechanical strength. BNC majorly consists of pure crystalline cellulose Iα (Sampaio et al. 2016).

2.3.3 Cellulose nanocrystals (CNCs)

CNCs have a broad range of size distribution, differing mainly due to the different synthesis methods. They are generally rod-shaped and vary from nanometers to several micrometres, with diameters of about 5–30 nm with a low aspect ratio (Beck-Candanedo et al. 2005).

2.4 Morphology of cellulose-based membranes

BNC has a higher crystallinity compared to other natural cellulose sources like cotton, flax, hemp etc (Sardjono et al. 2019). The roughness, charge, hydrophilicity of the surfaces and type of membrane material determine the adhesion of microorganisms to membrane surfaces (Nguyen et al. 2012). Membranes used for water treatment applications work on the principle of adsorption. The adsorption capabilities of these membranes will depend on the nature and availability of the functional groups acting as adsorption sites. In contrast, the pore structure in the membranes will determine the accessibility to the active sites. Finger-like pore patterns and differing pore sizes were observed in the metalized nanocellulose composite- thin film composite membranes (MNC-TFC) (Cruz-Tato et al. 2017). The finger-like pore formation occurs in two steps, initiation and propagation. The first step occurs by rupturing the polymer surface and then extending towards the bottom to reach the side of the finger pore.

As most of the studies of nanocellulose membranes are directed towards water treatment applications, properties influencing water filtration is briefly discussed. Dry membrane strength, wet membrane strength, membrane pore size and membrane porosity are the four major properties to be considered while studying nanocellulose membranes (Sharma et al. 2020). Dry membrane strength deals with membrane integrity during handling. Wet membrane strength is crucial for filtration membranes, and wet strength resins and cross-linking agents can reinforce them. Generally, as pore size decreases, selectivity increases. For TEMPO-oxidised nanocellulose membranes, the average pore size has been found to be 0.47 nm, making it suitable for gas separation (Fukuzumi et al. 2011). Surface coating and templating methods can be used to control the pore sizes. For water treatment, reverse osmosis (RO) membranes with pore size in the range of 1–10 nm are used, which require high energy and high pressure (15–30 bars) (Karim et al. 2016). On the other hand, nanocellulose incorporation into RO membranes can lead to the formation of interconnected "direct water channels" formed between the fibers and the matrix of the barrier layer. This will cause the permeance to increase without compromising on the selectivity (Ma et al. 2012).

3. Preparation Of Nanocellulose-based Membranes

Typical methods for synthesizing composite membranes are interfacial polymerization, vacuum filtration, electrospinning, freeze-drying and phase inversion (Mbakop et al. 2021). Vacuum filtration, also called the 'nanopaper approach', is employed at the industry and laboratory levels to produce nanocellulose based membranes and nanopapers (Mautner et al. 2015). The freeze-drying method was used to fabricate nanoporous membranes to remove dyes from water (Karim et al. 2014). This process is not optimal for mechanical performance but provides a porous structure. Electrospinning is another technique that can generate continuous fibres with good water flux and particle rejection, making it apt for microfiltration applications (Gopakumar et al. 2017). Membranes synthesized by the interfacial polymerization technique can be used for reverse osmosis (RO) and nanofiltration (NF) (Li et al. 2018). The process involves a poly-condensation reaction between two monomers completely dissolved in two immiscible solvents to produce a thin layer at the interface of a polymer substrate (Mbakop et al. 2021). The phase inversion technique was used for the preparation of poly (vinylidene fluoride) (PVDF) composite membranes with cellulose nanocrystals blended in (Bai et al. 2012). They can be effectively used for low-pressure filtrations. The preparation techniques for NCs based composite membranes and some of the CNCs, their synthesis and applications are depicted in Fig. 4 and Table 3 respectively.

Table 3
Type of CNCs, synthesis methods, and their applications

Type of CNCs	Reinforcement	Synthesis method	Applications	ref.
CNF	Carbon quantum dots (CQD)	• In situ synthesis of CD@CNF	Water treatment • Selective dye removal	(Ahn et al. 2021)
	MgO nanoparticles incorporated polycaprolactone (PCL)/gelatin	• Coaxial electrospinning	• Periodontal tissue regeneration	(Peng et al. 2021)
	Fe doped CQDs	• Rapid microwave-assisted method	• Colourimetric detection of H_2O_2 • and glucose	(Bandi et al. 2021)
	Polypyrrole	•	• Hemodialysis	(Ferraz et al. 2013)
CNC	Carbon quantum dot	Hydrothermal	• Sensing and removal of fluoride ions in ranges of 0-200 μM	(Li et al. 2020)
	Nitrogen doped CQDs	Hydrothermal	• Chemosensors for the detection of metal ions and bioimaging	(Lizundia et al. 2017)
	Poly(3-hydroxy butyrate-*co*-3-hydroxy hexanoate) (PHBH)	Silylation	• Bio-degradable polymers	(Xu et al. 2018)
	Poly (butylene adipate-coterphthalate) (PBAT)	Solvent casting	• Bio-degradable polymers	(Morelli et al. 2016)
	Polyurethane foam (RPUF)	ultrasonication (solvent-free)	Mechanical engineering	(Septevani et al. 2017)
	2-hydroxyethyl methyacrylate (HEMA)	Acid-hydrolysis	• Mechanical engineering	(Tatsumi et al. 2014)
	Poly(methyl methacrylate) (PMMA) and Poly(butyl acrylate) (PBA)	Grafting	Solar cell	(Maxim et al. 2020)
	Polyvinl alcohol (PVA) loaded with curcumin	Solvent casting	• Wound dressing applications	(Agarwal et al. 2013)

Type of CNCs	Reinforcement	Synthesis method	Applications	ref.
BNC	Polydopamine (PDA)	In situ incorporation of PDA into BNC during its (*Gluconaetobacter hansenii*) bacterial mediated growth	Removal of heavy metal ions like Cd, Pb etc, along with organic pollutant dyes like methylene blue (MB), methyl orange (MO) and rhodamine 6G (R6G) at high concentrations of 40–60 ppm	(Gholami Derami et al. 2019)
	Mesoporous polydopamine(mPDA) and Pd nanoparticles	Embedding mPDA into BNC matrix during growth process of BNC to generate mPDA-BNC membrane followed by in situ growth of Pd nanoparticles	Efficient dye removal (MB removal upto 99% even at high concentrations of 300ppm) • Waste water treatment at industrial levels	(Gholami Derami et al. 2020)
	Laccase from *Myceliophthora thermophila*	Immersion of BNC membranes into laccase enzyme solution	• Antibacterial properties in wound dressings	(Sampaio et al. 2016)
	Nisin	BNC membranes immersed into nisin solution	• Providing antimicrobial and antioxidant properties to food packaging material	(dos Santos et al. 2018)

4. Applications Of Cnc Based Membranes

The membranes of CNCs are studied extensively for their wide range of applications in industries, biomedical, and energy storage devices. Membranes derived from nanocellulose retain the properties of cellulose and mainly act as a substrate upon which functionalization can occur. The surfaces can be modified depending on the function to be performed (Sardjono et al. 2019). They are cost-effective, easy to fabricate and rarely release hazardous chemical effluents compared to other methods. A few of those applications are enlisted below.

4.1 Sensors

Sensors are devices used to detect analytes or stimuli that can be used for biomedical and industrial applications. Sensors have to be stable, ensure reproducibility, and be sensitive to measure over a range of concentrations. The hydroxyl groups present in cellulose make it suitable for sensing applications as it provides mechanical stability and flexibility (Ansari et al. 2021). The presence of extensive intrachain and interchain hydrogen bonds, hydroxyl groups, electrostatic interactions and tunable cellulose polarization make an array of stimuli-responsive cellulose nanomaterials (CNM) (Zhu et al. 2020).

Nanocellulose can be incorporated into sensor systems in different ways, and they can act as a template, a reducing agent, a dispersant, a reinforcing agent etc. (Dai et al. 2020). Nanocellulose -based membranes and nanopapers are 2D nanocomposites lightweight, flexible, thermally and chemically stable with microporous structure (Dai et al. 2020). These composites exhibit exceptional sensing capabilities by the introduction of carbon nanotubes (CNTs), carbon quantum dots (CQDs), organic dyes, metal nanoparticles etc. (Fan et al. 2020). Sensors based on films are rampant, while nanocellulose membrane-based sensors are still in the initial stages of development (Abbasi-Moayed et al. 2018) (Morales-Narváez et al. 2015).

4.1.1 Bio-sensors

Biosensors use a biological molecule as a recognition element. CNMs that are biocompatible and show low cytotoxicity are suitable for biological applications. Biomedical applications include using CNM based glucose monitoring methods, urea detection, drug delivery, tissue engineering etc.

The detection of glucose is vital for the control of diabetes mellitus. For instance, a hybrid cellulose nanocrystal/ magnetite biosensor was recently developed for the detection of glucose in sweat and saliva (Tracey et al. 2020). Regular strips have glucose oxidase (GOx) affixed, converting the glucose to gluconic acid with hydrogen peroxide as a by-product. The hybrid cellulose nanocrystal/ magnetite biosensor strip has magnetite nanoparticles that reduce H_2O_2 and oxidize ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid), resulting in a colour change, making it a self-indicating reaction. These films can be placed on the skin or the tongue to detect glucose. A novel method for the detection of small molecules and cells was developed, where gold nanorods were incorporated with cellulose nanofiber (CNF) to form a versatile membrane by Surface-Enhanced Raman Scattering (SERS) (Zhang et al. 2018). The CNF matrix, due to its nanoporous morphology, helps retain the analyte for competent SERS detection. Other examples of optical biosensing techniques include fluorescent approaches, colorimetric methods, and bioluminescence (Golmohammadi et al. 2017). A self-assembling BC-AuNP (Bacterial cellulose- gold nanoparticle) nanocomposite recently developed, leads to the generation of a colorimetric mechanoplasmonic bioanalytical sensor, that facilitates optical detection by mechanical stimuli (Eskilson et al. 2020).

4.1.2 Gas sensors

Detection of gases like NO_2, ammonia and ethylene are essential for industries. Colorimetric and electrochemical sensors have been used for gas detection alone or combined with other techniques. Mixing amine-based polymers with micro fibrillated cellulose (MFC) creates a hybrid transport membrane based on nanocellulose. For instance, a study demonstrated CO_2 capture from N_2 and CH_4. A polyvinyl amine product, Lupamin 9095, was added to enhance the CO_2 flux across the selective layer. The improvement in the CO_2 adsorption rate is indicative of the increased affinity of the material with the acid component on amine functionalization (Ansaloni et al. 2017). Likewise, gas separation membranes derived from nanocellulose could successfully separate CO_2 through a mobile carrier mechanism (Venturi et al. 2019). The amino acid L-arginine blended with carboxymethylated nanofibrillated cellulose (CMC-NFC) enhanced the permeability and exhibited absolute selectivity. Zhang et al. (2017) developed a functionalized cellulose/ graphene oxide (GO) proton-conducting membrane to detect ethanol (Zhang et al. 2017). GO has a low permeation for gases like methanol, ethanol and methane, but when it covalently links with cellulose fibres, it becomes an ideal material for electrochemical gas sensing applications. A very recent study using nanocellulose/graphene oxide (GONC) hybrid membrane attached to SnO_2 nanosheets (NS) looked into selective H_2 detection (Fig. 5) (Jung and Jang 2021). The pore size of 0.3 nm led to the effective removal of large gas molecules like H_2S, CO and selectively allowed the diffusion of H_2 molecules. The SnO_2 NS@GONC sensor showed greater selectivity for H_2 than the SnO_2 NS and SnO_2 NS@GO sensors (Fig. 6**).**

4.1.3 Chemical sensor

Cholesterol measurement is a routine test employed to check cardiovascular diseases. Chemical methods, enzymatic assays, colorimetric assays used are often tedious processes. Electrochemical sensing methods have gained prominence due to their selectivity, reproducibility, fast response and stability. Such a sensor was developed for cholesterol detection by combining both electrochemical sensing and molecular imprinting techniques (Anirudhan et al. 2018). Using glassy carbon electrode surface (GCE) with silyated graphene oxide-grafted chemically modified nanocellulose (Si-GO-g-CMNC), both cyclic voltammetry (CV) and differential pulse voltammetry (DPV) studies were conducted. CV showed a detection range of 5.18–25.9 micro mol/L and DPV, 0.6475–10.360 mmol/L. Cholesterol recovery within the scope of 98.0% indicated the reliability of the sensor. Some chemicals on prolonged exposure can cause serious health problems, for instance formaldehyde which is widely used in industries, is a dangerous air pollutant. A formaldehyde sensor based on nanofibrous polyethyeleimine (PEI)/ bacterial cellulose membranes coated with quartz crystal microbalance could detect formaldehyde in the range of 1-100 ppm at room temperature (Hu et al. 2011). Figure7 portrays that the amount of PEI in the membrane was key to the sensing properties. The presence of large number of hydroxyl groups in BC and amine groups in PEI provides the fibers with a large number of strong hydrogen bonds. The interaction between PEI and BC prevents the aggregation of PEI and ensures a uniform coating on the surface of BC nanofibers, which can then interact with formaldehyde molecules. This is illustrated in **Fig.8**.

4.2 Energy applications

Nanocellulose is a suitable material for energy storage applications due to its unique properties based on its intrinsic structure. They have a high Youngs modulus of 1.38 GPa and a strength of 2–3 GPa. Due to extensive hydroxyl groups, chemical modifications on the surface and integration with other active materials are possible. Flexible energy storage devices are made with nanocellulose fibres as they are used to fabricate films/aerogel substrates. Direct methanol fuel cells (DMFC) are becoming popular as their use also extends to portable devices, other than having a compact design, high power density, reliability etc. Nafion membranes, which are polymeric electrolyte membranes, are currently in use but are disadvantageous. They have a high methanol crossover, leading to Pt catalyst poisoning, reducing the electrical performance and affecting cell efficiency. Research later led to polyvinyl alcohol, a non-toxic and biodegradable polymer whose methanol barrier property was better than Nafion but had lower proton conductivity. A study used sulfosuccinate acid (SSA) to modify cellulose to form films (Seo et al. 2009). The presence of hydroxyl groups on cellulose makes it easy to modify. The increase in SSA content could add to the cellulose membranes' ion exchange capacity and proton conductivity. A study using nanostructured Bacterial cellulose-Poly(4-styrene sulfonic acid) (PSSA) composite membranes displayed through-plane proton conductivity higher than 0.1 S cm^{-1} at 94^0 C and 98% relative humidity (RH), which decreased to 0.0042 S cm^{-1} at 60% RH (Gadim et al. 2014). The composite membranes were produced by in situ free radical polymerization of sodium 4-styrenesulfonate using poly (ethylene glycol) diacrylate (PEGDA), as cross-linker. The high proton conductivity can be attributed to the presence of a large number of sulfonic acid groups in PSSA. The proton conductivity increases with increase in PEGDA content, as seen in Fig. 9. Also, very high temperatures tend to make Nafion and pure PSSA membranes soft, but the presence of BC gives these membranes ample mechanical strength.

Later, a simple impregnating nanocellulose membrane with SSA, which showed improved methanol barrier property and lower proton conductivity than Nafion117 was developed (Sriruangrungkamol and Chonkaew 2021). However, sulfonated-modified nanocellulose membranes have high prospects to emerge as eco-friendly polymer electrolyte membranes in future DMFC applications.

4.3 Electronics- related applications

Nanocellulose can be considered a highly flexible and ultra-thin substrate, supporting electronic components for various applications. Biodegradable membranes from CNC, CNF and BNC can be used in fuel cell applications (Bayer et al. 2016). The fabricated cellulose nanopapers exhibited proton conductivity dependent on relative humidity, method of preparation and temperature. The CNC paper membrane was more conductive than the CNF paper membrane, primarily due to the increased charge carriers and the hydrophilicity/ acidity of the sulfuric acid groups added during the synthesis process.

Recently, a study used nanocellulose membrane to fabricate renewable flexible electronics (Mao et al. 2021). They used evaporation induced transfer printing technology (Fig. 10) to create nanocellulose-based liquid metal (NC-LM) printed circuit as liquid metal ink cannot be directly applied onto the nanocellulose membrane. As shown in Fig. 11, the NC-LM circuits can be used as wrist bands or attached to the nails and can also be used as multi-layer circuits, layered on top of each other, as they are extremely thin. NC-LM based wearable electronics research is in its infancy and has tremendous potential as they are both economical and environmentally friendly. Supercapacitors are a significant application of nanocellulose-based electronic devices with other applications like electric vehicles, fuel cells, smart consumer electronic devices etc. (Hsu and Zhong 2019).

4.4 Desalination applications

Desalination and water treatment strategies are the need of the hour, especially in developing countries where real-life applications can be the difference between life and death. Nanocellulose membranes are suitable for water treatment applications due to their non-toxicity, recyclability, inert nature, mechanical performance, sustainability and energy efficiency. They can be used as conventional paper filters while controlling their pore sizes. The membranes synthesized by Liu et al. (2019) showed superior dye rejection performance to Nylon 66 membranes with similar pore sizes (Liu et al. 2019). These CNF membranes fabricated with an ultrathin Graphene oxide (GO) barrier layer are easy to create. They are superior to the membranes currently used for water purification and food industries.

There have been numerous reviews on the use of membranes for water treatment (Cruz-Tato et al. 2017; Tan et al. 2020; Mautner 2020). Many carboxyl and hydroxyl groups on the membrane surface aids in water treatment applications, acting as adsorbents. TEMPO-oxidized cellulose nanofibers (TOCN) that used lysozymes (LYS), a natural protein as an adhesive, showed excellent results for the removal of heavy metal ions oil droplets and molecules (> 3 nm). The carboxyl groups of TOCN and the amine groups of LYS have an electrostatic interaction that enables them to form stable membranes. The amyloid-like oligomers from LYS helped the TOCN to stick together. Due to the presence of various functional groups like hydroxyl, carboxyl, amino and thiol groups, it was an efficient water purifier, especially in the removal of boron, a toxic pollutant (Huang et al. 2021).

One of the challenges of using membranes is the risk of fouling. Earlier, fouling was treated using chemical methods, which were not very efficient as it provided only temporary relief and led to increasing costs and wastage of chemicals. The self-cleaning and anti-fouling properties of nanocellulose-enabled thin-film nanofibrous composite (TFNC) ultrafiltration membranes were studied for their ultrafiltration of BSA protein solution and wastewater. The adhesion of biomolecules to the membrane surface was hindered by surface charge, which can be controlled by the degree of oxidation of CNF (Yang et al. 2021). A novel technique by Jiang et al. (2019) uses membranes created from bacterial nanocellulose (BNC) incorporated with reduced activated carbon oxide (RGO) during its growth and inhibit biofouling, “the Achilles heel of membrane processes”, also the RGO/BNC membranes showed bactericidal activity upon illumination with light (Flemming et al. 1997; Jiang et al. 2019). Forward osmosis (FO) is a technique that can be effective against fouling, as it creates a lower transmembrane pressure when compared to other conventional water treatment methods. A study used this principle of FO to deal with wastewater treatment (Cruz-Tato et al. 2017). Silver and platinum nanoparticles were added to these nanocellulose based composite membranes to enhance their properties of the membranes. Interestingly, fouling continued in the membranes to an extent, but an improvement in solute rejection and permeation of the membrane was observed. Self-cleaning membranes are important as membranes under constant use tend to have very low flux and are unsuitable for practical applications. UV assisted self-cleaning TiO_2/TCNC membranes by Zhan et al. (2018) is a sustainable and straightforward technique for removing oil from oil/water emulsions (> 99.5%) (Zhan et al. 2018). Tunicate cellulose nanocrystals (TCNC) due to their pore size and special wettability are apt for oil/water separations. On UV-light irradiation, the membranes showed improved underwater oil contact angles and water fluxes. Multifunctional materials take care of a range of problems as they present a range of properties. Yet, processing poisonous cations, anions, and oil from water have many challenges. The oils that are also a pollutant can affect the adsorption of the membranes, affecting the removal of cations and anions directly. Since cellulose shows outstanding acid, alkali, and salt tolerances, they are suitable for synthesizing separation materials. Hydrogels have excellent water-retaining and absorbing abilities, leading researchers to combine both of their properties to fabricate a nanocellulose hydrogel coated titanate-bismuth oxide membrane for the treatment of cations, anions and oil contained in polluted water (Xiong et al. 2018). The cations were trapped in TNF's layers (titanate nanofibers). After the exchange with Na^+ ions, the anions formed irreversible compounds, like $Bi_4O_5I_2$, by occupying the oxygen holes of delta-Bi_2O_3, providing more stability. The removal efficiency of cations and anions was also observed due to the membranes' electrostatic adsorption and hydrogen bond interaction. A nanocomposite membrane that showed tremendous potential in adsorbing anionic and cationic organic dyes was developed by researchers (Vilela et al. 2019). When combined, zwitterionic poly (2-methacrylolyloxyethyl phosphorylcholine) (PMPC) and bacterial nanocellulose give optically transparent nanocomposites that inhibit the growth of pathogenic bacteria. The dye removal capacity for a nanocomposite membrane containing 79 wt.% of PMPC was estimated to be 4.44 ± 0.32 mg g^{-1} for methylene blue (cationic dye) and 4.56 ± 0.43 mg g^{-1} for methyl orange (anionic dye) (Fig. 12).

The active area of water decontamination has a new entrant in bacterial nanocellulose aerogel membranes (Leitch et al. 2016), which was first studied for membrane distillation (MD). Ferreira-Neto et al. (2020) created aerogel membranes of bacterial nanocellulose and molybdenum disulphide (MoS_2) nanosheets, which made it quite efficient in the removal of dyes and heavy metals (Ferreira-Neto et al. 2020). It is bifunctional, acting as both a photocatalyst and an adsorbent, unlike earlier membrane technologies that look into photocatalytic properties for in-flow water purification. The FT-IR and XRD analysis confirmed that the use of MoS_2 did not compromise the structural integrity of the BC membrane up to six photocatalytic cycles. Even though a surface passivation layer of MoO_3 was observed, it did not affect the overall performance of the membrane. The EDS and mass analysis showed only about $< 0.3\%$ of total Mo leached into the solution, indicating photostability of the membrane. One of the primary challenges of MD is sustainability as they require high input of energy, while photo-thermal membrane distillation (PMD) is efficient in terms of energy. A bilayer membrane made of environmentally sustainable materials, polydopamine (PDA) and bacterial nanocellulose (BNC) was developed for PMD, which exhibited a permeate flux of 1.0 kg m^{-2} h^{-1} under one sun irradiation (Wu et al. 2021). The membrane, fluoro-silanized using (tridecafluoro-1,1,2,2-tetrahydrooctyl)-trichlorosilane (FTCS), gives high salt rejection ($> 99.9\%$) and only permits vapor transport. High porosity ($\sim 93\%$) and excellent optical activity ($\sim 98\%$) enhance the PMD performance. These solar-driven membranes possess bactericidal properties, minimizing bio-film formation and microbial aggregation, thereby increasing the longevity of the membrane. A state-of-the-art solar-driven sweater desalination technique was developed, which combined the two-dimensional membrane and three-dimensional foam into a single product (Zhang et al. 2020). The membrane's mechanical strength combined with the foam's high porosity makes it different from conventional nanocellulose membranes. Functionalities are introduced to the nanocellulose foam membrane (AGM) by adding carbon nanotubes (CNT). The water evaporation rate of AGM-CNT (1.67 kg

m^{-2} h^{-1}) was higher than the normal CNF-CNT (1.1 kg m^{-2} h^{-1}) membranes, revealing the combined effect of the porous and hydrophilic nature of the AGM-CNT's.

4.5 Applications in dermatology and cosmetics

Research in dermatology and cosmetics is on the rise, especially the search for natural ingredients which are much more compatible with the skin. BC has been extensively commercialized for dermal requirements due to its high-water retention capacity and the ability to hydrate the skin (Almeida et al. 2014). A group of researchers could successfully study the effect of dry BC: CMC (Bacterial cellulose and Carboxymethyl Cellulose) incorporated into generic cosmetic creams, replacing the traditionally used surfactants (Martins et al. 2021). Both viscosity and texture of the creams could be replicated with the replacement of 5.5% surfactants with only 0.75% BC: CMC. More ingenious methods are being created to incorporate BC and other cellulosic derivatives into uses other than topical applications. More recently, researchers developed an innovative patch for dermo-cosmetic applications based on two biopolymers, hyaluronic acid (HA) and BC (Fonseca et al. 2021). The microneedle (MN) application method is durable to the human skin revealing its cutaneous compatibility. The effectiveness of the system was demonstrated using Rutin, a natural antioxidant. The peculiar porous structure, water retention ability, moldability and good mechanical properties make BC a good biopolymer for cosmetic purposes. The regenerative properties of HA and the capacity of BC to release bioactive molecules makes it suitable for skin applications. Transdermal drug delivery is another application of nanocellulose membranes. This method is now being preferred over the traditional ones as there is hardly any interaction with a systematic circulation.

A recent study demonstrated the transdermal delivery of crocin, an active agent of saffron (*Crocus sativus*), loaded into BNC membranes (Abba et al. 2019). A gradual release of crocin over 7 hours and cumulative release of 215 μg/cm^2 was observed, which can be associated with the unique morphology of BNC membranes having an entangled nanoscale structure and 3D network. Further research in this area can help include other water-soluble active compounds in transdermal delivery applications.

5. Conclusions And Outlook

This review has discussed nanocellulose derived membranes, their synthesis, and their applications. These membranes, which are basically made of nanocellulose, embody all the properties of nanocellulose and, when combined with other functional materials, show characteristic properties that make them a promising class of materials to be further explored. As researchers focus more on greener and sustainable alternatives, nanocellulose membranes are envisaged as promising materials in biomedical research and desalination applications. One of the significant challenges of using nanocellulose based membranes in desalination techniques is the problem of fouling. Membranes also have to undergo pretreatment before being used in practical applications. They are rarely used without modifications as structural and compositional augmentations are essential to enhance the properties of the membranes. Their reusability and reliability in the long run are yet to be studied. However, many advancements are still in their initial stages but the membranes currently produced are sufficiently stable both chemically and thermally. One of the advantages of membrane technology based on cellulosic materials is that it is incredibly energy efficient. They have a meagre environmental impact as no hazardous chemicals are involved in most of the cases. Cellulose is environmentally friendly, and an inexhaustible source which has tremendous potential to develop into an irreplaceable material of the future.

Declarations

Acknowledgements

Authors acknowledge Dr Archana G.R., and Dr Sreejith M for helping with the references. Varsha Lisa John is thankful to CHRIST (Deemed to be University) for the research fellowship. Vinod T. P. is thankful to Centre for Research, CHRIST (Deemed to be University) for research support (Monograph project, MNGDSC-1806).

competing interest

There are no conflicts to declare.

References

1. ’Strathmann H ’Giorno, L ’Drioli, E (2006) An Introduction to Membrane Science and Technology
2. Abba M, Ibrahim Z, Chong CS, et al (2019) Transdermal Delivery of Crocin Using Bacterial Nanocellulose Membrane. Fibers Polym 20:2025–2031. https://doi.org/10.1007/s12221-019-9076-8
3. Abbasi-Moayed S, Golmohammadi H, Hormozi-Nezhad MR (2018) A nanopaper-based artificial tongue: a ratiometric fluorescent sensor array on bacterial nanocellulose for chemical discrimination applications. Nanoscale 10:2492–2502. https://doi.org/10.1039/C7NR05801B
4. Abdelghaffar F (2021) Biosorption of anionic dye using nanocomposite derived from chitosan and silver Nanoparticles synthesized via cellulosic banana peel bio-waste. Environ Technol Innov 24:101852. https://doi.org/10.1016/j.eti.2021.101852
5. Agarwal R, Sarwar Alam M, Gupta B (2013) Preparation of curcumin loaded poly(Vinyl Alcohol)-poly(Ethylene Oxide)-carboxymethyl cellulose membranes for wound care application. J Biomater Tissue Eng 3:273–283. https://doi.org/10.1166/jbt.2013.1092
6. Agustin MB, Ahmmad B, Alonzo SMM, Patriana FM (2014) Bioplastic based on starch and cellulose nanocrystals from rice straw. J Reinf Plast Compos 33:2205–2213. https://doi.org/10.1177/0731684414558325
7. Ahn J, Pak S, Song Y, Kim H (2021) In-situ synthesis of carbon dot at cellulose nanofiber for durable water treatment membrane with high selectivity. Carbohydr Polym 255:117387. https://doi.org/10.1016/J.CARBPOL.2020.117387

8. Ai B, Zheng L, Li W, et al (2021) Biodegradable Cellulose Film Prepared From Banana Pseudo-Stem Using an Ionic Liquid for Mango Preservation. Front Plant Sci 12:. https://doi.org/10.3389/fpls.2021.625878
9. Almeida IF, Pereira T, Silva NHCS, et al (2014) Bacterial cellulose membranes as drug delivery systems: An in vivo skin compatibility study. Eur J Pharm Biopharm 86:332–336. https://doi.org/10.1016/j.ejpb.2013.08.008
10. Anirudhan TS, Deepa JR, Binussreejayan (2018) Electrochemical sensing of cholesterol by molecularly imprinted polymer of silylated graphene oxide and chemically modified nanocellulose polymer. Mater Sci Eng C 92:942–956. https://doi.org/10.1016/j.msec.2018.07.041
11. Ansaloni L, Salas-Gay J, Ligi S, Baschetti MG (2017) Nanocellulose-based membranes for CO2 capture. J Memb Sci 522:. https://doi.org/10.1016/j.memsci.2016.09.024
12. Ansari JR, Hegazy SM, Houkan MT, et al (2021) Nanocellulose-based materials/composites for sensors. In: Nanocellulose Based Composites for Electronics. Elsevier
13. Bai H, Wang X, Zhou Y, Zhang L (2012) Preparation and characterization of poly(vinylidene fluoride) composite membranes blended with nano-crystalline cellulose. Prog Nat Sci Mater Int 22:250–257. https://doi.org/10.1016/j.pnsc.2012.04.011
14. Bajpai P (2018) Wood-Based Products and Chemicals. In: Biermann's Handbook of Pulp and Paper. Elsevier, pp 233–247
15. Bandi R, Alle M, Park CW, et al (2021) Cellulose nanofibrils/carbon dots composite nanopapers for the smartphone-based colorimetric detection of hydrogen peroxide and glucose. Sensors Actuators, B Chem 330:129330. https://doi.org/10.1016/j.snb.2020.129330
16. Basu H, Saha S, Mahadevan IA, et al (2019) Humic acid coated cellulose derived from rice husk: A novel biosorbent for the removal of Ni and Cr. J Water Process Eng 32:100892. https://doi.org/10.1016/j.jwpe.2019.100892
17. Bayer T, Cunning B V., Selyanchyn R, et al (2016) High Temperature Proton Conduction in Nanocellulose Membranes: Paper Fuel Cells. Chem Mater 28:. https://doi.org/10.1021/acs.chemmater.6b01990
18. Beck-Candanedo S, Roman M, Gray D (2005) Effect of Reaction Conditions on the Properties and Behavior of Wood Cellulose Nanocrystal. Biomacromolecules 6(2) 1048-1054. https://doi.org/10.1021/bm049300p
19. Bhowmik S, Islam J, Debnath T, et al (2017) Reinforcement of Gelatin-Based Nanofilled Polymer Biocomposite by Crystalline Cellulose from Cotton for Advanced Wound Dressing Applications. Polymers (Basel) 9:222. https://doi.org/10.3390/polym9060222
20. Bourret A, Chanzy H, Lazaro R (1972) Crystallite Features of Valonia cellulose by Electron Diffraction and Dark-Field Electron Microscopy. Biopolymers 11:893–898. https://doi.org/10.1002/bip.1972.360110412
21. Chanzy H, Henrissat B (1985) Undirectional degradation of *valonia* cellulose microcrystals subjected to cellulase action. FEBS Lett 184:285–288. https://doi.org/10.1016/0014-5793(85)80623-2

22. Cherian BM, Leão AL, de Souza SF, et al (2010) Isolation of nanocellulose from pineapple leaf fibres by steam explosion. Carbohydr Polym 81:720–725. https://doi.org/10.1016/j.carbpol.2010.03.046
23. Chua KY, Azzahari AD, Abouloula CN, et al (2020) Cellulose-based polymer electrolyte derived from waste coconut husk: residual lignin as a natural plasticizer. J Polym Res 27:115. https://doi.org/10.1007/s10965-020-02110-8
24. Cruz-Tato P, Ortiz-Quiles EO, Vega-Figueroa K, et al (2017) Metalized Nanocellulose Composites as a Feasible Material for Membrane Supports: Design and Applications for Water Treatment. Environ Sci Technol 51:. https://doi.org/10.1021/acs.est.6b05955
25. Csiszár E, Nagy S (2017) A comparative study on cellulose nanocrystals extracted from bleached cotton and flax and used for casting films with glycerol and sorbitol plasticisers. Carbohydr Polym 174:740–749. https://doi.org/10.1016/j.carbpol.2017.06.103
26. Dai L, Wang Y, Zou X, et al (2020) Ultrasensitive Physical, Bio, and Chemical Sensors Derived from 1-, 2-, and 3-D Nanocellulosic Materials. Small 16:1–25. https://doi.org/10.1002/smll.201906567
27. Ditzel FI, Prestes E, Carvalho BM, et al (2017) Nanocrystalline cellulose extracted from pine wood and corncob. Carbohydr Polym 157:1577–1585. https://doi.org/10.1016/j.carbpol.2016.11.036
28. dos Santos CA, dos Santos GR, Soeiro VS, et al (2018) Bacterial nanocellulose membranes combined with nisin: a strategy to prevent microbial growth. Cellulose 25:6681–6689. https://doi.org/10.1007/s10570-018-2010-1
29. Eichhorn SJ (2018) Cellulose nanofibres for photonics and plasmonics. Curr Opin Green Sustain Chem 12:1–7. https://doi.org/10.1016/j.cogsc.2018.03.010
30. El Achaby M, El Miri N, Aboulkas A, et al (2017) Processing and properties of eco-friendly bio-nanocomposite films filled with cellulose nanocrystals from sugarcane bagasse. Int J Biol Macromol 96:340–352. https://doi.org/10.1016/j.ijbiomac.2016.12.040
31. Eskilson O, Lindström SB, Sepulveda B, et al (2020) Self-Assembly of Mechanoplasmonic Bacterial Cellulose–Metal Nanoparticle Composites. Adv Funct Mater 30:2004766. https://doi.org/10.1002/adfm.202004766
32. Fan J, Zhang S, Li F, et al (2020) Recent advances in cellulose-based membranes for their sensing applications. Cellulose 27:9157–9179. https://doi.org/10.1007/s10570-020-03445-7
33. Ferraz N, Leschinskaya A, Toomadj F, et al (2013) Membrane characterization and solute diffusion in porous composite nanocellulose membranes for hemodialysis. Cellulose 20:2959–2970. https://doi.org/10.1007/s10570-013-0045-x
34. Ferreira-Neto EP, Ullah S, Da Silva TCA, et al (2020) Bacterial Nanocellulose/MoS2Hybrid Aerogels as Bifunctional Adsorbent/Photocatalyst Membranes for in-Flow Water Decontamination. ACS Appl Mater Interfaces 12:. https://doi.org/10.1021/acsami.0c14137
35. Fick A (1855) Ueber Diffusion. Ann der Phys und Chemie 170:59–86. https://doi.org/10.1002/andp.18551700105
36. Flemming HC, Schaule G, Griebe T, et al (1997) Biofouling - The Achilles heel of membrane processes. Desalination 113:. https://doi.org/10.1016/S0011-9164(97)00132-X

37. Fonseca DFS, Vilela C, Pinto RJB, et al (2021) Bacterial nanocellulose-hyaluronic acid microneedle patches for skin applications: In vitro and in vivo evaluation. Mater Sci Eng C 118:. https://doi.org/10.1016/j.msec.2020.111350
38. French, A.D. Glucose, not cellobiose, is the repeating unit of cellulose and why that is important. *Cellulose* 24**,** 4605–4609 (2017). https://doi.org/10.1007/s10570-017-1450-3
39. Fukuzumi H, Saito T, Iwamoto S, et al (2011) Pore Size Determination of TEMPO-Oxidized Cellulose Nanofibril Films by Positron Annihilation Lifetime Spectroscopy. Biomacromolecules 12:4057–4062. https://doi.org/10.1021/bm201079n
40. Gadim TDO, Figueiredo AGPR, Rosero-Navarro NC, et al (2014) Nanostructured bacterial cellulose-poly(4-styrene sulfonic acid) composite membranes with high storage modulus and protonic conductivity. ACS Appl Mater Interfaces 6:7864–7875. https://doi.org/10.1021/am501191t
41. Galiano F, Briceño K, Marino T, et al (2018) Advances in biopolymer-based membrane preparation and applications. J Memb Sci 564:562–586. https://doi.org/10.1016/j.memsci.2018.07.059
42. Gao Y, Guo X, Liu Y, et al (2018) A full utilization of rice husk to evaluate phytochemical bioactivities and prepare cellulose nanocrystals. Sci Rep 8:10482. https://doi.org/10.1038/s41598-018-27635-3
43. Gardiner and Sarko (1985) Packing analysis of carbohydrates and polysaccharides. 16. The crystal structures of celluloses [illegible] and [illegible]. Can J Chem 63:173-180. https://doi.org/10.1139/v85-027
44. Gayathri G, Srinikethan G (2019) Bacterial Cellulose production by K. saccharivorans BC1 strain using crude distillery effluent as cheap and cost effective nutrient medium. Int J Biol Macromol 138:950–957. https://doi.org/10.1016/j.ijbiomac.2019.07.159
45. George J, Sabapathi SN (2015) Cellulose nanocrystals: Synthesis, functional properties, and applications. Nanotechnol Sci Appl 8:45–54. https://doi.org/10.2147/NSA.S64386
46. Gholami Derami H, Gupta P, Gupta R, et al (2020) Palladium Nanoparticle-Decorated Mesoporous Polydopamine/Bacterial Nanocellulose as a Catalytically Active Universal Dye Removal Ultrafiltration Membrane. ACS Appl Nano Mater 3:5437–5448. https://doi.org/10.1021/acsanm.0c00787
47. Gholami Derami H, Jiang Q, Ghim D, et al (2019) A Robust and Scalable Polydopamine/Bacterial Nanocellulose Hybrid Membrane for Efficient Wastewater Treatment. ACS Appl Nano Mater 2:1092–1101. https://doi.org/10.1021/acsanm.9b00022
48. Golmohammadi H, Morales-Narváez E, Naghdi T, Merkoçi A (2017) Nanocellulose in Sensing and Biosensing. Chem Mater 29:5426–5446. https://doi.org/10.1021/acs.chemmater.7b01170
49. Gong J, Li J, Xu J, et al (2017) Research on cellulose nanocrystals produced from cellulose sources with various polymorphs. RSC Adv 7:33486–33493. https://doi.org/10.1039/C7RA06222B
50. Gopakumar DA, Pasquini D, Henrique MA, et al (2017) Meldrum's Acid Modified Cellulose Nanofiber-Based Polyvinylidene Fluoride Microfiltration Membrane for Dye Water Treatment and Nanoparticle Removal. ACS Sustain Chem Eng 5:2026–2033. https://doi.org/10.1021/acssuschemeng.6b02952
51. Gorgieva S, Trček J (2019) Bacterial cellulose: Production, modification and perspectives in biomedical applications. Nanomaterials 9:1–20. https://doi.org/10.3390/nano9101352

52. Graham T (1833) XXVII. *On the law of the diffusion of gases*. London, Edinburgh, Dublin Philos Mag J Sci 2:175–190. https://doi.org/10.1080/14786443308648004
53. Guimaraes M, Botara VR, Novack KM, et al (2015) Preparation of cellulose nanofibrils from bamboo pulp by mechanical defibrillation for their applications in biodegradable composites. J Nanosci Nanotechnol 15:6751–6768. https://doi.org/10.1166/jnn.2015.10854
54. Güzel M, Akpınar Ö (2020) Preparation and characterization of bacterial cellulose produced from fruit and vegetable peels by Komagataeibacter hansenii GA2016. Int J Biol Macromol 162:1597–1604. https://doi.org/10.1016/j.ijbiomac.2020.08.049
55. Hanley Sj, Revol J-F, Godbout L, Gray Dg (1997) Atomic force microscopy and transmission electron microscopy of cellulose from Micrasterias denticulata; evidence for a chiral helical microfibril twist. Cellulose 4:209–220. https://doi.org/10.1023/A:1018483722417
56. Heinze T (2015) Cellulose: Structure and properties. Adv Polym Sci 271:1–52. https://doi.org/10.1007/12_2015_319
57. Ho Jin Y, Lee T, Kim JR, et al (2019) Improved production of bacterial cellulose from waste glycerol through investigation of inhibitory effects of crude glycerol-derived compounds by Gluconacetobacter xylinus. J Ind Eng Chem 75:158–163. https://doi.org/10.1016/j.jiec.2019.03.017
58. Hsu HH, Zhong W (2019) Nanocellulose-Based Conductive Membranes for Free-Standing Supercapacitors: A Review. Membranes (Basel) 9:. https://doi.org/10.3390/membranes9060074
59. Hu W, Chen S, Liu L, et al (2011) Formaldehyde sensors based on nanofibrous polyethyleneimine/bacterial cellulose membranes coated quartz crystal microbalance. Sensors Actuators B Chem 157:554–559. https://doi.org/10.1016/j.snb.2011.05.021
60. Huang Y, Yang P, Yang F, Chang C (2021) Self-supported nanoporous lysozyme/nanocellulose membranes for multifunctional wastewater purification. J Memb Sci 635:. https://doi.org/10.1016/j.memsci.2021.119537
61. A. Okoro, O. K. Amadi (2012) The Use of Okra Derived Cellulose Biomass for the Removal and Recovery of Cd and Pb Ions from the Aqueous Environment. Chem Sci Trans 1:683–687. https://doi.org/10.7598/cst2012.185
62. Islam MT, Alam MM, Patrucco A, et al (2014) Preparation of Nanocellulose: A Review. AATCC J Res 1:17–23. https://doi.org/10.14504/ajr.1.5.3
63. Jiang Q, Ghim D, Cao S, et al (2019) Photothermally Active Reduced Graphene Oxide/Bacterial Nanocellulose Composites as Biofouling-Resistant Ultrafiltration Membranes. Environ Sci Technol 53:. https://doi.org/10.1021/acs.est.8b02772
64. Jiang S, Xia Z, Farooq A, et al (2021) Efficient recovery of the dyed cotton–polyester fabric: cellulose nanocrystal extraction and its application in composite films. Cellulose 28:3235–3248. https://doi.org/10.1007/s10570-021-03738-5
65. Jung J-W, Jang J-S (2021) D-space-controlled graphene oxide hybrid membrane-loaded SnO2 nanosheets for selective H2 detection. J Sens Sci Technol 30:376–380. https://doi.org/10.46670/JSST.2021.30.6.376

66. Kalita E, Nath BK, Deb P, et al (2015) High quality fluorescent cellulose nanofibers from endemic rice husk: Isolation and characterization. Carbohydr Polym 122:308–313. https://doi.org/10.1016/j.carbpol.2014.12.075
67. Kargarzadeh H, Ioelovich M, Ahmad I, et al (2017) Methods for Extraction of Nanocellulose from Various Sources. In: Handbook of Nanocellulose and Cellulose Nanocomposites. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany
68. Karim Z, Claudpierre S, Grahn M, et al (2016) Nanocellulose based functional membranes for water cleaning: Tailoring of mechanical properties, porosity and metal ion capture. J Memb Sci 514:. https://doi.org/10.1016/j.memsci.2016.05.018
69. Karim Z, Mathew AP, Grahn M, et al (2014) Nanoporous membranes with cellulose nanocrystals as functional entity in chitosan: Removal of dyes from water. Carbohydr Polym 112:668–676. https://doi.org/10.1016/j.carbpol.2014.06.048
70. Kasiri N, Fathi M (2018) Production of cellulose nanocrystals from pistachio shells and their application for stabilizing Pickering emulsions. Int J Biol Macromol 106:1023–1031. https://doi.org/10.1016/j.ijbiomac.2017.08.112
71. Keplinger T, Wittel FK, Rüggeberg M, Burgert I (2021) Wood Derived Cellulose Scaffolds—Processing and Mechanics. Adv Mater 33:2001375. https://doi.org/10.1002/adma.202001375
72. Khui PLN, Rahman MR, Bakri MK Bin (2021) A review on the extraction of cellulose and nanocellulose as a filler through solid waste management. J Thermoplast Compos Mater 089270572110208. https://doi.org/10.1177/08927057211020800
73. Kim HG, Kim Y-S, Kwac LK, Shin HK (2020) Characterization of Activated Carbon Paper Electrodes Prepared by Rice Husk-Isolated Cellulose Fibers for Supercapacitor Applications. Molecules 25:3951. https://doi.org/10.3390/molecules25173951
74. Kim N-H, Herth W, Vuong R, Chanzy H (1996) The Cellulose System in the Cell Wall ofMicrasterias. J Struct Biol 117:195–203. https://doi.org/10.1006/jsbi.1996.0083
75. Klemm, D., Heublein, B., Fink, H.-P., & Bohn, A. (2005). Cellulose: Fascinating Biopolymer and Sustainable Raw Material. Angew. Chem. Int. Ed., 44(22), 3358–3393. doi:10.1002/anie.200460587
76. Klemm D, Cranston ED, Fischer D, et al (2018) Nanocellulose as a natural source for groundbreaking applications in materials science: Today's state. Mater Today 21:720–748. https://doi.org/10.1016/J.MATTOD.2018.02.001
77. Kolff Wj, Berk Htj, Welle Nm, et al (2009) The Artificial Kidney: a dialyser with a great area. Acta Med Scand 117:121–134. https://doi.org/10.1111/j.0954-6820.1944.tb03951.x
78. Lam NT, Chollakup R, Smitthipong W, et al (2017) Utilizing cellulose from sugarcane bagasse mixed with poly(vinyl alcohol) for tissue engineering scaffold fabrication. Ind Crops Prod 100:183–197. https://doi.org/10.1016/j.indcrop.2017.02.031
79. Langan P, Nishiyama Y, Chanzy H (2001) X-ray structure of mercerized cellulose II at 1 Å resolution. Biomacromolecules 2:410–416. https://doi.org/10.1021/bm005612q

80. Leitch ME, Li C, Ikkala O, et al (2016) Bacterial Nanocellulose Aerogel Membranes: Novel High-Porosity Materials for Membrane Distillation. Environ Sci Technol Lett 3:. https://doi.org/10.1021/acs.estlett.6b00030
81. Li M, Li X, Jiang M, et al (2020) Engineering a ratiometric fluorescent sensor membrane containing carbon dots for efficient fluoride detection and removal. Chem Eng J 399:125741. https://doi.org/10.1016/J.CEJ.2020.125741
82. Li S, Liu S, Huang F, et al (2018) Preparation and Characterization of Cellulose-Based Nanofiltration Membranes by Interfacial Polymerization with Piperazine and Trimesoyl Chloride. ACS Sustain Chem Eng 6:13168–13176. https://doi.org/10.1021/acssuschemeng.8b02720
83. Liu D (2019) The Artificial Cell, the Semipermeable Membrane, and the Life that Never Was, 1864–1901. Hist Stud Nat Sci 49:504–555. https://doi.org/10.1525/hsns.2019.49.5.504
84. Liu P, Zhu C, Mathew AP (2019) Mechanically robust high flux graphene oxide - nanocellulose membranes for dye removal from water. J Hazard Mater 371:484–493. https://doi.org/10.1016/j.jhazmat.2019.03.009
85. Lizundia E, Nguyen TD, Vilas JL, et al (2017) Chiroptical luminescent nanostructured cellulose films. Mater Chem Front 1:979–987. https://doi.org/10.1039/c6qm00225k
86. Lonsdale HK (1982) The growth of membrane technology. J Memb Sci 10:81–181. https://doi.org/10.1016/S0376-7388(00)81408-8
87. Ma H, Burger C, Hsiao BS, Chu B (2012) Highly Permeable Polymer Membranes Containing Directed Channels for Water Purification. ACS Macro Lett 1:723–726. https://doi.org/10.1021/mz300163h
88. Manoukian OS, Sardashti N, Stedman T, et al (2019) Biomaterials for Tissue Engineering and Regenerative Medicine. In: Encyclopedia of Biomedical Engineering. Elsevier, pp 462–482
89. Mao Y, Wu Y, Zhang P, et al (2021) Nanocellulose-based reusable liquid metal printed electronics fabricated by evaporation-induced transfer printing. J Mater Sci Technol 61:132–137. https://doi.org/10.1016/j.jmst.2020.05.040
90. Martins D, Rocha C, Dourado F, Gama M (2021) Bacterial Cellulose-Carboxymethyl Cellulose (BC:CMC) dry formulation as stabilizer and texturizing agent for surfactant-free cosmetic formulations. Colloids Surfaces A Physicochem Eng Asp 617:126380. https://doi.org/10.1016/j.colsurfa.2021.126380
91. Mason EA (1991) From pig bladders and cracked jars to polysulfones: An historical perspective on membrane transport. J Memb Sci 60:125–145. https://doi.org/10.1016/S0376-7388(00)81529-X
92. Mautner A (2020) Nanocellulose water treatment membranes and filters: a review. Polym Int 69:. https://doi.org/10.1002/pi.5993
93. Mautner A, Lee KY, Tammelin T, et al (2015) Cellulose nanopapers as tight aqueous ultra-filtration membranes. React Funct Polym 86:209–214. https://doi.org/10.1016/j.reactfunctpolym.2014.09.014
94. Maxim AA, Sadyk SN, Aidarkhanov D, et al (2020) PMMA thin film with embedded carbon quantum dots for post-fabrication improvement of light harvesting in perovskite solar cells. Nanomaterials 10

95. Mbakop S, Nthunya LN, Onyango MS (2021) Recent Advances in the Synthesis of Nanocellulose Functionalized–Hybrid Membranes and Application in Water Quality Improvement. Processes 9:611. https://doi.org/10.3390/pr9040611
96. Melvin Ng HK, Lim GK, Leo CP (2020) N-modified carbon quantum dot in 3D-network of microfibrillated cellulose for building photoluminescent thin film as tartrazine sensor. J Photochem Photobiol A Chem 389:112286. https://doi.org/10.1016/j.jphotochem.2019.112286
97. Mohamed MA, Salleh WNW, Jaafar J, et al (2015) Feasibility of recycled newspaper as cellulose source for regenerated cellulose membrane fabrication. J Appl Polym Sci 132:n/a-n/a. https://doi.org/10.1002/app.42684
98. Molina-Ramírez C, Álvarez J, Zuluaga R, et al (2020) A Novel Approach Using Conventional Methodologies to Scale up BNC Production Using Komagataeibacter medellinensis and Rotten Banana Waste as Alternative. Processes 8:1469. https://doi.org/10.3390/pr8111469
99. Mondragon G, Santamaria-Echart A, Hormaiztegui ME V., et al (2018) Nanocomposites of Waterborne Polyurethane Reinforced with Cellulose Nanocrystals from Sisal Fibres. J Polym Environ 26:1869–1880. https://doi.org/10.1007/s10924-017-1089-z
100. Morales-Narváez E, Golmohammadi H, Naghdi T, et al (2015) Nanopaper as an Optical Sensing Platform. ACS Nano 9:7296–7305. https://doi.org/10.1021/acsnano.5b03097
101. Morelli CL, Belgacem MN, Branciforti MC, et al (2016) Supramolecular aromatic interactions to enhance biodegradable film properties through incorporation of functionalized cellulose nanocrystals. Compos Part A Appl Sci Manuf 83:80–88. https://doi.org/10.1016/j.compositesa.2015.10.038
102. Muhmed SA, Nor NAM, Jaafar J, et al (2020) Emerging chitosan and cellulose green materials for ion exchange membrane fuel cell: a review. Energy, Ecol Environ 5:85–107. https://doi.org/10.1007/s40974-019-00127-4
103. Nascimento FX, Torres CAV, Freitas F, et al (2021) Functional and genomic characterization of Komagataeibacter uvaceti FXV3, a multiple stress resistant bacterium producing increased levels of cellulose. Biotechnol Reports 30:e00606. https://doi.org/10.1016/j.btre.2021.e00606
104. Nguyen T, Roddick F, Fan L (2012) Biofouling of Water Treatment Membranes: A Review of the Underlying Causes, Monitoring Techniques and Control Measures. Membranes (Basel) 2:804–840. https://doi.org/10.3390/membranes2040804
105. Niaounakis M (2017) The Problem of Marine Plastic Debris. In: Management of Marine Plastic Debris. Elsevier, pp 1–55
106. Nishiyama Y, Langan P, Chanzy H (2002) Crystal Structure and Hydrogen-Bonding System in Cellulose Iβ from Synchrotron X-ray and Neutron Fiber Diffraction. J Am Chem Soc 124:9074–9082. https://doi.org/10.1021/ja0257319
107. Nishiyama Y, Sugiyama J, Chanzy H, Langan P (2003) Crystal Structure and Hydrogen Bonding System in Cellulose I $_{\alpha}$ from Synchrotron X-ray and Neutron Fiber Diffraction. J Am Chem Soc 125:14300–14306. https://doi.org/10.1021/ja037055w

108. Obele CM, Ejimofor MI, Atuanya CU, Ibenta M. (2021) Cassava stem cellulose (CSC)Nanocrystal for optimal methylene BlueBio sorption with response surface design. Curr Res Green Sustain Chem 4:100067. https://doi.org/10.1016/j.crgsc.2021.100067
109. Olivera S, Nataraj D, Archana S, et al (2018) Alpha-Cellulose Derived from Teakwood Sawdust for Cationic Dyes Removal. Mater Focus 7:132–139. https://doi.org/10.1166/mat.2018.1490
110. Ou Z, Zhou Q, Rao X, et al (2021) Cellulose Isolated From Waste Rubber Wood and Its Application in PLA Based Composite Films. Front Bioeng Biotechnol 9:. https://doi.org/10.3389/fbioe.2021.666399
111. Oyekanmi AA, Saharudin NI, Hazwan CM, et al (2021) Improved Hydrophobicity of Macroalgae Biopolymer Film Incorporated with Kenaf Derived CNF Using Silane Coupling Agent. Molecules 26:2254. https://doi.org/10.3390/molecules26082254
112. Padinjakkara A, Scarinzi G, Santagata G, et al (2020) Enhancement of Adhesive Strength of Epoxy/Carboxyl-Terminated Poly(butadiene- *co* -acrylonitrile) Nanocomposites Using Waste Hemp Fiber-Derived Cellulose Nanofibers. Ind Eng Chem Res 59:10904–10913. https://doi.org/10.1021/acs.iecr.0c01053
113. Pavalaydon K, Ramasawmy H, Surroop D (2021) Comparative evaluation of cellulose nanocrystals from bagasse and coir agro-wastes for reinforcing PVA-based composites. Environ Dev Sustain. https://doi.org/10.1007/s10668-021-01852-9
114. Peng W, Ren S, Zhang Y, et al (2021) MgO Nanoparticles-Incorporated PCL/Gelatin-Derived Coaxial Electrospinning Nanocellulose Membranes for Periodontal Tissue Regeneration. Front Bioeng Biotechnol 9:. https://doi.org/10.3389/fbioe.2021.668428
115. Raghav N, Sharma MR, Kennedy JF (2021) Nanocellulose: A mini-review on types and use in drug delivery systems. Carbohydr Polym Technol Appl 2:100031. https://doi.org/10.1016/J.CARPTA.2020.100031
116. Rashad A, Mustafa K, Heggset EB, Syverud K (2017) Cytocompatibility of Wood-Derived Cellulose Nanofibril Hydrogels with Different Surface Chemistry. Biomacromolecules 18:1238–1248. https://doi.org/10.1021/acs.biomac.6b01911
117. Sampaio LMP, Padrão J, Faria J, et al (2016) Laccase immobilization on bacterial nanocellulose membranes: Antimicrobial, kinetic and stability properties. Carbohydr Polym 145:1–12. https://doi.org/10.1016/j.carbpol.2016.03.009
118. Sardjono SA, Suryanto H, Aminnudin, Muhajir M (2019) Crystallinity and morphology of the bacterial nanocellulose membrane extracted from pineapple peel waste using high-pressure homogenizer. p 080015
119. Semjonovs P, Ruklisha M, Paegle L, et al (2017) Cellulose synthesis by Komagataeibacter rhaeticus strain P 1463 isolated from Kombucha. Appl Microbiol Biotechnol 101:1003–1012. https://doi.org/10.1007/s00253-016-7761-8
120. Seo JA, Kim JC, Koh JK, et al (2009) Preparation and characterization of crosslinked cellulose/sulfosuccinic acid membranes as proton conducting electrolytes. Ionics (Kiel) 15:555–560. https://doi.org/10.1007/s11581-009-0314-8

121. Septevani AA, Evans DAC, Annamalai PK, Martin DJ (2017) The use of cellulose nanocrystals to enhance the thermal insulation properties and sustainability of rigid polyurethane foam. Ind Crops Prod 107:114–121. https://doi.org/10.1016/j.indcrop.2017.05.039
122. Shahi N, Lee E, Min B, Kim D-J (2021) Rice Husk-Derived Cellulose Nanofibers: A Potential Sensor for Water-Soluble Gases. Sensors 21:4415. https://doi.org/10.3390/s21134415
123. Sharma PR, Sharma SK, Lindström T, Hsiao BS (2020) Nanocellulose-Enabled Membranes for Water Purification: Perspectives. Adv Sustain Syst 4:1900114. https://doi.org/10.1002/adsu.201900114
124. Sijabat EK, Nuruddin A, Aditiawati P, Purwasasmita BS (2020) Optimization on the synthesis of bacterial nano cellulose (BNC) from banana peel waste for water filter membrane applications. Mater Res Express 7:. https://doi.org/10.1088/2053-1591/ab8df7
125. Sriruangrungkamol A, Chonkaew W (2021) Modification of nanocellulose membrane by impregnation method with sulfosuccinic acid for direct methanol fuel cell applications. Polym Bull 78:3705–3728. https://doi.org/10.1007/s00289-020-03289-y
126. Sullivan F, Simon L, Ioannidis N, et al (2018) Nitration Kinetics of Cellulose Fibers Derived from Wood Pulp in Mixed Acids. Ind Eng Chem Res 57:1883–1893. https://doi.org/10.1021/acs.iecr.7b03818
127. Taflick T, Schwendler LA, Rosa SML, et al (2017) Cellulose nanocrystals from acacia bark–Influence of solvent extraction. Int J Biol Macromol 101:553–561. https://doi.org/10.1016/j.ijbiomac.2017.03.076
128. Tan HF, Ooi BS, Leo CP (2020) Future perspectives of nanocellulose-based membrane for water treatment. J. Water Process Eng. 37
129. Tang L, Feng Y, He W, Yang F (2019) Combination of graphene oxide with flax-derived cellulose dissolved in NaOH/urea medium to generate hierarchically structured composite carbon aerogels. Ind Crops Prod 130:179–183. https://doi.org/10.1016/j.indcrop.2018.12.068
130. Tatsumi M, Kimura F, Kimura T, et al (2014) Anisotropic polymer composites synthesized by immobilizing cellulose nanocrystal suspensions specifically oriented under magnetic fields. Biomacromolecules 15:4579–4589. https://doi.org/10.1021/bm501629g
131. Taweecheep P, Naloka K, Matsutani M, et al (2019) Superfine bacterial nanocellulose produced by reverse mutations in the bcsC gene during adaptive breeding of Komagataeibacter oboediens. Carbohydr Polym 226:115243. https://doi.org/10.1016/j.carbpol.2019.115243
132. Tayeb A, Amini E, Ghasemi S, Tajvidi M (2018) Cellulose Nanomaterials—Binding Properties and Applications: A Review. Molecules 23:2684. https://doi.org/10.3390/molecules23102684
133. Teodoro KBR, Sanfelice RC, Migliorini FL, et al (2021) A Review on the Role and Performance of Cellulose Nanomaterials in Sensors. ACS Sensors. https://doi.org/10.1021/acssensors.1c00473
134. Teow YH, Amirudin SN, Ho KC (2020) Sustainable approach to the synthesis of cellulose membrane from oil palm empty fruit bunch for dye wastewater treatment. J Water Process Eng 34:101182. https://doi.org/10.1016/j.jwpe.2020.101182
135. Thinkohkaew K, Rodthongkum N, Ummartyotin S (2020) Coconut husk (Cocos nucifera) cellulose reinforced poly vinyl alcohol-based hydrogel composite with control-release behavior of methylene

blue. J Mater Res Technol 9:6602–6611. https://doi.org/10.1016/j.jmrt.2020.04.051

136. Tibolla H, Pelissari FM, Rodrigues MI, Menegalli FC (2017) Cellulose nanofibers produced from banana peel by enzymatic treatment: Study of process conditions. Ind Crops Prod 95:664–674. https://doi.org/10.1016/j.indcrop.2016.11.035

137. Tracey CT, Torlopov MA, Martakov IS, et al (2020) Hybrid cellulose nanocrystal/magnetite glucose biosensors. Carbohydr Polym 247:116704. https://doi.org/10.1016/J.CARBPOL.2020.116704

138. Trache D, Hussin MH, Haafiz MKM, Kumar Thakur V (2017) Recent progress in cellulose nanocrystals: sources and production 1. 29 Nanoscale 9:1763–1786. https://doi.org/10.1039/C6NR09494E

139. Trache D, Tarchoun AF, Derradji M, et al (2020) Nanocellulose: From Fundamentals to Advanced Applications

140. van't Hoff J (1888) XII. *The function of osmotic pressure in the analogy between solutions and gases*. London, Edinburgh, Dublin Philos Mag J Sci 26:81–105. https://doi.org/10.1080/14786448808628243

141. Vázquez MI, Algarra M, Benavente J (2015) Modification of regenerated cellulose membrane based on thiol dendrimer. Carbohydr Polym 131:273–279. https://doi.org/10.1016/j.carbpol.2015.05.067

142. Venturi D, Chrysanthou A, Dhuiège B, et al (2019) Arginine/Nanocellulose Membranes for Carbon Capture Applications. Nanomaterials 9:877. https://doi.org/10.3390/nano9060877

143. Vilela C, Moreirinha C, Almeida A, et al (2019) Zwitterionic Nanocellulose-Based Membranes for Organic Dye Removal. Materials (Basel) 12:1404. https://doi.org/10.3390/ma12091404

144. Wada M, Chanzy H, Nishiyama Y, Langan P (2004) Cellulose III_I Crystal Structure and Hydrogen Bonding by Synchrotron X-ray and Neutron Fiber Diffraction. Macromolecules 37:8548–8555. https://doi.org/10.1021/ma0485585

145. Wada M, Heux L, Nishiyama Y, Langan P (2009) X-ray Crystallographic, Scanning Microprobe X-ray Diffraction, and Cross-Polarized/Magic Angle Spinning ^{13}C NMR Studies of the Structure of Cellulose $\square_{\square}$. Biomacromolecules 10(2):302-309. https://doi.org/10.1021/bm8010227

146. Wang W, Bai Q, Liang T, et al (2017) Preparation of amino-functionalized regenerated cellulose membranes with high catalytic activity. Int J Biol Macromol 102:944–951. https://doi.org/10.1016/j.ijbiomac.2017.04.096

147. Wu X, Cao S, Ghim D, et al (2021) A thermally engineered polydopamine and bacterial nanocellulose bilayer membrane for photothermal membrane distillation with bactericidal capability. Nano Energy 79:105353. https://doi.org/10.1016/j.nanoen.2020.105353

148. Xiong Y, Wang C, Wang H, et al (2018) Nano-cellulose hydrogel coated flexible titanate-bismuth oxide membrane for trinity synergistic treatment of super-intricate anion/cation/oily-water. Chem Eng J 337:143–151. https://doi.org/10.1016/j.cej.2017.12.080

149. Xu P, Cao Y, Wu B, et al (2018) Effects of modified nanocrystalline cellulose on the hydrophilicity, crystallization and mechanical behaviors of poly(3-hydroxybutyrate-: Co -3-hydroxyhexanoate). New

J Chem 42:11972–11978. https://doi.org/10.1039/c8nj02012d

150. Yang M, Hadi P, Yin X, et al (2021) Antifouling nanocellulose membranes: How subtle adjustment of surface charge lead to self-cleaning property. J Memb Sci 618:. https://doi.org/10.1016/j.memsci.2020.118739
151. Yang X, Liu H, Han F, et al (2017) Fabrication of cellulose nanocrystal from Carex meyeriana Kunth and its application in the adsorption of methylene blue. Carbohydr Polym 175:464–472. https://doi.org/10.1016/j.carbpol.2017.08.007
152. Yu B, Fan G, Zhao S, et al (2021) Simultaneous isolation of cellulose and lignin from wheat straw and catalytic conversion to valuable chemical products. Appl Biol Chem 64:15. https://doi.org/10.1186/s13765-020-00579-x
153. Zainuddin N, Ahmad I, Kargarzadeh H, Ramli S (2017) Hydrophobic kenaf nanocrystalline cellulose for the binding of curcumin. Carbohydr Polym 163:261–269. https://doi.org/10.1016/j.carbpol.2017.01.036
154. Zanchetta E, Damergi E, Patel B, et al (2021) Algal cellulose, production and potential use in plastics: Challenges and opportunities. Algal Res 56:102288. https://doi.org/10.1016/j.algal.2021.102288
155. Zhai L, Kim H-C, Muthoka RM, et al (2021) Environment-Friendly Zinc Oxide Nanorods-Grown Cellulose Nanofiber Nanocomposite and Its Electromechanical and UV Sensing Behaviors. Nanomaterials 11:. https://doi.org/10.3390/nano11061419
156. Zhan H, Peng N, Lei X, et al (2018) UV-induced self-cleanable TiO2/nanocellulose membrane for selective separation of oil/water emulsion. Carbohydr Polym 201:464–470. https://doi.org/10.1016/j.carbpol.2018.08.093
157. Zhang F, Li Y, Cai H, et al (2020) Processing nanocellulose foam into high-performance membranes for harvesting energy from nature. Carbohydr Polym 241:116253. https://doi.org/10.1016/j.carbpol.2020.116253
158. Zhang J, Jiang G, Goledzinowski M, et al (2017) Green Solid Electrolyte with Cofunctionalized Nanocellulose/Graphene Oxide Interpenetrating Network for Electrochemical Gas Sensors. Small Methods 1:. https://doi.org/10.1002/smtd.201700237
159. Zhang S, Xiong R, Mahmoud MA, et al (2018) Dual-Excitation Nanocellulose Plasmonic Membranes for Molecular and Cellular SERS Detection. ACS Appl Mater Interfaces 10:18380–18389. https://doi.org/10.1021/acsami.8b04817
160. Zhou S, Nyholm L, Strømme M, Wang Z (2019) Cladophora Cellulose: Unique Biopolymer Nanofibrils for Emerging Energy, Environmental, and Life Science Applications. Acc Chem Res 52:2232–2243. https://doi.org/10.1021/acs.accounts.9b00215
161. Zhu Q, Liu S, Sun J, et al (2020) Stimuli-responsive cellulose nanomaterials for smart applications. Carbohydr Polym 235:115933. https://doi.org/10.1016/J.CARBPOL.2020.115933

Figures

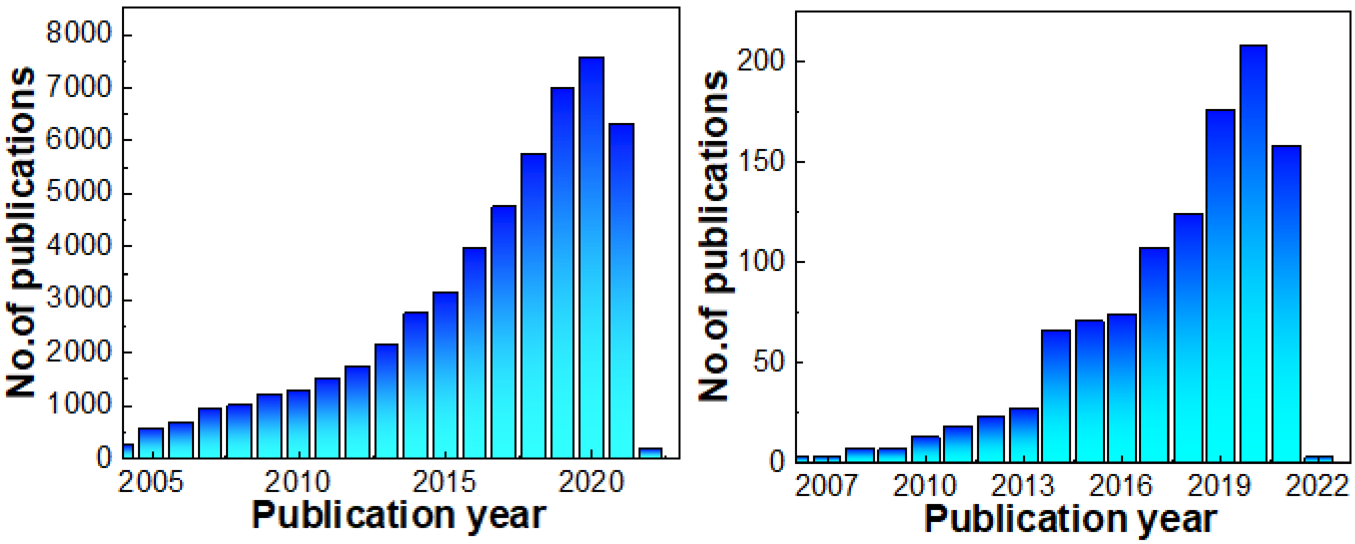

Figure 1

Statistics depicting the surge in active research on CNCs and their membranes. The literature search focused on documents containing “cellulose nanostructures” and “membranes of cellulose nanostructures” in their title, abstract, and keywords. Data courtesy: Web of Science (acquired in November 2021).

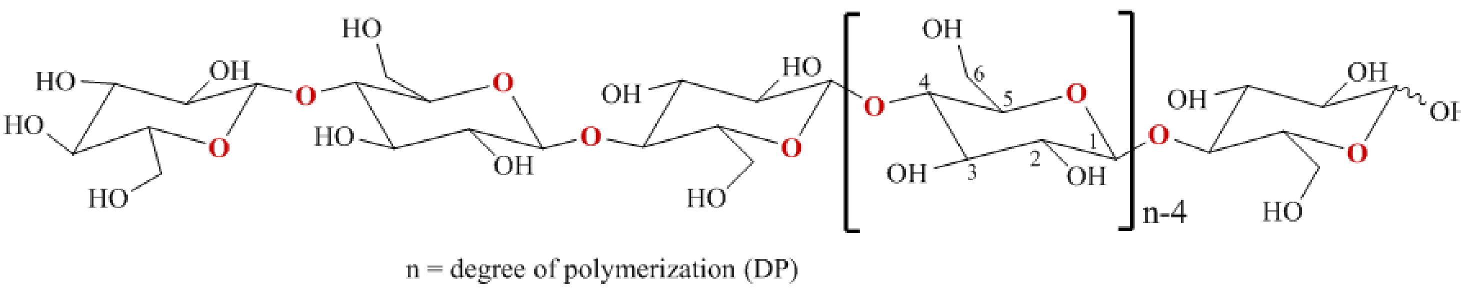

Figure 2

Molecular structure of cellulose.

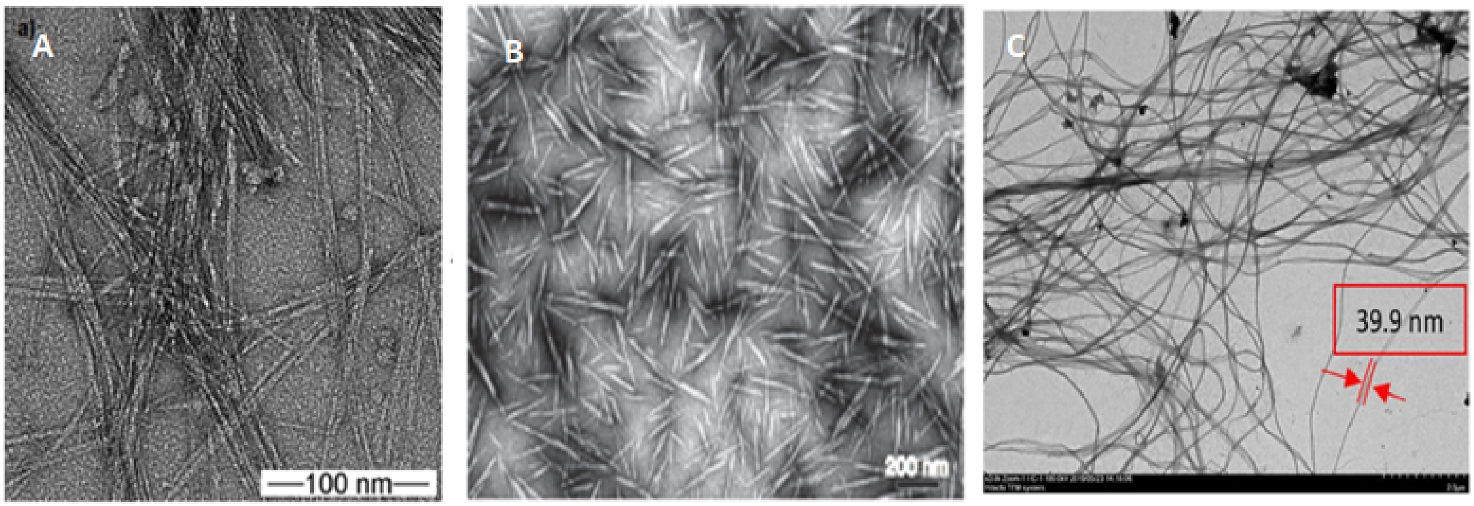

Figure 3

A) CNF from banana peel. Reproduced with permission(Tibolla et al. 2017). Copyright 2017, Elsevier B) CNC from ramie fibre. Reproduced with permission(Tayeb et al. 2018). Copyright 2021, The Royal Society of Chemistry. C) BNC from banana peel. Reproduced with permission(Sijabat et al. 2020). Copyright 2020, IOP Publishing.

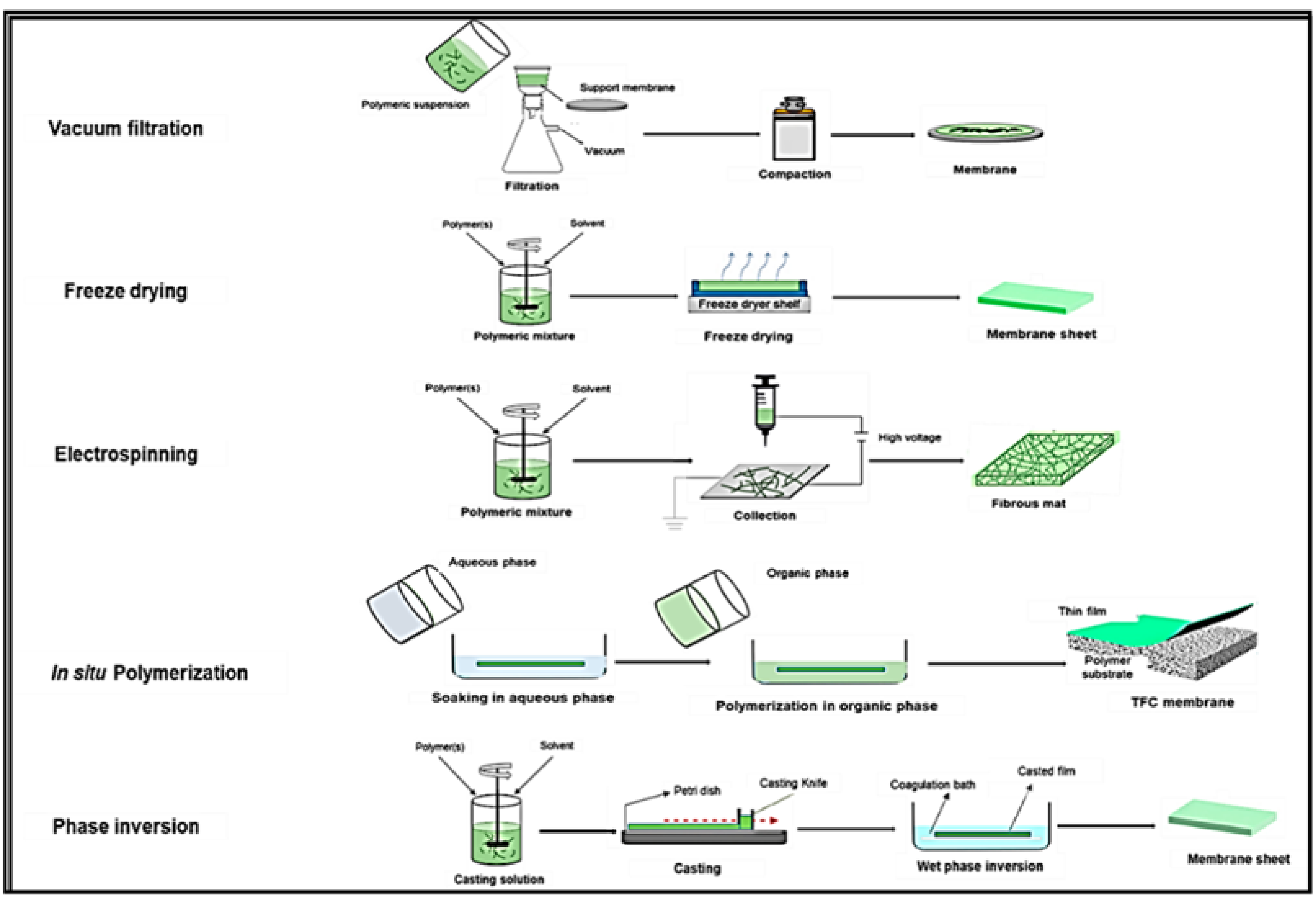

Figure 4

Schematic illustration of commonly utilized preparation techniques for NCs based composite membranes. Reproduced with permission (Mbakop et al. 2021). Copyright 2021, MDPI.

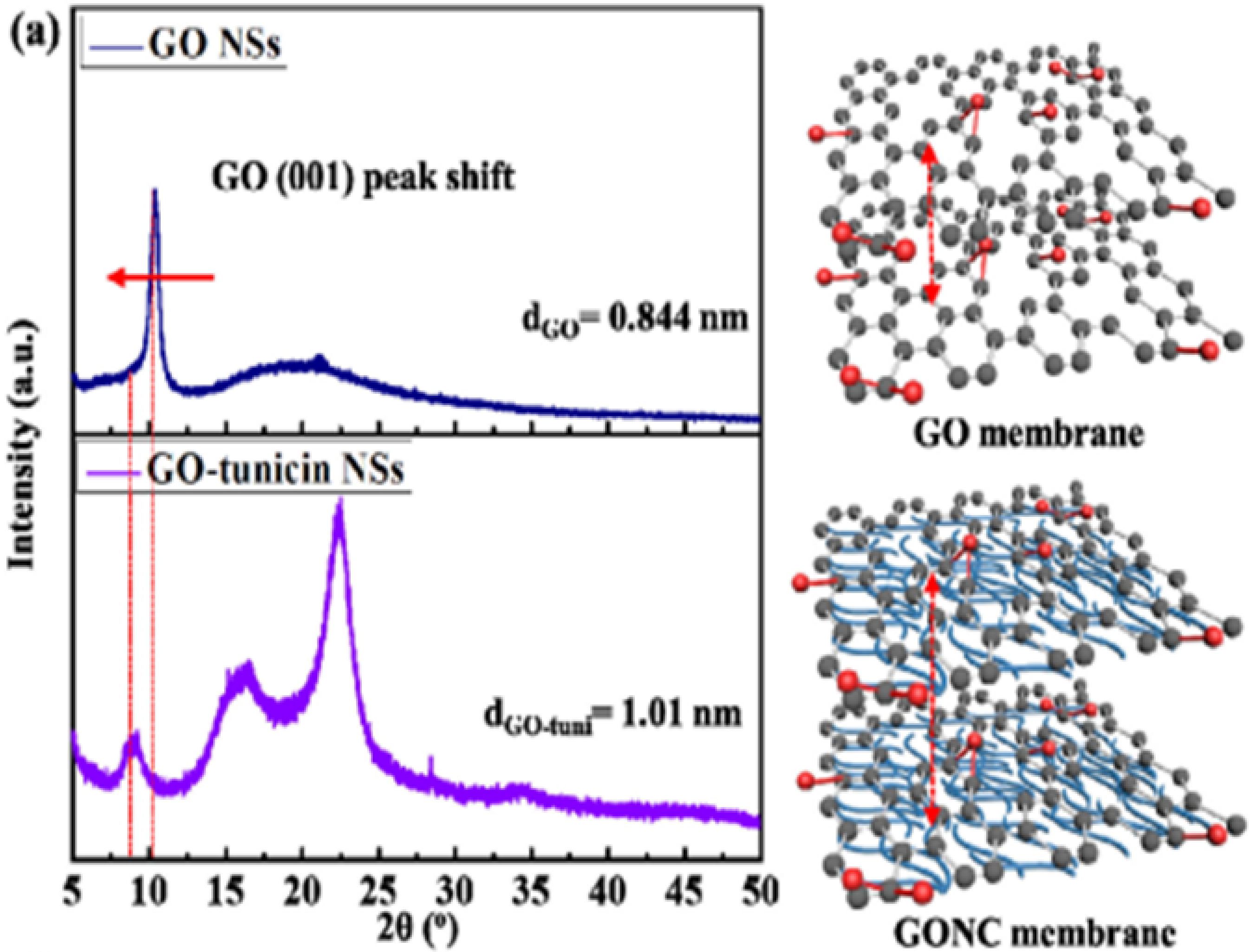

Figure 5

XRD patterns of GO and GONC with corresponding d-space values, and schematic images of GO and GONC. Reproduced with permission (Jung and Jang 2021). Copyright 2021, Korean Sensors Society.

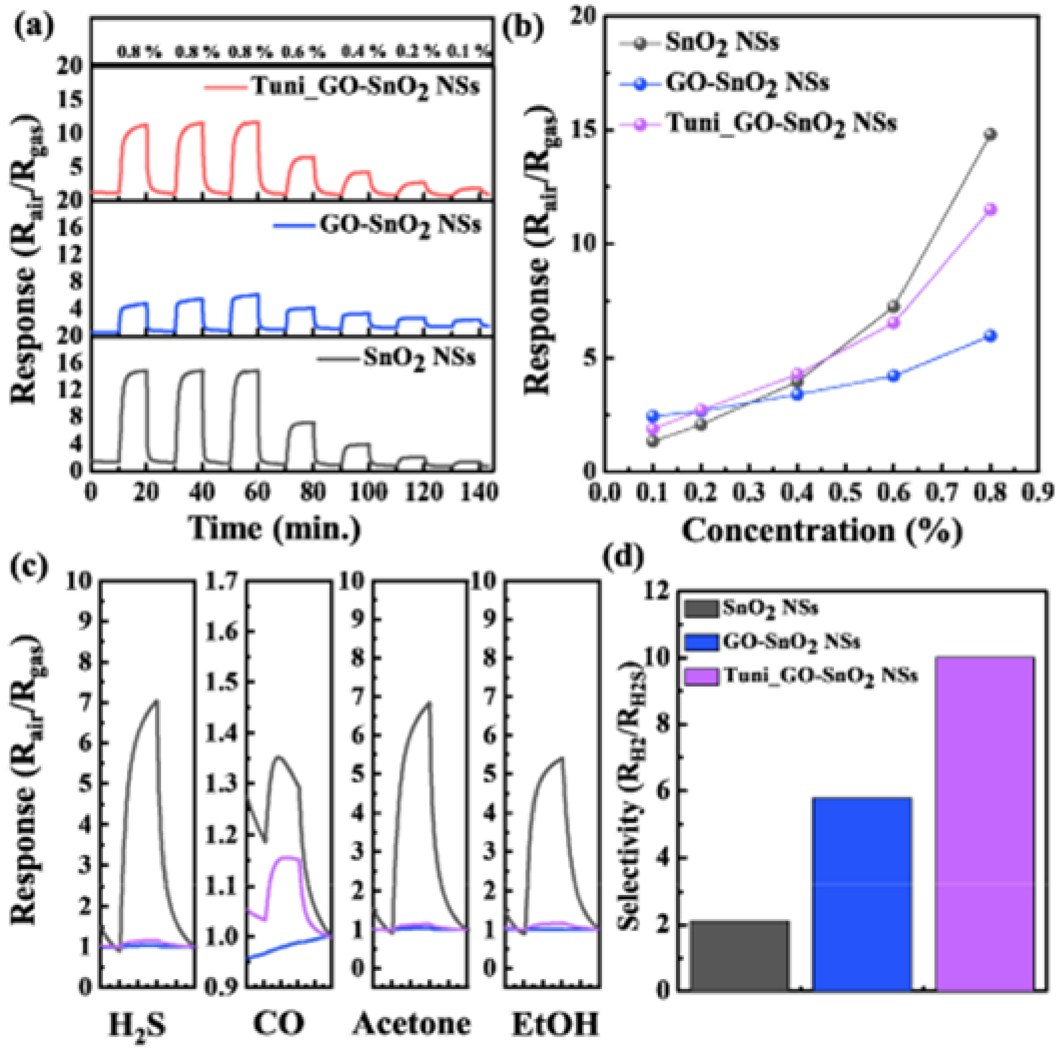

Figure 6

a) Hydrogen gas sensing properties of SnO_2 NS-, SnO_2 NSs@GO-, and SnO_2 NSs@GONC-based sensors, b) graph of hydrogen gas response values with respect to hydrogen gas concentration, for each sensor, c) sensing response kinetics of each sensor to H_2S, CO, acetone and ethanol, d) sensing selectivity polts of SnO_2 NS-, SnO_2 NSs@GO-, and SnO_2 NSs@GONC-based sensors. Reproduced with permission (Jung and Jang 2021). Copyright 2021, Korean Senors Society.

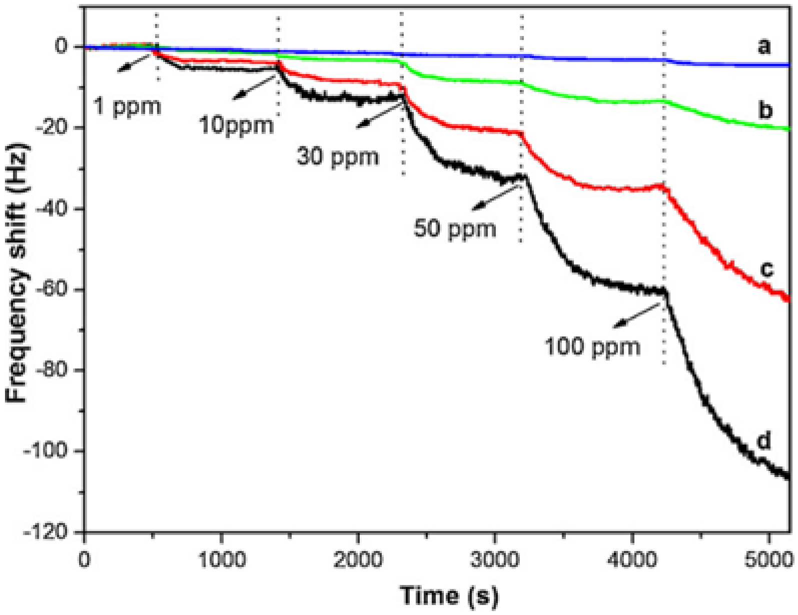

Figure 7

Response of sensors coated with (a) BC membrane, (b) PEI membrane, (c) PEI/BC membranes with a weight ratio of 0.67/1 and (d) PEI/BC membranes with a weight ratio of 1.34/1. Reproduced with permission (Hu et al. 2011). Copyright 2011, Elsevier.

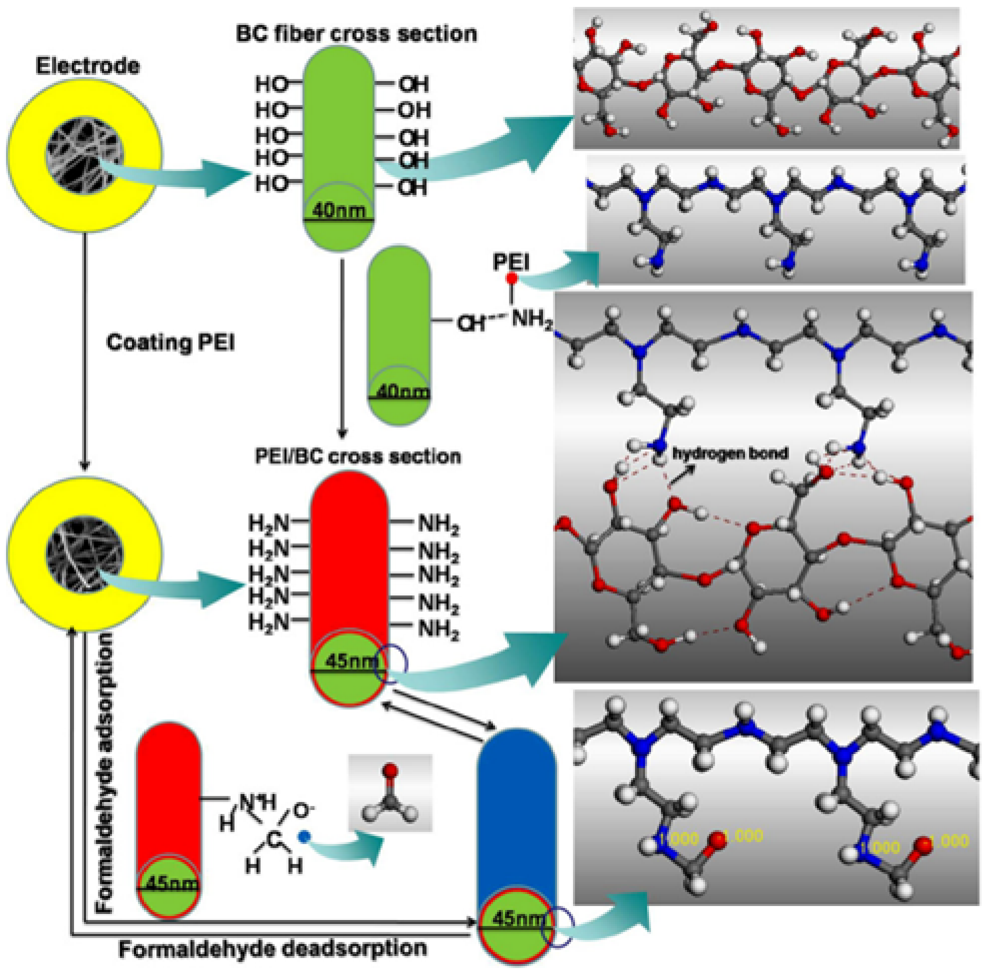

Figure 8

Schematic diagram of the interaction of BC and PEI, and formaldehyde and PEI. Reproduced with permission (Hu et al. 2011). Copyright 2011, Elsevier.

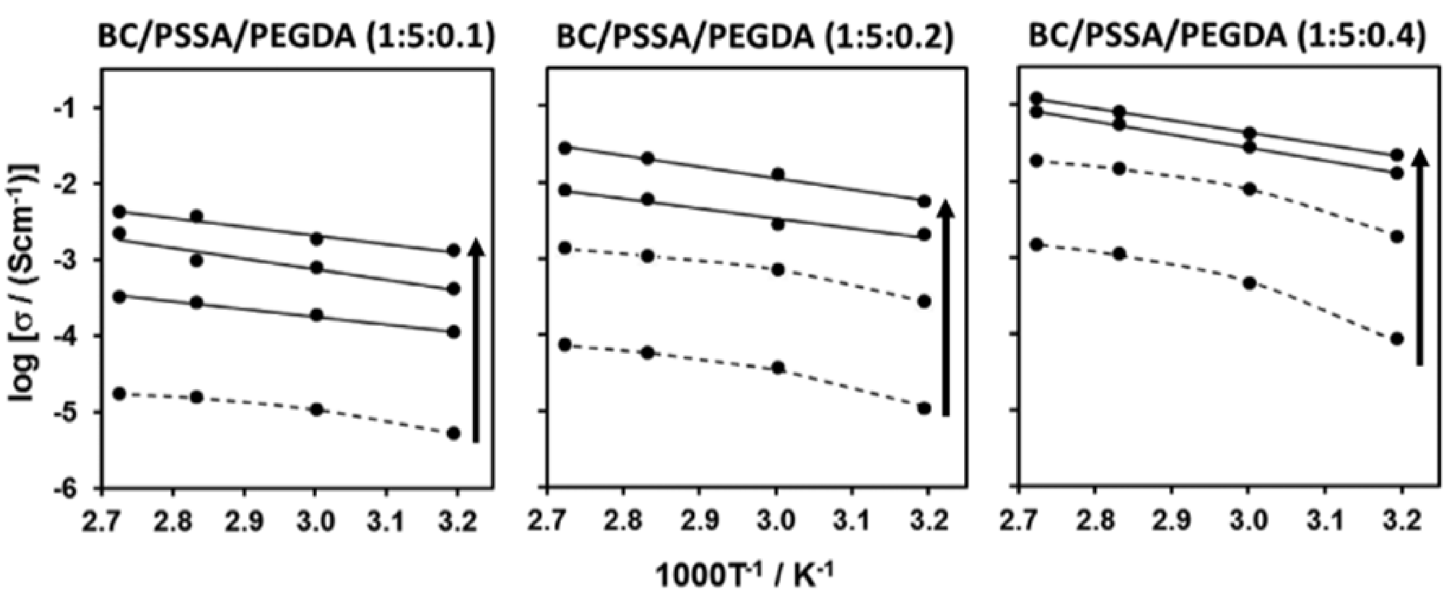

Figure 9

Arrhenius plots of the total conductivity of nanocomposite membranes with variable content of cross-linker measured at RH of 30%, 60%, 80% and 98% (increasing in the direction of the arrows). The straight lines are linear fits to the Arrhenius model, whereas the dashed curves are fits to the Vogel-Tamman-Fulcher (VTF) equation. Reproduced with permission (Gadim et al. 2014). Copyright 2014, American Chemical Society.

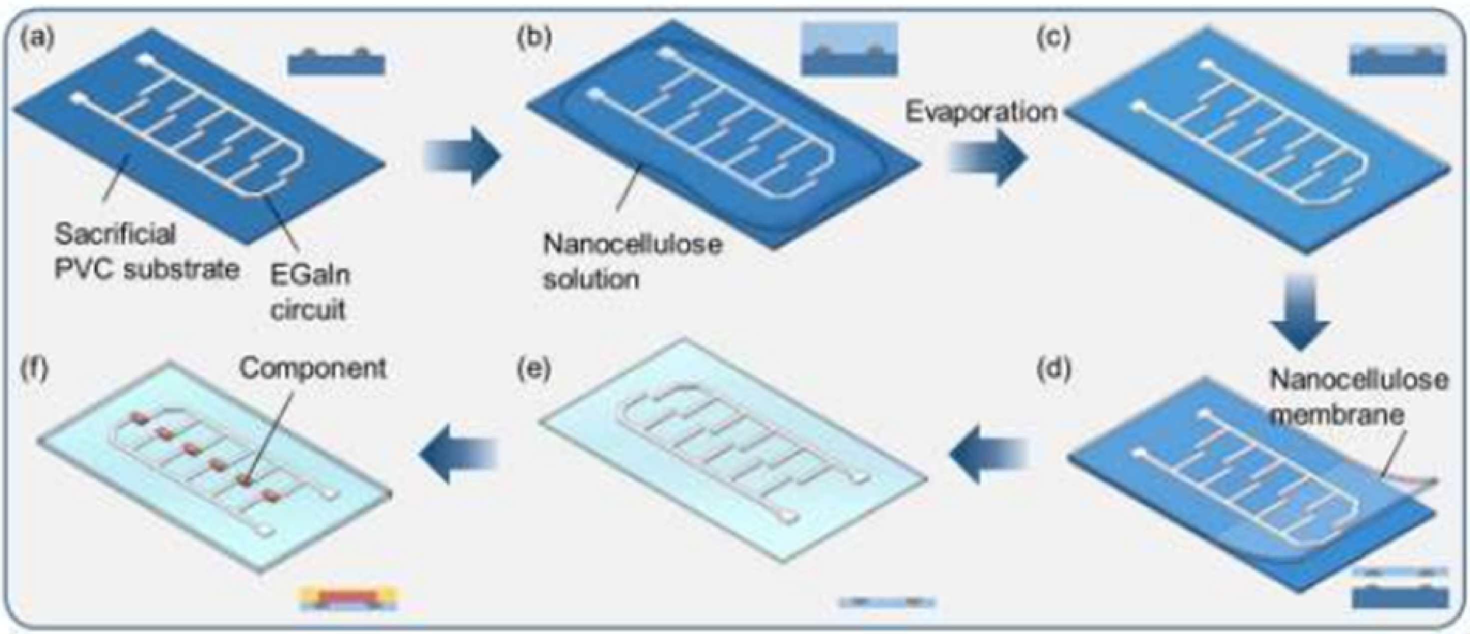

Figure 10

Schematic diagram of the process of the fabrication of the NC-LM circuit using the evaporation-induced transfer printing technology: a) Printing liquid metal circuit on a PVC substrate b) Pouring the nanocellulose solution onto the PVC substrate c) Evaporation and fil-formation d) Peeling the NC-LM circuit off the sacrificial substrate e) NC-LM circuit with EGaIn ink embedded in the nanocellulose membrane f) Mounting the components. Reproduced with permission (Mao et al. 2021). Copyright 2021, Elsevier.

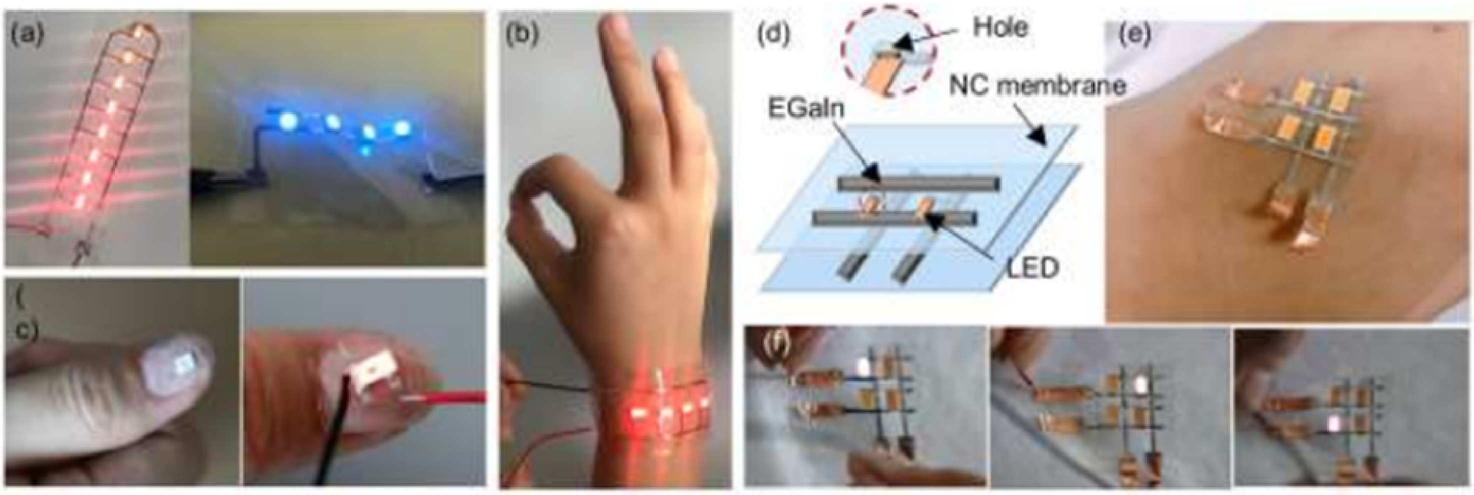

Figure 11

Samples of the NC-LM circuit and its applications in the double-layer circuit fabrication: a) Flexible NC-LM circuits connected with LEDs b) NC-LM circuit rolled around the wrist as a wristband c) a tiny NC-LM circuit stuck to the fingernail compliantly d) schematic diagram of the double layer NC-LM circuit e) practical pictures of a 2*2 LED array circuit f) performance of the LED array circuit. Reproduced with permission (Mao et al. 2021). Copyright 2021, Elsevier.

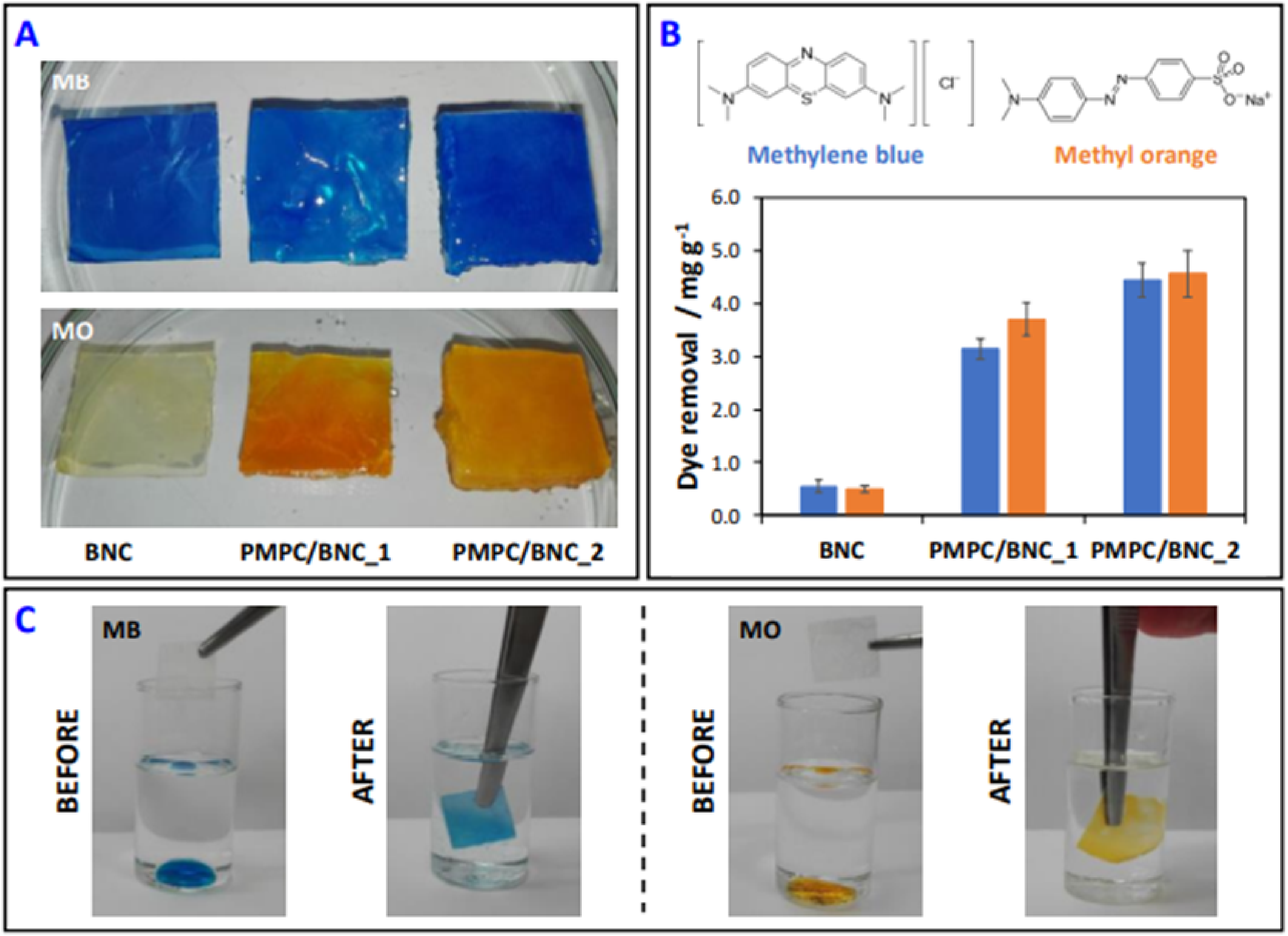

Figure 12

A, B) Photographs depicting the dye removal capacity of BNC, PMPC/BNC-1 and PMPC/BNC-2 after 12 hr immersion in dye aqueous solution and C) photograph of MB and MO aqueous solution removal from paraffin wax oil by PMPC/BNC-2. Reproduced with permission (Vilela et al. 2019). Copyright issued by creative commons license, MDPI publisher,2019.