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Water Purification in the Bioeconomy: Nanocellulose–Cellulose Acetate Reverse Osmosis Membranes

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Received: 30 June 2026 | **Revised:** 28 July 2026 | **Accepted:** 4 August 2026

Keywords: cellulose acetate | desalination | membrane | nanocellulose | reverse osmosis

ABSTRACT

Water purification via reverse osmosis (RO) is a key technology benefiting societies worldwide. Widely used at residential, commercial, municipal, and industrial level, RO purification systems are employed also for medical applications as well as for seawater desalination. The semipermeable asymmetric membrane is the key enabling technology for modern reverse osmosis. Following the conclusion of the nanocellulose hype technology cycle, this study proposes a practical framework for the development of nanocellulose–cellulose acetate nanocomposite RO membranes. A bioeconomy perspective on the technology concludes the study.

1 | Introduction

Water purification via reverse osmosis (RO) is a key technology benefiting societies worldwide [1]. Widely used at residential, commercial, municipal, and industrial level, RO purification systems are employed also for medical applications as well as for seawater desalination. The semipermeable asymmetric membrane invented by Loeb and Sourirajan in 1962 is the key technology enabling reverse osmosis. The scientists casted a thin film acetone-based solution of cellulose acetate (CA) in the presence of dissolved magnesium perchlorate acting as "pore-producing agent" [2]. The resulting CA membrane made via said "phase inversion technique" had an asymmetric structure: a dense active surface layer 0.1–0.2 μm thick (responsible for the salt rejection property) formed on the side exposed to air, supported by an underlying 100–200 μm thick porous layer. The new physically asymmetric but chemically homogeneous CA membrane reached performance levels an order of magnitude greater than modified cellulose acetate ultrafiltration membranes marketed by a German company [1].

Owing to better rejection and flux at lower operating pressures than conventional asymmetric CA membrane resulting in lower power consumption, today most world's seawater reverse osmosis (SWRO) desalination plants primarily rely on RO using thin film composite (TFC) polyamide (PA) membrane for salt removal developed by Cadotte in 1972 [3]. The interfacial composite PA membrane (the membrane industry standard known today as FT30) typically consists of a polysulfone porous support layer (50 μm thick) and a thin film dense layer (0.2 μm thick) made of a salt rejecting fully aromatic polyamide obtained from in situ interfacial polymerization reaction of a polyfunctional amine such as *m*-phenylenediamine with a polyfunctional acid chloride such as trimesoyl chloride [4].

The relatively low energy cost of water desalination over PA membranes, today about 2.25 kWh/m^3 (with a theoretical minimum energy for desalination of seawater with a salinity of 35 g/L being about 1.07 kWh/m^3 at 50% recovery) is substantially lower than other desalination technologies making RO the technology of choice [5]. According to recent estimates, 5015 desalination plants with a minimum capacity of 2000 m^3/d using RO technology were in operation worldwide in 2025 for an overall freshwater production capacity of 90 (89.4) million m^3/d [6]. Due to the higher chlorine resistance when compared to PA membranes, asymmetric CA membranes in 2012 were used in about 25% of RO water desalination plants [7], chiefly for the purification of dirty waters that would severely foul PA membranes, which have a rougher surface [8]. Today, the share of desalination plants using CA membranes is likely lower than 10%.

In 2024, sales of PA membrane exceeded 78% of $4.3 billion RO membrane market, with half (49%) supplied to desalination plants and the remainder split between RO purification systems (residential, commercial, municipal, and industrial), and for medical use (for hospitals, dialysis and other medical devices) [9]. Driven by rapidly expanding demand in all three main sectors, the RO membrane marked is expected to reach $9.5 billion by 2034, growing at annual growth rate exceeding 8% from 2025 to 2034.

Since the early 2000s, research in the field of seawater desalination via RO is flourishing [10]. The main goal is to reduce desalination economic (and environmental) costs by increasing the energy and material efficiency of membrane-based desalination technology. Research is aimed at finding ways to valorize brine by-product of desalination [1], as well as to develop membranes of lower cost and longer durability compared to PA membranes.

Research achievements of practical relevance include the recent introduction of a new process technology developed in Great Britain in which water is treated in discrete cycles recirculating the solution [11]. The method reduces energy costs, maximizes recovery, and reduces the need for antiscalants. Traditional RO technology indeed uses constant high pressure and keeps the membranes exposed to highly concentrated feedwater. Besides resulting in higher energy demand and brine waste production, this leads large RO plants to use chemical pre-treatment (specifically softeners to reduce water hardness, antiscalants to inhibit mineral precipitation, and biocides to manage microbial growth) to prevent severe membrane fouling and scaling. Without this, inorganic scale, colloidal silt, and biofouling would quickly reduce permeate flow, increase pressure, and cause irreversible membrane damage [12].

Thanks to its exceptional mechanical strength, and tunable surface, nanocellulose in all its main forms cellulose nanocrystal (CNC), cellulose nanofiber (CNF), and bacterial nanocellulose (BC) has attracted substantial research interest to develop nanocellulose-based membranes for water desalination. Yet, due to its much higher cost when compared to other polymeric matrix material, research on new RO desalination membranes based on nanocellulose has chiefly focused on its use as nanofiller to produce enhanced PA membranes [13].

Following the conclusion of the nanocellulose hype technology cycle [14], this perspective study investigates the feasibility of nanocellulose-based RO membranes in which nanocellulose and cellulose acetate are used to fabricate the membrane. As recently done by Seibel and coworkers with their review on reuse of spent RO membranes [15], this study proposes a practical framework for the development of NC@CA membranes. Aimed to foster practically relevant developments, this study critically analyzes the current limitations, recent selected experimental findings, technological barriers, and commercialization challenges.

2 | Why Nanocellulose–Cellulose Acetate Membranes?

In 2007, researchers in the USA developed a new generation of cellulose acetate membranes affording higher (99%) rejection of salts than conventional CA membranes (97%) [16]. Requiring no changes to CA membrane manufacturing equipment, and suitable as a drop-in replacement for existing CA membranes, the new membrane manufacturing process involves dissolving the CA in a green solvent such as 2-methyltetrahydrofuran in order to remove rod-like impurities, followed by precipitation of purified CA with an excess methanol. This not only removes rod-like impurities present in commercial cellulose diacetate consisting of low molecular weight polymers, eventually affording a CA of higher molecular weight, but also results in a more robust membrane having smaller pores (higher selectivity) [7].

We briefly remind that the 4-step acetic acid process conventionally used to produce CA in the form of cellulose diacetate comprises: (1) a pretreatment and activation step in which wood pulp cellulose is disintegrated, sprayed and mixed with acetic acid together with a small quantity of sulfuric acid catalyst, (2) an acetylation step in which the activated cellulose is treated with a previously cooled acid mixture of acetic anhydride, acetic acid, and sulfuric acid to produce cellulose triacetate, (3) a ripening step in which cellulose triacetate obtained in the acetylation step is hydrolyzed to give cellulose diacetate, and (4) a final step in which cellulose diacetate is separated from the reaction solution, purified, and dried.

Indeed, the new CA membrane allowed to operate a large RO plant at lower operating pressure due to increased salt rejection and improved flux. In detail, results of long-term pilot tests completed at a RO large water purification plant (Water Quality Improvement Center) in Arizona indicate a threefold decrease in salt passage through the new CA membrane as compared to commercial CA membrane while maintaining equal water production [7].

Clearly illustrating the economic and technology relevance of CA-based RO membranes, the Japan-based manufacturer of membrane cellulose triacetate (CTA)-based hollow fiber (HF) RO semipermeable membrane for SWRO plants, in the early 2020s commercialized one new CTA-HF membrane for brine concentration (BC, via osmotically assisted reverse osmosis process) whose joint RO/BC operation provides a SWRO desalination technology minimizing the volume of brine disposal from the RO plant (by increasing the recovery ratio and the amount of produced freshwater), without requiring extra energy [17]. This example alone shows that the CA-based membrane manufacturing infrastructure (casting, module assembly) is already developed and applied research in the field flourishing. A Japan-Saudi Arabia joint venture company, for example, was established in 2010 as the first company to manufacture in Saudi Arabia CTA-HF membranes supplied to desalination plants in the Arabian Peninsula. Noticeably, the company lately changed name and

TABLE 1 | Selected studies describing research achievements with nanocellulose/cellulose acetate nanocomposite membranes for water purification.

Study	Country	Refs. (Year)
Improved anti-biofouling resistances using novel nanocelluloses/cellulose acetate extracted from rice straw-based membranes for water desalination.	Egypt	[21] (2022)
Nanocellulose acetate membranes: preparation and application.	Iraq	[20] (2021)
Enhanced water filtration performance in electrospun cellulose acetate membranes via TEMPO-mediated cellulose nanocrystal incorporation and hot pressing.	Spain	[23] (2025)
Preparation of nanocellulose acetate from bleached hardwood pulp and its application for seawater desalination.	Vietnam	[19] (2020)
Ultra-high flux alkali-treated cellulose triacetate/cellulose nanocrystal nanocomposite membrane for pervaporation desalination.	Belgium	[22] (2021)
Desalination performance of a forward osmosis membrane from acetylated nata de coco (bacterial cellulose).	Philippines	[34] (2019)

expanded production to meet the growing freshwater demand in the Middle East and Africa [18].

Selected research outcomes briefly reviewed in the following suggest four main reasons to advance applied research aimed at developing new generation nanocellulose/cellulose acetate (NC@CA) composite membranes for water desalination and purification based on reverse osmosis: (i) enhanced separation performance, (ii) enhanced mechanical stability and durability, (iii) reduced biofouling and scaling, and (iv) unique sustainability profile.

Table 1 presents a list of selected studies describing important research achievements in the field of NC@CA nanocomposite membranes, the year of publication, and the country hosting the research team.

2.1 | Enhanced Separation Performance

In 2020 Dien and coworkers in Vietnam reported that nanocellulose acetate (NCA, readily prepared from commercial bleached wood cellulose pulp via a four-step hydrothermal process) employed as a filtration material is able to reduce the salinity of the seawater from 22.9% to 3.9%, while cellulose acetate reduced salinity to 6.2% only [19]. Reuse of the material in a second run reduced salinity from 22.9% to 9.8%. Shortly afterward, researchers in Iraq reported that NCA membranes obtained by expanding a saturated solution of cellulose acetate nanoparticles with an average diameter <40 nm onto a glass surface effectively remove salt from water [20]. In detail, the conductivity of water passing through the membrane reduced conductivity of an aqueous solution of NaCl from 984 to 1.8 µS/cm at a flow rate of 0.7 L/min. The CA nanoparticles were sustainably obtained via hydrolysis and ball milling of cotton obtained in three steps (bleaching, cellulose esterification, and milling).

In 2022 Morsy and coworkers in Egypt reported that a NCA@CA composite membrane prepared with optimal NCA 40% concentration prepared via phase inversion technique dissolving NCA and CA in acetic acid, acetone and dioxane and using methanol as a non-solvent, had 97.2% salt rejection and high flux of 2.2 L/m^{2}h [21].

The membrane has an asymmetric structure consisting of a dense top layer and a porous sublayer (Figure 1) due to nanocellulose fibers leading to formation of finger-like cavities in the sublayer of the prepared membrane. The year before, Van der Bruggen and coworkers in Belgium reported that a simple treatment with aqueous NaOH for 30 min of cellulose triacetate/cellulose nanocrystal (CTA/CNC) pervaporation desalination membrane resulted in a dramatic improvement in water flux with full retention of its selectivity while being able to handle high salinity feed with stable, excellent performance (salt rejection >99%) during 12 h pervaporation experiments [22]. In brief, alkaline treatment of the CNC@CA nanocomposite membrane resulted in partial deacetylation of CTA resulting into largely enhanced absorption of water compared to the untreated membrane due to the increased hydrophilicity of the treated membrane. Structural investigation unveiled that alkaline treatment does not significantly change the membrane surface morphology bur rather drives a gelation process on the membrane that improves the hydrophilicity, leading to an increased water flux. Though applied in pervaporation membrane these findings are relevant also to forthcoming applications of NC@CA membranes in SWRO desalination plants.

2.2 | Enhanced Mechanical Stability

Noting that nanocellulose membranes offer sustainable alternatives to commercial polyamide RO membranes but generally "lag in commercial maturity and durability" [23], in 2025 Eceiza and coworkers in Spain reported how CNF@CA and CNC@CA membranes obtained via electro-spinning and hot pressing, not only have substantially enhanced filtration performance (in dye removal and microparticle rejection), but also enhanced mechanical strength [23].

Again, membranes were obtained thermal treatment via phase inversion method using a benign acetone/acetic-acid solvent mixture followed by hot pressing at 100°C. SEM imaging clearly showed that membranes functionalized with 1 and 3 wt%

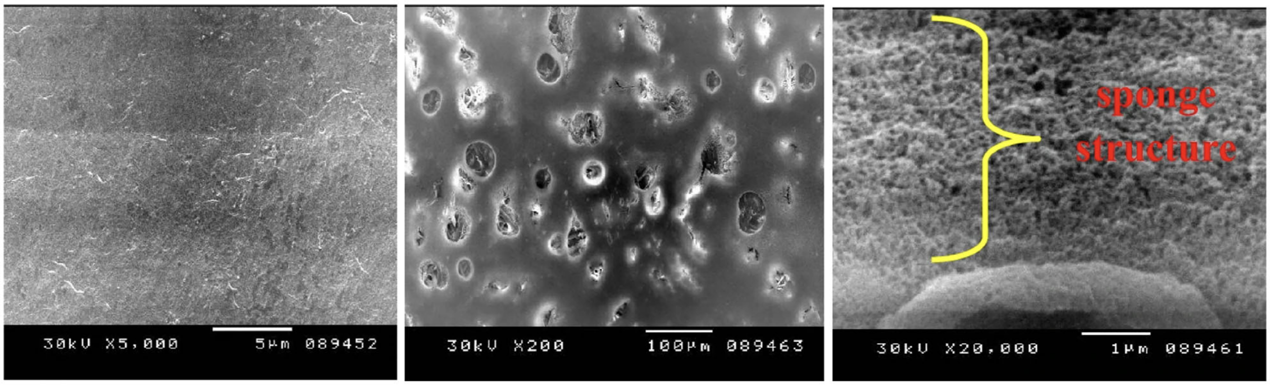

FIGURE 1 | SEM images of surface (left), bottom (middle), and cross section (right) of NCA@CA composite membrane with 40% NCA. Reproduced from Ref. [21], CC-BY Creative Commons License.

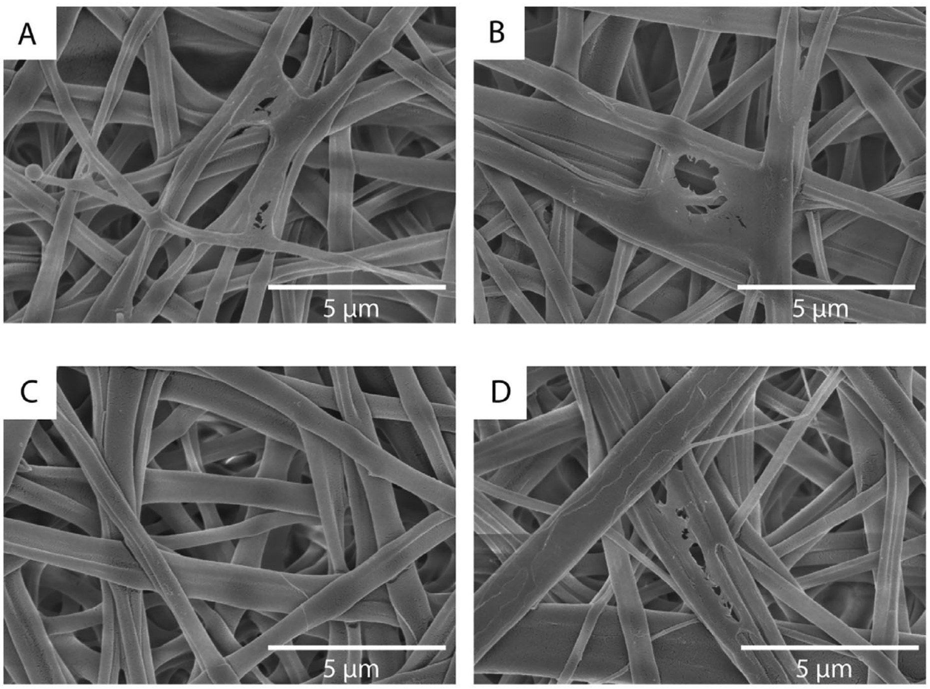

FIGURE 2 | SEM micrographs of 12 wt% CA in 4:1 A:AA (acetone:acetic acid) after hot pressing: (A) upper surface of electrospun CA fibers with 1 wt% CNC dispersion impregnation, (B) upper surface of electrospun CA fibers with 3 wt% CNC dispersion impregnation, (C) upper surface of electrospun CA fibers with 1 wt% CNF dispersion impregnation, and (D) upper surface of electrospun CA fibers with 3 wt% CNF dispersion impregnation. Reproduced from Ref. [23], CC-BY Creative Commons License.

CNC or CNF concentrations altered the morphology within the fiber interstices, though the under-lying fibrous structure remained visible across all functionalized mats (Figure 2). More pronounced morphological changes were observed using higher nanocellulose loads, particularly using CNF obtained via TEMPO-mediated carboxylation of the nanofibers. In brief, CNF exhibited an even stronger degree of interaction with CA fibers, resulting in a higher deposition rate, eventually further improving the mechanical and functional properties of the membranes.

2.3 | Reduced Biofouling and Scaling

CA membranes are substantially less prone to scaling when compared to rough PA membranes [24]. For example, comparison of the latter membranes in forward and reverse osmosis under silica scaling shows that the flux decline rates for both membranes are similar, but the flux recovery after cleaning with deionized water (around 80% in the RO mode) for the CA membrane was 30–40% higher than that of the PA membrane [25]. Atomic force measurements indicate that membrane surface roughness increases the adhesion force between the PA membrane and a silica gel layer, significantly decreasing the cleaning efficiency of the PA membrane.

In general, CA membranes are generally less prone to organic and biofouling compared to PA thin-film composite membranes, primarily due to their higher surface hydrophilicity and nm-scale smoother surface morphology which reduces the surface area available for protein attachment [26]. Remarkably in view of forthcoming practical applications, CA membranes functionalized with nanocellulose show substantially lower protein (albumin) adsorption due to surface containing a nm-scale homogenous mixture of strongly hydrated negatively charged carboxylate groups of nanocellulose imparting strong electrostatic repulsion with the negatively charged protein [27, 21]. Similarly, addition of negatively charged nanochitosan particles CA-based membranes increases both structural stability membrane hydrophilicity, decreasing protein adsorption and significantly improving antifouling performance [28].

Immersed in river water or seawater, cellulose acetate slowly undergoes hydrolysis due to the action of microorganisms more abundant in river water and significantly slower in seawater in which bacterial density generally ranges from 10^4 to 10^6 per milliliter [29]. To further enhance the chemical stability of CA-based membranes in large-scale desalination plants standard CA made of cellulose diacetate (DCA) was replaced long ago by cellulose triacetate (CTA) which resists harsh pH swings and biological degradation [17]. Contrary to PA membranes that do not bear chlorine concentration >1 ppm, CTA is stable in the presence of chlorine enabling the use of chlorine injection as antifoulant for RO membranes in large SWRO plants. In other words, CTA-based membranes can be used for stable RO operation without any biological fouling problems for a long period by implementing a simply controlled intermittent chlorine injection [17]. Indeed, already in the late 1990s experimental tests for seawater desalination at Las Palmas, Spain, using a module made of CTA-based hollow-fiber membranes clearly showed that the module was able to produce high-quality water without any chemical cleanings during 4600 h operation thanks to its high chlorine resistance and anti-biofouling tolerance [30].

Modules for SWRO plants based on CA membranes certified to have a salt rejection rate of 99.8% (pressure of 5.39 MPa, seawater feed containing 35 g/L NaCl at 25°C) are supplied with specification of being stable in operating pH range of feed water between 4 and 8, with feed water temperature that should not exceed 40°C [31].

2.4 | Unique Sustainability Profile

The use of renewable, biodegradable and biocompatible NC@CA composite membranes in RO plants would provide a solution to the environmental impact of waste from spent RO membranes. Unlike synthetic polymers that persist in the environment, semisynthetic cellulose acetate films are compostable. For example, manufacturers of CA films ensure that their products are certified as being industrially compostable according to the European (EN13432) or American (ASTM D6400) standard [32].

CA, furthermore, is a renewable polymer that today can be prepared in new and sustainable ways, for example via the eco-friendly, solvent-free acetylation of biowaste cellulose feedstocks catalyzed by iodine [33, 34].

Similarly, CA can be readily obtained via acetylation of nata de coco (NDC), affording membranes produced via the phase inversion technique showing analogous excellent desalination performance (water flux and salt rejection ability) [35]. Separation performance growing with increasing polymer concentration suggests that performance is inversely correlated with the pore size (the smaller the membrane pore size the better salt rejection).

Usually produced from coconut water (or coconut milk) by the microorganism *Acetobacter aceti* subsp. *xylinum* through a fermentation process under static conditions, nata de coco is one of the first commercially available products of bacterial nanocellulose [36]. Originated in the Philippines during the 1990s and soon spread to nearby countries, production of NDC is carried out by large and mid-size companies and small companies in East Asian countries such as the Philippines, Indonesia, China, Vietnam, Malaysia, Japan, and Thailand.

PA membranes used in RO desalination plants have a short lifespan of 2–5 years [15]. Currently, more than 1 million spent RO membranes are discarded every year, with an annual growth rate exceeding 8% due to ongoing expansion of seawater desalination generating a substantial amount of contaminated polysulfone and polyamide plastics [37].

3 | Technological Barriers and Commercialization Challenges

To date (mid 2026) no nanocellulose-based membranes for water purification via RO has been commercialized. To investigate whether nanocellulose-based membranes are practically suitable for replacing PA membranes, we asked the opinion of Professor Hsiao, a leading expert in nanocellulose for water purification [38]. Co-inventor with Sharma of the nitro-oxidation process for nanocellulose production combining pulping and oxidation in one step by treatment of untreated biomass (typically, a non-wood plant) with nitric acid and sodium nitrite at 50°C for 12 h [39], Professor Hsiao considers these membranes more suitable for forward-osmosis desalination:

"I think nanocellulose-based membrane may be more suitable for forward-osmosis desalination, which has not yet been fully adopted by the industry due to economic reasons. For reverse-osmosis desalination, the benefits of involving nanocellulose to enhance polyamide membranes are only marginal. However, nanocellulose-derived microfiltration, ultrafiltration and specialty membranes (e.g., MBR) can definitely displace many polymeric counterparts in the future. Unfortunately, there are not yet commercialized nanocellulose-based membranes for water desalination. However, my startup company SWFTLABS (www.swftlabs.com) will probably start commercializing nanocellulose-based adsorbents for PFAS removal soon [40]".

Evidence of company's interest in nanocellulose/cellulose acetate membranes for water purification via reverse osmosis across the world is shown for instance by an ongoing industrial-academic collaborative project in Vietnam [41] based on research conducted at Hanoi University of Science and Technology [19].

In general, for a biobased product to replace an alternative product sourced from oil, the required bioproduct needs to outcompete the oil-derived alternative in terms of price, quality and ease of supply [42]. Competitive price is achieved via a green (waste-free) chemistry production route starting from low-cost and readily accessible raw material. Product quality and ease of supply can be achieved through a lean, digitally managed production process affording batch-to-batch consistency so as to meet purity and reproducibility requirements of advanced applications such as RO water purification.

Remarkably, a similar shift is taking place with new nanocellulose production routes, which rather than relying on cellulose pulp sourced at high economic and environmental cost from lignin-rich wood, are shifting to lignin-poor cellulose feedstocks such as agro-industrial waste (citrus processing waste, rice husk, etc.) and non-wood plants, adopting new, greener production routes.

One new nanocellulose company based in South Korea, for example, uses discarded biomass feedstock including rice husk as raw material due to its high cellulose content and large availability at low cost [43], whereas the aforementioned NOP process has been scaled up to 1 ton using raw jute as cellulose feedstock [44].

For nanocellulose to enter large-volume product markets such as construction materials, membranes, and consumer goods, its price (>$20/kg in 2023) needs to be reduced to $2–3/kg [45]. The large of amount of electrical energy required to fibrillate cellulose nanofibers (20 000–70 000 kWh per ton) and obtain CNC or CNF following partial functionalization of cellobiose units (with sulfate groups in the case of CNC, carboxylates or phosphorylates in the case of CNF) explains why commercialization of nanocellulose remained confined to a few high-performance products [46]. Since the early 2020s, however, the emergence of the first green production routes applied to lignin-poor biomass feedstocks is achieving long-awaited reduction in production cost [47].

New generation NC@CA membranes would employ high quality (high molecular weight) CA previously purified from the rod-like impurities discovered in commercial CA, and eventually removed [7, 16]. Furthermore, CA would no longer be produced by the acetic acid process, but rather via the eco-friendly, solvent-free acetylation of agricultural waste cellulose catalyzed by iodine.

In brief, nanocellulose/cellulose acetate composite membranes hold potential to compete with PA membranes in RO desalination plants. The prohibitively high price of nanocellulose that for decades limited uptake of nanocellulose in nearly all industrial sectors is a thing of the past [14]. When and if applied research will demonstrate prolonged durability of economically viable NC@CA nanocomposite membranes showing high separation performance, said RO membranes will be commercialized. It is instructive, therefore, to learn that selected nanocellulose companies lately started commercialization of advanced semipermeable nanocellulose-based membranes for electrochemical applications [48].

In addition, the design and development of high-performance RO membranes made of nanocellulose/cellulose acetate will use machine learning (ML) models to identify the optimal synthesis protocol for RO performance (highest salt rejection, and permeate flux, minimal biofouling, and prolonged membrane durability) reducing experimental costs and process time [49]. In this manner, rather than by the time-consuming and expensive experimental study of the impact of the numerous individual parameters on membrane properties and performance, the optimal membrane synthesis conditions (type of solvent, relative amounts of nanocellulose and cellulose acetate, amount of water, post-synthesis thermal treatment) will be readily identified computationally via ML technique describing the membrane performance as a function of its synthesis protocol [50].

For example, recently Mohammadi and coworkers used a ML genetic algorithm to identify the optimal values for various parameters (including polymeric precursors concentration, nano-additive concentration in casting solution, concentration of solvent, concentration of pore forming agent, forward osmosis process temperature, etc.), to prepare forward osmosis membranes having the highest performance in water purification [51].

4 | Conclusions

Today used in less than 10% of RO desalination plants (though very large ones, chiefly based in the Middle East), cellulose acetate was the polymer comprising the original commercial asymmetric membranes for water desalination via RO. New generation CA membranes fabricated from purified CA free from rod-like low molecular weight polymers afford vastly superior asymmetric membranes showing separation performance levels (salt rejection and flux) comparable to state of the art polyamide membranes currently dominating the RO membrane market, though requiring a higher electricity input in SWRO plants.

A clear distinction should be made between experimentally demonstrated facts and future expectations.

Experimental facts briefly summarized in this study show that enhanced cellulose diacetate of lower cost and higher quality today may be produced via the solvent-free catalytic route starting from agricultural waste cellulose feedstocks or from nata de coco, in place of the acetic acid process conventionally used to acetylate wood pulp cellulose. Other experimental facts demonstrated on laboratory scale are that added to cellulose triacetate to form the nanocomposite NC@CA membrane via phase inversion technique, due to its negative charge and unique nanoscale morphology, nanocellulose enhances separation performance, mechanical properties (strength and flexibility), fouling and scaling resistance. Finally, these new membranes might be particularly well suited for use in new generation RO water purification systems employing reduced average operating pressure thanks to treatment of water in discrete cycles recirculating the solution.

However, stable enhanced performance of nanocellulose–cellulose acetate nanocomposite membranes under real SWRO desalination plant conditions remains to be demonstrated. Similarly, the uptake of NC@CA membrane manufacturing requires to demonstrate its technical and economic viability. When (and if) applied research will achieve these key objectives, these biobased membranes will enter the multibillion RO membrane market.

Supporting expectations is the fact that today numerous suppliers of nanocellulose of reliable high quality now exist from which CA-based manufacturers will be able to source either cellulose nanocrystal or cellulose nanofiber to prepare the nanocomposite membranes. This study provides an actionable insight aimed at fostering practically relevant developments. Should the aforementioned objectives be achieved, a new era in RO membrane manufacturing will commence, reconnecting the industry's future with its origins since for more than a decade since the invention of the RO asymmetric membrane, CA-based membranes were the RO membranes of choice in the SWRO desalination industry.

Author Contributions

Rosaria Ciriminna: conceptualization, methodology, writing – review and editing, formal analysis, and funding acquisition. **Giuseppe Angellotti:** writing – review and editing, formal analysis, and methodology. **Giovanna Li Petri:** writing – review and editing, methodology, and formal analysis. **Cristina Della Pina:** conceptualization, methodology, writing – review and editing, and formal analysis. **Mario Pagliaro:** conceptualization, methodology, writing – original draft, formal analysis, and supervision.

Acknowledgments

M.P. thanks Professor Benjamin Hsiao, Stony Brook University, United States of America, for helpful correspondence. R.C. and M.P. thank Italy's Ministero dell'Università e della Ricerca for funding, "Progetto FutuRaw. Le materie prime del futuro da fonti non-critiche, residuali e rinnovabili," Fondo Ordinario Enti di Ricerca, 2022, CNR (CUP B53C23008390005).

Open access publishing facilitated by Consiglio Nazionale delle Ricerche, as part of the Wiley - CRUI-CARE agreement.

Funding

R.C. and M.P. thank Italy's Ministero dell'Università e della Ricerca for funding, "Progetto FutuRaw. Le materie prime del futuro da fonti non-critiche, residuali e rinnovabili," Fondo Ordinario Enti di Ricerca, 2022, CNR (CUP B53C23008390005).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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