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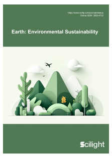

Perspective

Biodesalination: Can Nature Help Solve the Global Freshwater Crisis?

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Abstract: Water scarcity is a pressing global challenge affecting over 2.2 billion people. The increasing demand for freshwater, driven by population growth, water pollution, industrialisation, urbanisation and climate change, has intensified pressure on conventional freshwater sources. With over 97% of Earth's water stored in oceans, desalination of seawater has become an increasingly attractive strategy to augment water supply, particularly in arid and semi-arid regions. Conventional desalination technologies, including reverse osmosis (RO), multi-stage flash distillation, multi-effect distillation, and electrodialysis, have demonstrated high efficacy in converting saline water into potable water. However, these systems are associated with several critical drawbacks, including high energy consumption, greenhouse gas (GHG) emissions, substantial operational and capital costs, and the generation of concentrated brine, which can severely impact marine ecosystems when discharged untreated. For instance, RO plants typically consume 3–4 kWh/m^3, while thermal desalination approaches may require 10–15 kWh/m^3. Furthermore, fossil-fuel driven desalination contributes approximately 0.3–1.7 kg CO_2 per m^3 of water produced, highlighting the urgent need for more sustainable and energy-efficient desalination solutions. Biodesalination has emerged as a promising alternative, harnessing biological systems and bioinspired mechanisms for salt removal. This paper explores the principles, mechanisms, recent advances, and prospects of biodesalination as a sustainable approach. These include: (i) aquaporin-based biomimetic membranes that offer exceptional water permeability and selectivity; (ii) microalgal systems such as *Chlorella vulgaris* and *Arthrospira platensis* capable of 28–82% salt removal through biosorption and bioaccumulation; (iii) genetically engineered cyanobacteria with enhanced ion-exchange capacities; (iv) halophilic microorganisms capable of thriving in high-salinity environments; (v) halophyte-based phytodesalination; and (vi) microbial desalination cells (MDCs), which integrate desalination with wastewater treatment and bioelectricity generation (achieving up to 1.8 kWh/m^3). Biodesalination offers a low-energy, sustainable alternative to tackle the global freshwater crisis. Leveraging biological and nature-driven processes alongside engineering innovations and data-driven optimisation and scale-up, it can complement or partially replace conventional desalination, contributing to achieving the UN Sustainable Development Goal 6 (Clean Water and Sanitation).

Keywords: aquaporin; bioaccumulation; bioelectrode; biodesalination; biosorption; biomimicry; desalination; phytodesalination; microalgae; halophiles, and microbial desalination cells (MDCs)

1. Introduction—A World Running Out of Fresh Water

Water scarcity is an escalating global crisis of the 21st century. More than 2.2 billion people already live in regions facing severe water shortage, and the demand for freshwater is projected to increase with rising populations, intensive agriculture, industrialisation and climate change [1]. Without robust and manageable new strategies, water stress will threaten economic development, public health and food security [2,3]. With the abundance of seawater resources, desalination is used increasingly to augment freshwater supplies in arid and semi-arid regions. Desalination is essentially the process of converting salty seawater into freshwater that can be used for drinking, agriculture, and various domestic and industrial purposes. Operating as a super-powered filter, seawater enters the desalination unit, salt and other dissolved ions are removed, and clean water is discharged. This paper is structured to discuss the potential application of biodesalination as a sustainable alternative to conventional desalination technologies. The concepts of biodesalination, ranging from bioinspired approaches to bioelectrochemical systems, are discussed.

2. Conventional Desalination: Energy-Intensive and Unsustainable

Conventional desalination technologies such as reverse osmosis (RO), multi-stage flash distillation, multi-effect distillation, vapour compression, and electrodialysis have proven effective in producing freshwater from seawater [4]. Nevertheless, these technologies come with significant drawbacks. They demand substantial capital investment and high operational costs, and consume large amounts of energy, making them difficult to implement in resource-limited regions [5]. Seawater reverse osmosis (SWRO) plants typically require about 3–4 kWh/m^3 of electrical energy, while thermal desalination, such as multi-stage flash distillation, consumes about 10–15 kWh/m^3 of energy equivalent [6]. This energy requirement directly impacts operational expenditure (OPEX), as SWRO desalination typically costs between USD 0.39–0.66 per m^3 of water produced, with energy consumption accounting for about 40–60% of total OPEX [7,8]. Moreover, most desalination plants (e.g., Figure 1) rely on fossil-fuel energy, contributing to greenhouse gas emissions [4,5]. Conventional fossil-fuel-driven RO emits approximately 0.3–1.7 kgCO$_2$/m^3 of produced water, highlighting the necessity for transitioning to sustainable energy sources [9]. Global desalination plants collectively produce approximately 141.5 million m^3 of brine daily. Most of the concentrated brine is discharged back into the oceans, often with minimal treatment, contributing to environmental pollution, which negatively affects marine ecosystems [10].

Figure 1. Rabigh 3 Independent Water Plant (IWP) in Saudi Arabia with a total capacity of 600,000 m^3/day.Reprinted with permission from Ref. [11]. Copyright 2026, Veolia Water Technologies.

For desalination systems to become sustainable in the long term and contribute to the UN Sustainable Development Goal 6 (Clean Water and Sanitation), they must evolve towards a circular economy approach, maximising resource recovery from every litre of seawater while maintaining a low environmental footprint at minimal cost [12]. Scientists and engineers are now turning to an alternative approach that looks to nature itself: Biodesalination. Biodesalination offers potential sustainability benefits, as systems such as microbial desalination cells (MDCs) utilise the chemical energy stored in organic substrates to drive ion transport, thereby reducing or eliminating the need for external energy input for desalination. However, ancillary energy requirements (e.g., pumping and post-treatment remain necessary for practical operation. Biological systems operate at ambient temperature and pressure, thereby reducing energy demand [6,13]. For instance, Microalgae-based biodesalination harnesses solar energy through photosynthesis, with a preliminary life-cycle analysis suggesting potential energy reductions of 30–50% compared to conventional RO [6,13]. Furthermore, algae-based biodesalination has demonstrated the potential to sequester CO_2, thereby offsetting operational emissions, with studies reporting sequestration rates of approximately 0.15–0.30 kg of CO_2 per m^3 of treated water [6,13]. Microbial Desalination Cells (MDCs), which are bioelectrochemical technologies, can generate about 1.8 kWh of bioelectricity from about 1 m^3 of wastewater while simultaneously desalinating seawater and treating wastewater [14,15]. MDCs have been shown to reduce the net energy demand of RO systems when applied as a pre-treatment step. Integrating MDCs with conventional desalination technologies offers a promising approach to improving overall energy efficiency [14]. In this hybrid configuration, MDCs partially remove salts from seawater before it enters the RO unit. By lowering the salinity of the feedwater, the osmotic pressure across the RO membrane is reduced, thereby decreasing the hydraulic pressure required for separation and ultimately lowering the energy consumption of the desalination process [14]. Biodesalination systems, unlike conventional desalination, which typically requires extensive infrastructure and reliable energy access, can be installed in decentralised modular units in resource-limited areas to desalinate saline or brackish water from boreholes or underground sources.

3. Biodesalination: Harnessing Nature for Freshwater

Biodesalination is an emerging field which explores how microbes, algae and plants can naturally filter salt from seawater [16]. If developed at scale, it could offer a low-energy, sustainable pathway to expand global freshwater supply [6]. These biological agents not only tolerate salt but also actively manage it to purify water for human use. This approach can reduce net energy consumption and greenhouse gas emissions, while minimising harmful by-products [9,10].

4. Six Promising Directions for Biodesalination

4.1. Aquaporins

A fascinating avenue within biodesalination draws inspiration from aquaporins, specialised water channel proteins found in the cell membrane of all living organisms [17,18]. These proteins were discovered in 1992 by molecular biologist Peter Courtland Agre in the kidneys and red blood cells. Aquaporins enable the selective and highly efficient transport of water molecules while blocking the passage of salts, making them an ideal model for filtration [18,19] (Figure 2). Scientists are now exploring biomimicry to design synthetic membranes that incorporate aquaporin proteins or mimic their structure and function. Such a bioinspired membrane can achieve high water permeability with a good salt removal rate while operating at lower pressure [18]. Commercial aquaporins developed by the Danish water technology company Aquaporin are now in use, providing advanced filtration solutions for applications such as wastewater treatment and desalination [19]. Aquaporin-based biomimetic membranes operate under the same thermodynamic and mechanical constraints as standard filtration methods (e.g., RO). They still require hydraulic pressure exceeding the feed osmotic pressure to drive water transport across the membrane [20,21].

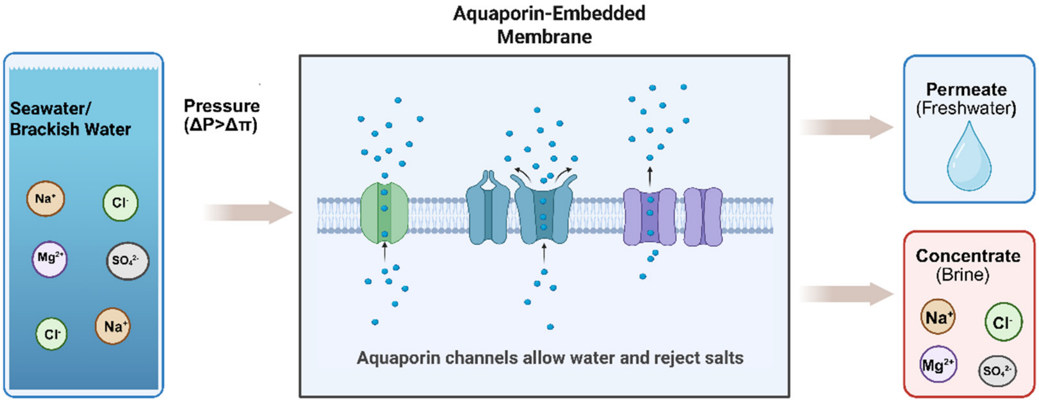

Figure 2. Schematic of aquaporin-based desalination, where applied pressure ($\Delta P > \Delta\pi$, i.e., the applied pressure exceeds the osmotic pressure) forces water through aquaporin channels that selectively allow water molecules to pass while rejecting dissolved salts, producing freshwater (permeate) and concentrated brine.

While Aquaporins offer an elegant biological solution for water transport, several limitations hinder their widespread application in desalination. Aquaporin-embedded membranes are constrained by the intrinsic fragility of protein-based systems, including sensitivity to oxidants, pH extremes, temperature fluctuations and mechanical stresses typical of desalination operations. Their incorporation into synthetic matrices is also technically demanding, and large-scale manufacturing still incurs significant costs due to the need for controlled protein expression, purification, and membrane assembly.

At the module and plant scale, the advantages of aquaporins are further moderated by transport resistances in the surrounding polymer matrix, which limit the practical flux enhancement achievable over conventional polyamide membranes. Salt rejection can also be compromised by defects in protein integration or by the passage of small neutral solutes through certain aquaporin isoforms. In addition, aquaporin-based membranes are susceptible to biofouling and have shorter operational lifetimes, constraining cleaning options and increasing replacement frequency.

Together, these factors highlight why aquaporin technologies—despite their biological sophistication—have yet to disrupt mainstream desalination. Their development continues to provide valuable insights into biomimetic membrane design, but significant advances in stability, manufacturability and module engineering will be required before aquaporins can offer a competitive alternative to established desalination technologies.

4.2. Microalgae as Salt Absorbers

Microalgae species such as *Chlorella vulgaris*, *Dunaliella salina*, and *Arthrospira platensis* are known to absorb salts to the functional groups in their cell walls and sequester carbon dioxide from the atmosphere [22]. These organisms employ two main mechanisms: biosorption and bioaccumulation [22]. Biosorption refers to the passive binding of salts to the surface of microalgae biomass, while bioaccumulation involves the active uptake and storage of salts within the cells [6,22]. Studies have shown that *Arthrospira* can reduce salinity in aquaculture wastewater by up to 45%, while *Dunaliella salina* achieved a 35% reduction, indicating significant potential for applications in desalination and wastewater treatment [13]. Recent advances in algae-based biodesalination demonstrate that intact *Arthrospira platensis* biomass can achieve salt removal efficiencies of 28% under optimised conditions (20% biomass, 30 ppt salinity, 30 min) [23]. The study highlights the critical role of surface-bound extracellular polymeric substances (EPS), which significantly enhance ion adsorption via functional groups, enabling heterogeneous, multilayer binding and confirming EPS-driven mechanisms as central to improved desalination performance [23]. Table 1 summarises the best-performing microalgae species reported for biodesalination. Studies have shown that optimal temperature, pH, and light intensity are important factors for microalgae growth, which is necessary for biodesalination [24]. Microalgae require a light-dark cycle to sustain efficient photosynthesis and metabolic balance. Most microalgae (*Chlorella*, *Chlamydomonas*, *Scenedesmus*, and *Nannochloropsis*) show optimal growth within a temperature of 20–30 °C, while suitable light intensities vary between 33 and 400 μmol $m^{-2}s^{-1}$ depending on species characteristics [24]. Microalgae desalination systems require substantial capital investment, with land demands ranging from 5–10 m^2 per m^3/day, significantly higher than 0.1–0.5 m^2 required for RO plants. Furthermore, the costs associated with photobioreactor construction and nutrient supply contribute to overall expenditures [25]. To harness microalgae for industrial-scale desalination, strategies including the use of large-scale photobioreactors (Figures 3 and 4) or open pond systems, as well as the development of engineered strains, could optimise salt uptake and rapid growth of biomass [22,26]. The harvested algal biomass can be processed into bioplastics (halophilic polyhydroxyalkanoate fermentation), biofuels, or biofertilisers via biomass volarisation. This approach could maximise resource recovery and serve as a strategy for addressing brine discharge challenges associated with RO [27].

Figure 3. Aerial view of a microalgae farm. Reprinted with permission from Ref. [28]. Copyright 2026, Cyanotech Corporation.

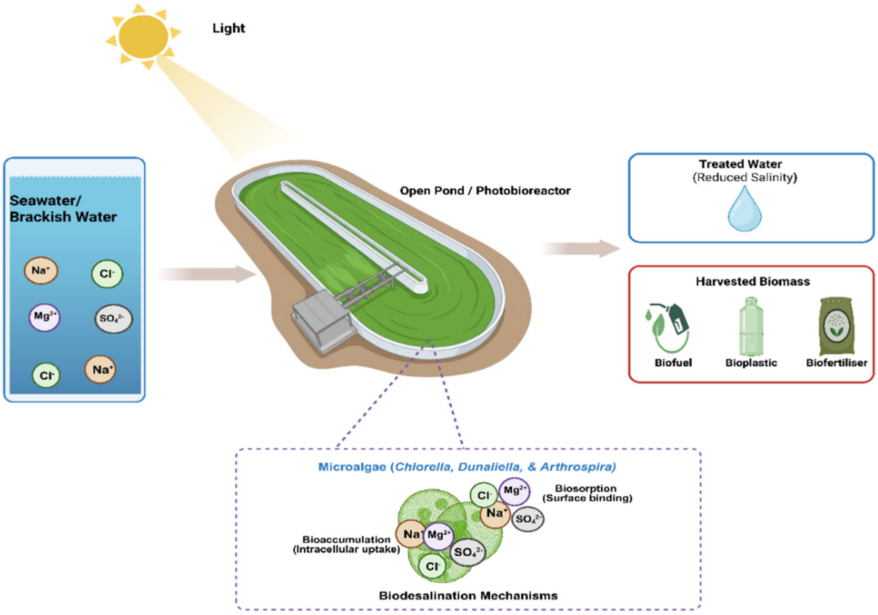

Figure 4. Schematic of microalgae-based biodesalination in an open pond/photobioreactor, where seawater or brackish water is treated under light by microalgae (e.g., *Chlorella, Dunaliella,* and *Arthrospira*). Salts are removed via biosorption and bioaccumulation, producing treated water with reduced salinity and harvested biomass for applications such as biofuel, bioplastics, and biofertiliser.

Table 1. Comparison of best-performing microalgae used in biodesalination.

Microalgae	Initial Salinity	Desalination Performance	Reference
Scenedesmus obliquus	2.8–8.8 gL^{-1} (brackish water)	2792 mg/L/h	[29]
Chlorella vulgaris	Seawater (24–55 ppt)	TDS removal from 900–500 mg/l; desalination efficiency of 50–82%.	[30]
Scenedesmus quadricauda	Seawater (35 ppt)	High salt assimilation during growth; desalination efficiency of 79 -80%	[31]
Spirulina maxima	Synthetic saline water	Chloride bioaccumulation increased significantly; desalination efficiency of 32–49%.	[32]
Phormidium keutzingianum	30 gL^{-1} (high-salinity brackish water)	28.54 mg/L/h	[33]

Desalination efficiency is defined as the percentage of total dissolved solids (TDS) or salt removed from the initial saline medium. The unit mg/L/h (milligrams per litre per hour) represents the salt removal rate, i.e., the mass of salt (in milligrams) removed from one litre of solution per hour.

4.3. Cyanobacteria (Blue-Green Algae) as Natural Ion Exchangers

Cyanobacteria are photosynthetic microorganisms found abundantly in oceans and lakes [34,35]. Cyanobacteria thrive in saline environments with minimal nutrient requirements, making them well-suited as natural ion exchangers [36]. Through genetic engineering, their membrane transport proteins can be modified to selectively remove sodium and chloride from water [6,17]. Specific engineering strategies that could be used include overexpression of native ion transporters, for example, optimising the expression of Na^+/H^+ antiporters (e.g., NhaP-type) to increase sodium efflux, heterologous expression of light-driven pumps, such as halorhodopsin, enabling light-activated chloride import [37] (Figure 5). Additionally, knocking out regulatory genes that limit ion uptake under high-salinity conditions could be explored. Furthermore, synthetic biology approaches could be used to enhance the ion-exchange capacity of cyanobacteria by increasing the abundance of functional groups on the cell surface or in extracellular polymeric substances (EPS) [38]. Cyanobacterial cell walls and EPS contain negatively charged functional groups, including carboxyl, hydroxyl, phosphate, and amino groups, which act as binding sites for cations and facilitate the adsorption of heavy metals through complexation and electrostatic interactions [39]. A consortium of five British universities tested the principles of using cyanobacteria as ion exchangers for removing sodium and chloride from seawater [36]. Their project focused on isolating and characterising candidate strains with the potential to be osmotically and ionically adaptable. The selection panel identified two *Euryhaline* strains: *Synechococcus* Strain

PCC 7002 (marine origin) and *Synechocystis* Strain PCC 6803 (freshwater origin) [36]. Through genetic modification, they successfully introduced a codon-optimised halorhodopsin gene into *Synechocystis* PCC 6803, resulting in 15–20% improved chloride uptake under light conditions compared to the wild-type [36]. The project demonstrated that photosynthetic cyanobacteria could serve as low-salt reservoirs, confirming their potential for biodesalination [36]. A recent study used dried *Nostoc spongiaeforme* FACHB-130 and hydrothermally pretreated *Mentha piperita* L. powder in a combined cyanobacterium-plant biodesalination system to treat Red seawater, achieving 20.6% reduction in electrical conductivity and 34.5% chloride ion removal [40].

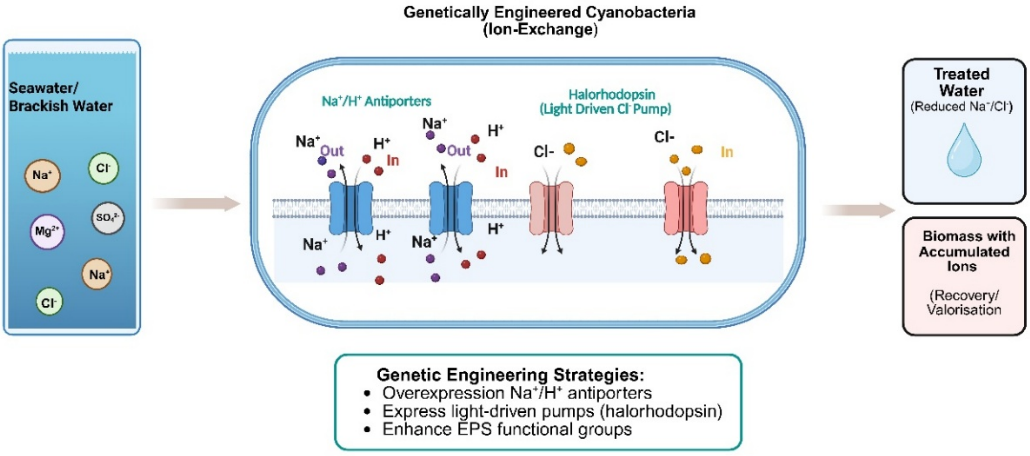

Figure 5. Schematic Cyanobacteria-based biodesalination system. Engineered cells (e.g., *Synechocystis* PCC 6803) remove ions from seawater using Na^+/H^+ antiporters (Na^+ efflux) and light-driven halorhodopsin (Cl^- uptake), with enhanced EPS aiding ion binding. Output includes desalinated water and ion-rich biomass for recovery.

4.4. Halophiles in Extreme Environments

These are salt-loving microbes, including *haloarchaea* and *halobacteria*, which thrive in hypersaline lakes or water bodies using a specialised ion pump and solute accumulation mechanisms [41]. These extremophiles have evolved specialised cellular and metabolic structures to maintain osmotic balance [41,42] (Figure 6). Their natural resilience makes them attractive candidates for biodesalination systems. For instance, *Halobacillus halophilus* has been studied for its dual ability to desalinate seawater and degrade crude oil [42]. Research has shown that this halophile can remove 3–5% of salt from seawater while simultaneously degrading 1–7.5% of crude oil, highlighting its potential for integrated bioremediation and biodesalination applications [42]. Halophiles do not destroy or metabolise salt. They redistribute or transform it through intracellular accumulation or precipitation [41,42]. Desalination, therefore, always requires a downstream step to remove the salty biomass or harvest the precipitated salts. To finalise desalination, downstream operations, including solid-liquid separation methods such as centrifugation, membrane microfiltration, and sedimentation, could be used to recover salt-laden halophiles from desalinated water. The recovered salt can be used as an industrial feedstock in aquaculture or processed into biofertiliser, thereby contributing to resource recovery.

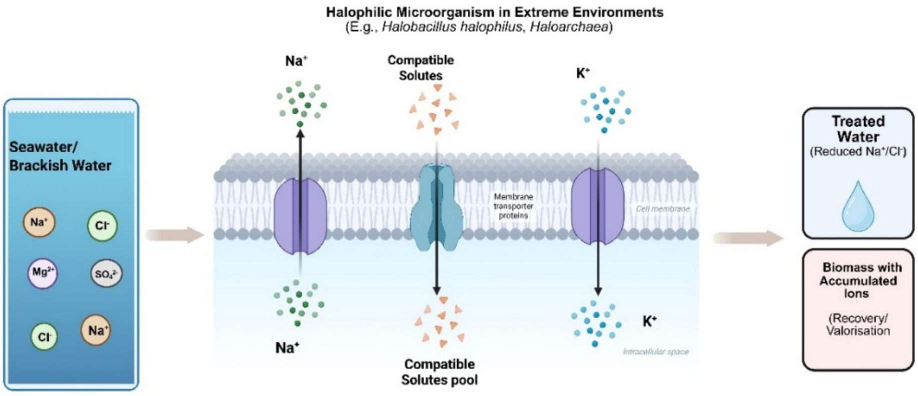

Figure 6. Schematic halophile-based biodesalination system. Halophilic microorganisms (e.g., *Halobacillus halophilus* and *haloarchaea*) remove salts from seawater by selectively transporting ions across membrane proteins to maintain osmotic balance.

4.5. Plant-Based Desalination (Phytodesalination)

This approach harnesses the natural mechanism found in some plants to remove salt from seawater or brackish water [43]. This involves the use of halophyte plants, which absorb and accumulate salt into their tissues [44,45] (Figure 7). Another method mimics the transpiration process, in which water is drawn to the plant's roots, evaporates from the leaves, and leaves the salt behind [44,45], thereby affecting the soil's salinity. For instance, mangrove trees possess specialised root structures, such as casparian bands and suberin lamellae, that filter up to 95% of salt, acting as ultrafiltration membranes for water adsorption [37]. Some mangroves also use foliar glands to secrete excess salt [46,47]. This can be replicated using bio-inspired material to develop a scalable desalination system [44,45].

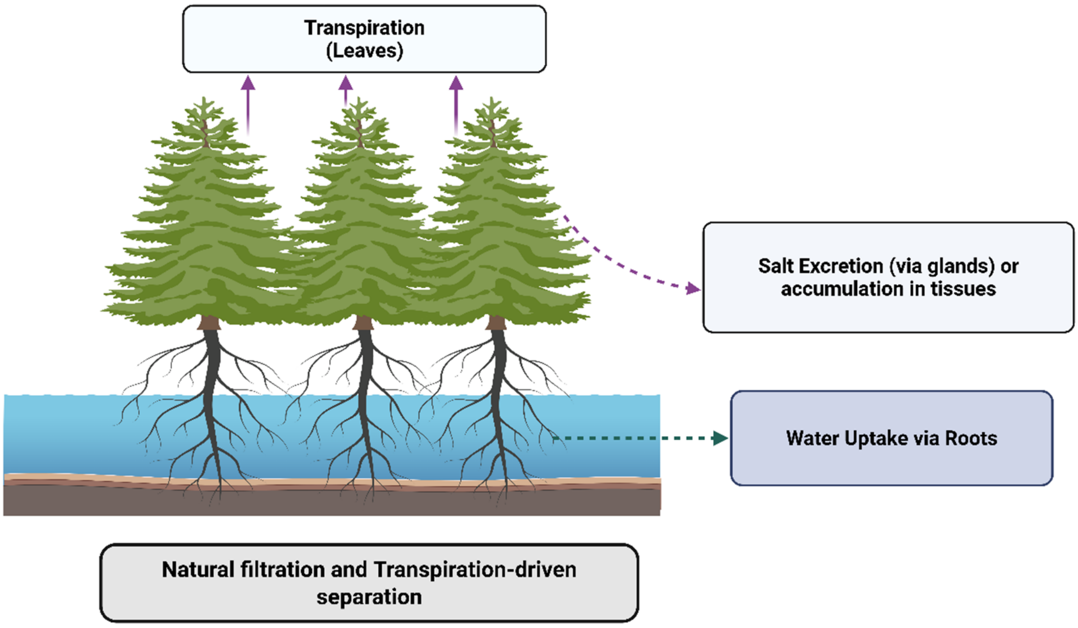

Figure 7. Schematic diagram of phytodesalination. Halophyte plants absorb saline water through roots with selective barriers (e.g., Casparian bands), filtering most salts. Water is transported upward and lost via transpiration, while salts are retained, accumulated in tissues, or excreted through glands, enabling natural desalination.

4.6. Microbial Desalination Cell

Microbial Desalination Cell (MDC, Figures 8 and 9) is a promising technology that evolved from the Microbial Fuel Cell (MFC) [48]. This technology can simultaneously desalinate seawater, generate bioenergy and treat wastewater. The process is based on the breakdown of organic matter present in wastewater in the anode chamber of an MFC reactor, utilising microbes known as electroactive bacteria (e.g., *Shewanella oneidensis*) that can exchange electrons outside their cells [49,50]. The exchanged electrons pass through a circuit. This flow of electrons creates a concentration gradient that causes ions in seawater in the desalination chamber to migrate during desalination [27]. As electrons flow from the anode to the cathode, this movement establishes an electrical potential [49,50]. The potential drives anions to the anode chamber through the anion exchange membrane (AEM), while cations move to the anode cathode chamber through the cation exchange membrane (CEM), effectively separating salts from seawater [26]. The energy generated (bioenergy) can be harvested for other processes. Currently, significant effort is being made to optimise and scale up MDCs [49,51]. Recent advances in MDC configuration include Osmotic MDC, Plant MDC, Stack Structure MDC, Capacitive MDC, Upflow MDC, and Biocathode MDC, each tailored to enhance salt removal, energy efficiency, and scalability [52–57]. One of the largest efforts to bring MDCs out of the lab for large-scale application is the MIDES (Microbial Desalination for Low-Energy Drinking Water) project, funded by the European Union [58]. MIDES successfully piloted the MDC system in several locations, producing clean drinking water in an energy-efficient manner [58]. Research is continuing to optimise the MDC technology [58]. Using advanced 3D bioprinting technology to precisely immobilise electroactive bacteria within a hydrogel matrix, an innovative 3D-printed bioelectrode has recently been developed [59]. This has helped address the persistent challenge of membrane biofouling, where microorganisms accumulate on the membrane, reducing MDC efficiency [58]. As a result, the 3D-bioelectrodes have improved the overall desalination rate, overcoming one of the main barriers to scale up of MDC for real-world applications [59].

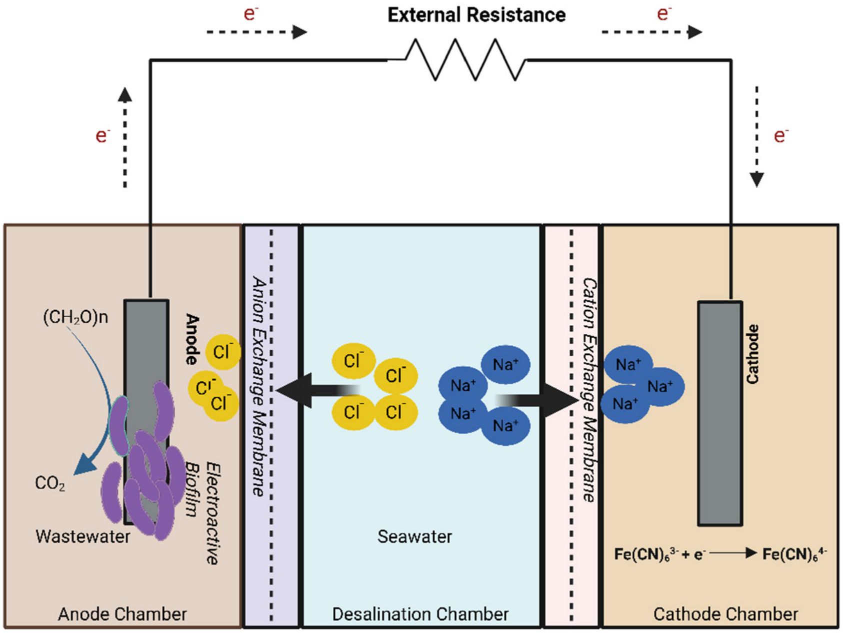

Figure 8. Schematic of a microbial desalination cell (MDC). Microbes oxidise wastewater at the anode, generating electrons that flow to the cathode, while Na^+ and Cl^- migrate across ion exchange membranes, enabling desalination.

Other recent studies highlight material innovation to boost performance in RO-reject wastewater treatment. A borophene-Fe_3O_4 nanocomposite anode improved electron transfer and bioelectrochemical activity, achieving a power density of 5.2 Wm^{-3} with 90% desalination efficiency [60]. Similarly, a low-cost rice husk-soil ceramic membrane increased ion-exchange capacity, hydrophilicity, and fouling resistance, yielding higher power density (112 ± 5 mWm^{-2}) and 81% COD removal than conventional membranes [61]. Together, these advancements demonstrate that optimised electrodes and sustainable membranes are important strategies for optimising MDC efficiency. MDCs require significant capital investment, mainly attributed to the expense of ion-exchange membranes (AEM and CEM) and electrodes, with the cathode representing approximately 40% of the total capital costs [62–64]. MDCs offer energy savings of 4 kWh/m^3 compared to RO and up to 196 kWh/m^3 compared to thermal technologies. Furthermore, MDCs present opportunities for revenue generation through the recovery of resources such as ammonia, phosphorus, and volatile fatty acids (VFAs) from wastewater [64].

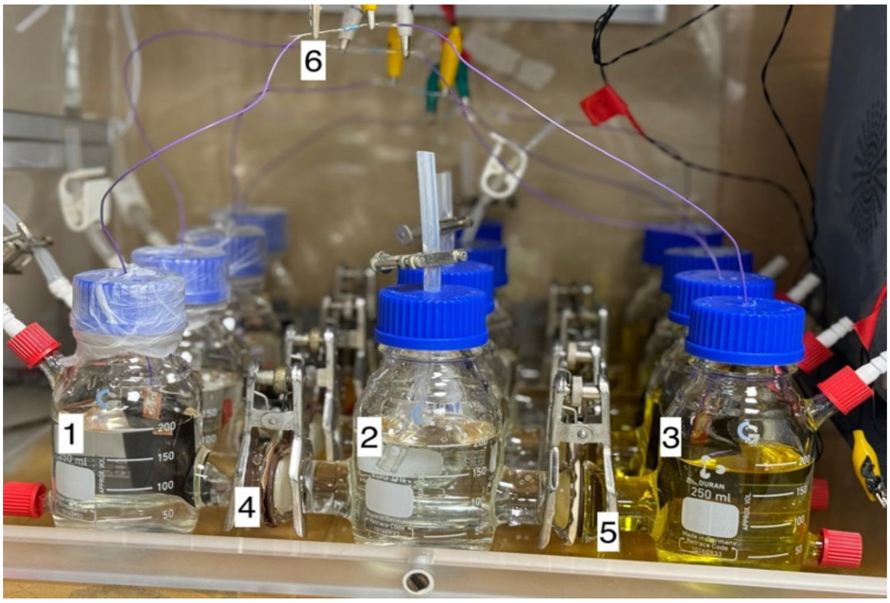

Figure 9. Picture of MDC developed by the Sustainable Biotechnology Research Group, University of Westminster. 1—Anode chamber containing synthetic wastewater. 2—Desalination chamber containing brackish or seawater. 3—Cathode chamber containing potassium ferricyanide. 4—Anion Exchange Membrane. 5—Cation Exchange Membrane and 6—External resistor. Reprinted with permission from Ref. [59]. Copyright 2025, Elsevier Inc. Licensed under the Creative Commons CC-BY license.

5. Future Prospects for Biodesalination

5.1. Economic Constraints and Cost Competitiveness

From an economic perspective, biodesalination is less competitive than RO because of its higher capital and operational costs. Life cycle cost analysis indicates that standalone multi-stage microalgae desalination systems incur considerably greater capital expenditure (CAPEX) (USD 4200–5800 per m^3/day) and operational expenditure (OPEX) (USD 1.20–1.80 per m^3) compared to SWRO (USD 1000–2500 per m^3/day CAPEX; USD 0.39–0.66 per m^3 OPEX for medium-scale facilities) [25,65,66]. Although energy consumption for algae-based systems (1.2–2.0 kWh/m^3 using solar and biomass energy) is lower than that of SWRO (3.4–4.0 kWh/m^3), and carbon footprint assessments demonstrate potential net negative emissions (-0.15 to 0.10 kg CO_2/m^3 versus 1.4 to 1.8 kg CO_2/m^3 for SWRO), significant capital costs are driven by nutrient cost, algae pond (requires 5–10 m^2 per m^3/day) and photobioreactor construction as well as biomass harvesting processes [6,25,65–67]. Even when considering possible revenue streams from high-value biomass by-products such as bioplastics, biofuels, and animal feed, which help reduce OPEX, the overall expenditure for standalone algae systems remains 27% higher than hybrid algae low-pressure RO systems and 33% higher than conventional SWRO, mainly due to elevated capital costs [25,65,66]. Hybrid systems that combine biological processes with low-pressure RO are regarded as the most economically viable and environmentally sustainable solution, particularly when biomass reuse and CO_2 bio-fixation are factored in. The capital cost of MDCs is estimated at USD 4.75 per 100 cm^3 of desalinated water, with nearly 85% of this expense attributed to high-value components such as ion-exchange membranes and electrodes. However, simultaneous bioelectricity generation and wastewater treatment offer a significant opportunity to offset these costs compared with RO systems [38,68].

5.2. Process Intensification and System Integration

Process intensification and hybrid system design are critical for advancing biodesalination toward practical deployment. Among the various biodesalination methods, MDCs stand out for their potential for scale-up. Pilot-scale demonstrations conducted by the EU Horizon MIDES project validated the viability of MDCs for producing potable water from seawater and brackish water with low energy consumption (<0.5 kWh/m^3) [69]. These trials utilised stacks comprising 15 MDC units (each 0.4 m^2), capable of treating thousands of litres per day while concurrently generating electricity [69]. The technological readiness level (TRL) for MDC technology is currently estimated at approximately 6–7, signifying that prototypes have been successfully demonstrated under relevant conditions, although the technology has not yet reached full commercial deployment [70]. Looking forward, MDCs could be deployed in decentralised setups with modular desalination capacities ranging from 5000 to 10,000 L/day, a manageable scale for small communities of about 50 to 100 people, and multiple modular units can further expand this capacity. Such systems would not only provide access to clean water but also harness the bioenergy produced in the process to power basic household needs, contributing to the drive towards net-zero carbon emissions. An equally promising aspect is the ability to utilise wastewater as a source of organic matter to sustain MDC operations, creating a closed-loop cycle of water purification, waste management, and energy recovery. One promising strategy for brine valorisation is integrating electrodialysis (ED) with MDCs to enable simultaneous resource recovery and desalination. The brine is initially treated by ED to produce hydrochloric acid (HCl) and sodium hydroxide (NaOH). The NaOH is used to sequester CO_2 from the air, producing sodium carbonate (Na_2CO_3), which is then desalinated using MDC to produce bioelectricity and portable water, while simultaneously treating wastewater. The accumulated ions in the anode and cathode chambers of the MDC could be recovered for potential industrial use.

Achieving large-scale industrial adoption of biodesalination technologies necessitates coordinated progress across several critical areas. One promising strategy is the hybridisation of biodesalination systems with conventional desalination methods such as reverse osmosis (RO) [65]. By utilising biodesalination as a pre-treatment step, the salinity of feed water can be significantly reduced prior to RO, thereby decreasing the pressure and energy requirements of the final desalination stage [65]. This approach could reduce the net energy demand on RO systems and improve operational efficiency. In parallel, the development of large-scale closed-system photobioreactors is essential for advancing microalgae-based biodesalination [71]. Transitioning from traditional open-pond systems to controlled, closed environments enable enhanced optimisation and standardisation of operational parameters [65,71]. Closed photobioreactors offer improved control overgrowth conditions, minimise contamination risks, and enable consistent performance [65,71]. These improvements are key to scaling up microalgae-based biodesalination technologies in a reliable, industrially viable manner. The biomass produced by the desalination process can be transformed into valuable products such as bioplastics and biofuels, or used as animal feed, thereby enhancing sustainability [30,71].

5.3. Artificial Intelligence and Machine Learning for Optimisation of Biodesalination Systems

The future of biodesalination lies in integrating artificial intelligence (AI) and machine learning (ML) to optimise biodesalination systems. For instance, ML models could be trained using deep learning techniques on lab-scale MDC data to enable real-time optimisation of operational parameters. Researchers have used advanced ML algorithms, such as Support Vector Machines (SVMs), Neural Networks, and Random Forests, to classify spectral data and accurately assess water-quality variations [72]. ML provides accurate performance optimisation of systems using experimental data to establish predictive models [73–75]. AI-driven optimisation has been reported to improve desalination system performance by up to 10% [75]. Table 2 summarises the opportunities for integrating ML algorithms into MDC technology. However, the realisation of this vision faces several challenges. Significant capital investment is needed for the design and construction of large-scale bioreactors, as well as the development of affordable, robust electrodes and durable ion-exchange membranes. With continued advances in these areas, MDCs may soon play a pivotal role in sustainable water management and renewable energy production.

Table 2. Summary of opportunities for integrating ML algorithms into MDC technology.

ML Algorithm	Definition	Opportunity for MDC Integration	Limitations/Challenges	References
Random Forest (RF)	Ensemble learning method that combines many decision trees to improve prediction accuracy and reduce variance.	Prediction of complex MDC performance metrics, such as voltage output, desalination rate, & COD removal from multivariate operational data.	Requires careful feature selection; model interpretability is limited compared to simpler regression; performance depends on dataset quality/size.	[76]
Feed-Forward Neural Network (FFNN/ANN)	A type of artificial neural network where information flows from input to output through one or more hidden layers; it can model nonlinear mappings.	Captures highly nonlinear relationships among MDC inputs (salinity, COD, pH, temperature) and outputs (power density, desalination efficiency); useful for integrating continuous sensor data.	Data-intensive; prone to overfitting without regularisation.	[77,78]
Particle Swarm Optimisation (PSO)	Meta-heuristic optimisation algorithm inspired by flocking/swarm behaviour; searches for optimal solutions by evolving a population of candidate solutions.	Optimisation of MDC operational parameters (electrode spacing, load resistance, salinity, flow rate) using predictive models (RF or ANN) as objective functions.	No guarantee of global optimum; sensitive to swarm parameters; may converge prematurely on local optimal in high-dimensional spaces.	[37]
Support Vector Regression	Regression variant of SVM that fits within an ε-insensitive band to tolerate errors; effective with nonlinear kernels.	Prediction of MDC performance where relationships are complex, but data volume is moderate; robust against overfitting if kernels are chosen well.	Kernel selection and parameter tuning required; less interpretable; scalability issues with large datasets.	[79]
Gradient Boosting Machines (GBM/XGBoost)	Sequential ensemble of weak learners (usually trees) that correct previous errors, high predictive performance.	Accurate prediction of MDC performance metrics and handling of nonlinear dependencies; valuable for complex system predictions.	Sensitive to hyperparameters; risk of overfitting on small MDC datasets; requires cross-validation.	[38]
Gaussian Process Regression (GPR)	Probabilistic non-parametric model that provides predictive mean and uncertainty.	Predictions with uncertainty quantifications, important for experimental planning and system optimisation in MDC.	Computational cost increases with dataset size, careful kernel selection is needed.	[40]
Reinforcement Learning (RL)	Learns optimal strategies by interacting with the environment to maximise cumulative reward.	Potential for adaptive real-time control of MDC operation (variable loads, flow conditions).	Requires large exploration data or accurate simulators, complex implementation.	[80]

6. Conclusions

There is currently growing interest in breakthrough desalination technologies that dramatically reduce energy use, costs, and environmental impact while scaling for real-world deployment. This review has highlighted the potential of various biodesalination methods, including aquaporin-based biomimetic membranes, microalgal salt adsorption, MDCs, and phytodesalination. These nature-inspired approaches offer a pathway towards a more sustainable water future by operating at ambient conditions, enabling resource recovery, and even offering the potential for carbon sequestration or bioenergy generation. Despite promising laboratory results, scale-up challenges remain. Among biodesalination approaches, MDCs have shown potential for large-scale integrated water desalination, wastewater treatment, and bioenergy generation, with successful pilot-scale demonstrations as a pretreatment step for RO. Future research should prioritise improving MDC efficiency for scale-up by developing durable, cost-effective membranes and electrode materials, and optimising bioreactor configuration to maximise both desalination performance and bioenergy recovery. With continued innovation and scaling, biodesalination has the potential to transform sustainable water desalination and help address global water scarcity.

Author Contributions

G.K.: Validation, Supervision, Project administration, Conceptualisation. N.C.: Writing—review & editing, Writing—original draft, Visualisation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. T.K.: Validation, Supervision, Project administration, Conceptualisation. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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