

Design and Construction of an Integrated Electrodialysis System with Automated Control for Brackish Water Treatment [†]

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Abstract

The increasing pressure on water resources is one of the most critical challenges of the 21st century. Demographic, industrial, and climatic factors are drastically reducing the availability of fresh water, with particularly pronounced effects in arid regions and the Mediterranean basin. Agriculture, which accounts for about 70% of global water withdrawals, is at the centre of this crisis, making it essential to explore unconventional sources such as brackish water. Desalination emerges as a key technology to address this challenge. Electrodialysis offers an attractive alternative, particularly suitable for moderately salty water (1000–5000 mg/L of total dissolved solids), thanks to its energy efficiency within specific salinity ranges and the ability to precisely control the quality of the produced water. At the same time, agrivoltaic systems that integrate energy production and agriculture are spreading, requiring compact, modular treatment devices that can be integrated with renewable sources. This research objective is the design and building of an affordable and reproducible electrodialysis (ED) prototype, equipping the system with automated sensor-based control, validating the device performance on brackish water and analyzing the feasibility of integration in agrivoltaic contexts.

Keywords: electrodialysis; brackish water; IoT monitoring; low-cost prototype; desalination; membrane process; electrodeionisation; agrivoltaics

1. Introduction

Freshwater is a fundamental resource that supports all forms of life on Earth. Although the planet is largely covered by water, only a very small fraction of it is accessible and suitable for human use. This limited availability makes freshwater a precious resource, and its supply is increasingly threatened by several global factors [1]. Desalination emerges as a key technology to address this challenge; traditional methods such as reverse osmosis, while effective, have significant limitations in terms of energy consumption and plant complexity [2,3].

In addition to stand-alone desalination applications, compact electrodialysis modules can play a significant role in advanced agrivoltaic systems, where water, energy, and crop management are considered in an integrated manner. In this framework, photovoltaic surfaces can be used not only for renewable energy production but also for rainwater harvesting, while the electricity produced by the plant can support low-consumption devices for water treatment and monitoring. A dedicated water management platform can



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therefore collect, monitor, and balance different water sources, such as recovered rainwater and slightly brackish groundwater, according to irrigation needs (Figure 1).

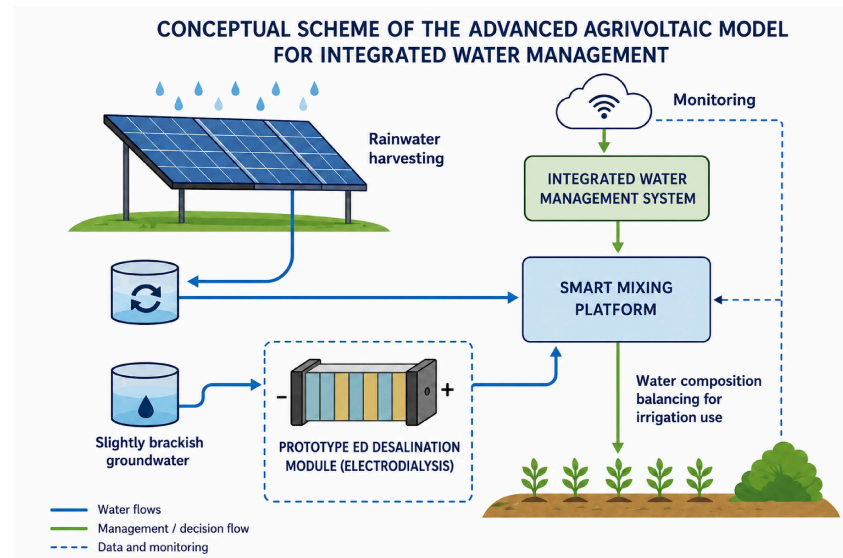


Figure 1. General advanced agrivoltaic system architecture.

Electrodialysis is an electrochemical process for separating salts from water [4]. This method is based on direct physical and chemical principles. It uses special membranes, as thin as sheets of paper, that are selectively permeable only to ions [5]. Therefore, they allow only ions with a specific charge to pass through, and to achieve this, the system requires a continuous electric current [6–9].

Within this broader conceptual framework, this study focuses on the design, construction, and preliminary experimental validation of a prototype electrodialysis module [10,11] for treating brackish water. The prototype should be viewed as an initial functional component of the proposed integrated water management model, rather than as a comprehensive agrivoltaic feasibility analysis. Its performance was evaluated under laboratory conditions in terms of salinity reduction, automated sensor-based monitoring, and specific energy consumption. In this scenario, advanced agrivoltaic systems can serve as integrated platforms for the joint management of water, energy, and crops. Within this context, photovoltaic surfaces can be utilized for both renewable energy generation and rainwater harvesting, while a water management module can monitor, treat, and balance various water sources based on irrigation needs. Against this conceptual backdrop, this study proposes the design and construction of a cost-effective and reproducible electrodialysis (ED) prototype, conceived as the initial functional module of a broader advanced agrivoltaic water management system. The prototype was equipped with an automated, sensor-based control system and experimentally tested using brackish water to evaluate its desalination performance and energy consumption.

The prototype has been sized with the following specifications:

- Design Flow Rate: 10–50 L/h (Lab Scale);
- Salt removal efficiency: to be evaluated experimentally, without a predetermined value;
- Target energy consumption: <2 kWh/m³;
- Inlet water: 1000–5000 mg/L (moderately brackish water);
- Configuration: Recirculating Batch;
- Current Density: 70–80% of Limit Current Density (LCD);
- Stack configuration: 5–10 pairs of cells with commercial membranes.

The system's performance was then assessed based on the percentage of desalination achieved and the corresponding energy consumption. The idea is to use the ED unit not only to purify water but also to indirectly assess its quality. By monitoring changes in salinity during treatment, valuable information about the liquid's composition can be obtained. The final step is a feasibility analysis examining how the ED system can be integrated with agrivoltaic systems. Desalinated water could support crops in these innovative environments.

2. Materials and Methods

The physical system was conceived as a compact, self-contained unit operating in a recirculating batch configuration. The architecture (Figure 2) includes four identical tanks arranged in two overlapping pairs (S1–S4), a centrally positioned ED and seven pumps (P1–P7) for handling fluids according to a specific layout scheme.

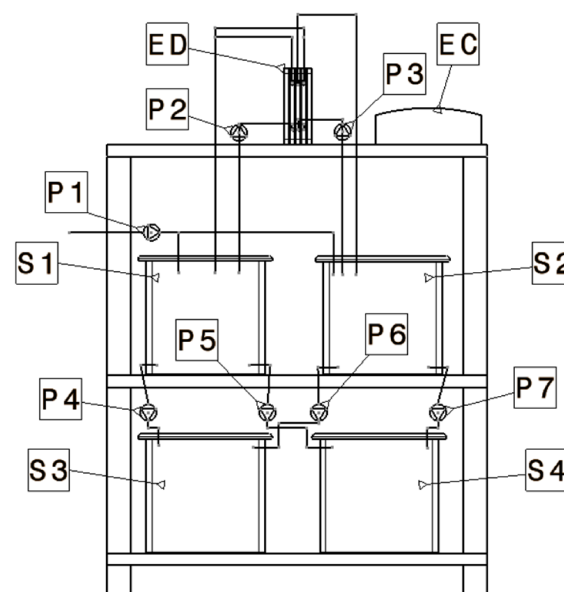


Figure 2. General system architecture.

The operating cycle includes:

- Filling of the upper tanks (S1–S2) with brackish water;
- Power supply of the ED channels via dedicated pumps (P2–P3);
- Ion separation by electric field;
- Diluted and concentrated flow recirculation until desired thresholds are reached;
- Transfer of desalinated water and brine to the lower.

A key feature is periodic polarity reversal, which helps to regenerate membranes and maintain system efficiency.

The operating principle is based on the ion separation using selective membranes and an electric field (as shown in Figure 3), with the generation of:

- Desalinated flow (desalinated water)
- Concentrated flow (brine)
- Normal and reverse polarity operating cycles

The diluted and concentrated compartments have been sized with a thickness of 6 mm, an optimal compromise between reduced electrical resistance and ease of construction. The main characteristics of materials and construction technologies are:

- Structural components: 3D printed with FDM technology with PLA (polylactic acid) filament, chosen for the balance between mechanical properties, ease of printing and sustainability
- Fill pattern: 20% cubic with three perimeter loops for robustness
- Sealing system: Manually cut silicone rubber sheet gaskets and silicone sealant for waterproofing the molded parts
- Pressing: Self-built metal frame for uniform force distribution
- Plumbing connections: Clear PVC pipes and barbette fittings

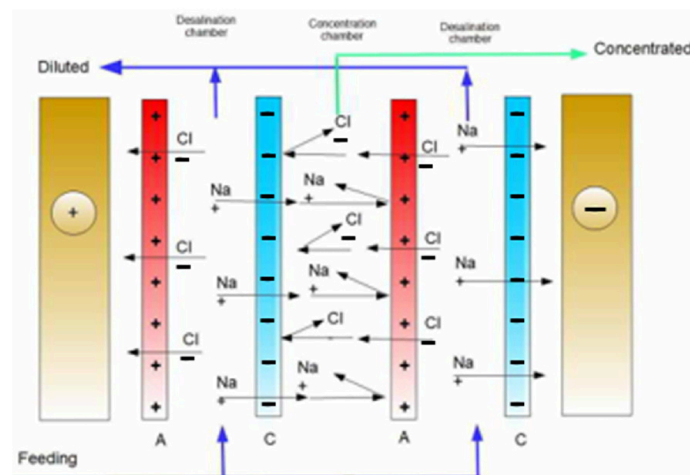


Figure 3. ED cell: general operating principle.

Electrochemical components: Ion exchange membranes:

- Cation-exchange membranes (CEMs): allow the selective passage of positive ions;
- Anionic membranes (AEM): allow the selective passage of negative ions

The alternation of these membranes creates the dilution and concentration chambers.

The electrodes are made of galvanized steel foil, cut into a square shape (dimensions defined by the stack geometry). The zinc coating was removed locally to allow the welding of a copper wire, which was subsequently protected with resin. The electrodes are housed in separate compartments to prevent direct contact with the brackish solution and the consequent formation of unwanted gases.

The assembly followed a precise sequence:

1. Installation of the terminal body and first electrode
2. First membrane placement (anionic or cationic based on the polarity of the adjacent electrode)
3. Alternation of membranes, gaskets and spacers according to the sequence: electrode → diaphragm → gasket → spacer
4. Completion of the battery with the opposite electrode and the end body
5. Compression by means of eight threaded rods with nuts and washers
6. Installing the outer metal frame to stabilize the assembly

The final stack includes 4 stages in total: two for the passage of desalinated water and two for brackish water.

Figure 4 shows the realization of the membranes using a 3D printer (a), the assembly method (b) of the polarized sheets (electrodes), and the overall stratigraphy of the sequence of polarized membranes to form the entire ED prototype.

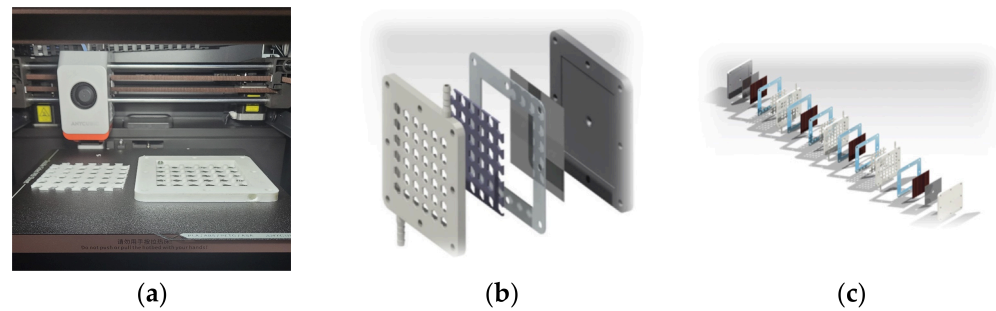


Figure 4. (a) 3D printed components; (b) channel layer detail; (c) rendering of the stratigraphy of the final ED prototype.

3. Experimental Setup and Results

The experimental setup for the laboratory tests consisted of an ED cell, two storage tanks, and two recirculation pumps (Figure 5). At the beginning of each test, the two tanks are filled with equal volumes of the model saline solution, prepared at a known concentration, thus establishing controlled initial conditions that are perfectly comparable between the two branches of the system. Once the experiment is started, the pumps are activated, and the fluid contained in the two tanks is sent to the respective channels of the electrodialysis cell, creating a recirculation batch configuration. Inside the cell, the electric field applied to the electrodes induces the selective migration of ions through the ion-exchange membranes, determining the progressive differentiation of the two flows: in one of the two channels, the solution tends to reduce its salt content, while in the other, a corresponding salt enrichment occurs. The two flows exiting the cell are then returned to their respective tanks, thus establishing a closed circuit in which ion separation evolves. In this way, starting from two identical initial conditions, it is possible to experimentally observe the effect of the ED process and monitor the progressive decrease in salinity in the dilute compartment and the simultaneous increase in the concentrated compartment. This configuration was chosen because it allows for a clear analysis of the system's behavior, isolating the main operating variables and facilitating the experimental evaluation of the prototype's performance. To monitor the ED process, the two tanks of the prototype were equipped with essential sensors, consisting of a pH sensor, a Total Dissolved Solids (TDS) sensor, and a voltage divider to measure the voltage applied to the electrodes. The pH sensor was used to monitor the acidity or basicity of the solutions; specifically, an analogue pH sensor compatible with Arduino's analogue readout was used. A CQRobot TDS sensor was used to measure salinity, based on the indirect measurement of the electrical conductivity of the solution. The experimental setup was completed with the remote visualization of the operating parameters and the recording of the process data, and sending them to the IoT cloud platform (AWS) using graphs for remote consultation (Grafana).

The experimental conditions are the following:

- Membrane type: two types of commercial ion-exchange membranes, TCEM8040 cation-exchange membranes and TAEM8040 anion-exchange membranes;
- Effective membrane area: 0.0081 m^2 ;
- Number of membranes: two pairs of membranes;
- Tank volume of 5 L and effective tank volume used equal to 2.5 L;
- Flow rate: the pumps (powered at 24 V) had a rated flow rate of 2 L/min;
- Voltage: 31 V;
- Current: 0.051 A;
- Operating current density: $i = 6.37 \text{ A/m}^2$;
- Operating time: Approximately maximum 1.5–2 h per test.

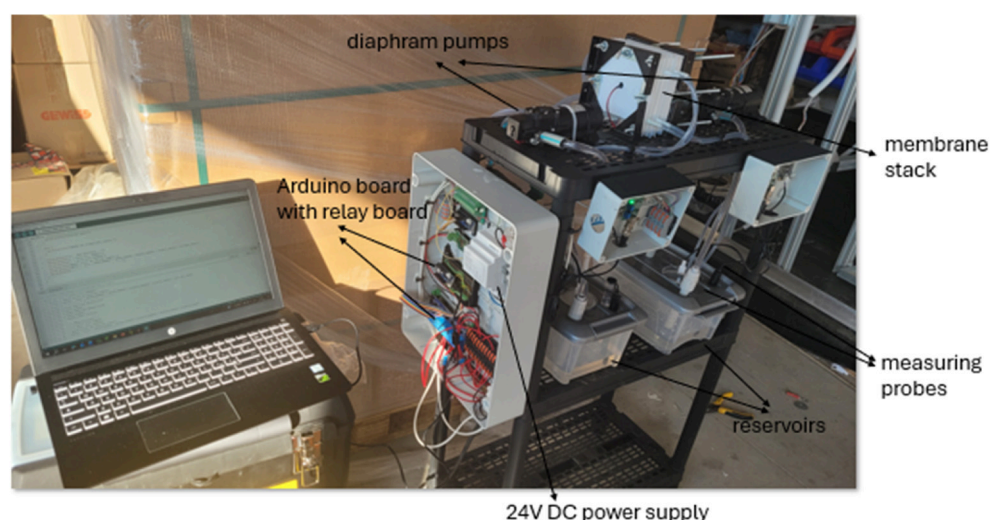


Figure 5. Photo of the experimental setup.

The TDS monitored values of 2 experimental tests (Test1 and Test2) are summarized in Table 1 and (Test 1) in Figure 6. About Test1, the first part, lasting approximately two hours, shows the effect of the desalination plant, which differentiates the TDS between the two mixtures. In the second part, after two hours, the TDS values stabilize, likely due to fouling of the membranes or electrodes, resulting in the accumulation of ions or substances during prolonged operation. Test2 was conducted to evaluate desalination performance, using a lower starting concentration.

Table 1. Experimental test results.

Test Name	Initial TDS Value [ppm]	Final TDS Value [ppm]	Desalination Percentage [%]	Operating Time [h]	Desalination Rate [ppm/min]
Test1	2400	2200 (desalted) 2570 (brackish)	8.3	0.5	6.66
Test2	1350	1020 (desalted) 1400 (brackish)	24.4	0.5	11

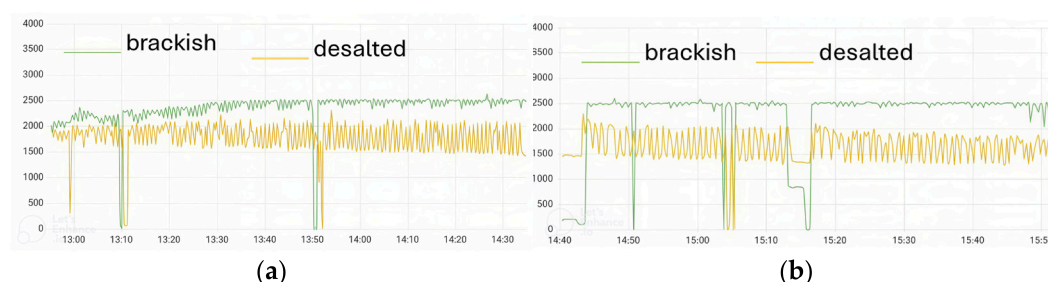


Figure 6. Test results: (a) Test 1, first part; (b) Test 1, second part.

Finally, to evaluate the Specific Energy Consumption (SEC) of the proposed prototype, that is crucial for the large-scale feasibility of the self-built electrodialysis system with automated control for the treatment, Equation (1) has been used where in the first equality of (1) P is the power in kilowatt [kW], t is the working time [h], V is the desalted water volume [m³]. In the tests, the power has been calculated by the measured constant tension

(31 Volts) and current (0.051 A) with a power of about 1.6 W, a working time of 2.5 h for a volume of desalted solution of 1.25 L (Test1).

$$SEC \left(\frac{\text{kWh}}{\text{m}^3} \right) = \frac{P * t}{V_{acqua}} = \frac{V * I}{V_{acqua}} * t = \frac{0.0016 \text{ kW} \cdot 2.5 \text{ h}}{0.00125 \text{ m}^3} = \frac{0.004 \text{ kWh}}{0.00125 \text{ m}^3} = 3.2 \text{ kWh/m}^3 \quad (1)$$

4. Discussion and Conclusions

The work demonstrated the feasibility of a self-built electrodialysis system with automated control for the treatment of brackish water, validating the operating principle through an experimental campaign.

The results achieved may be summarized as follows:

1. Prototype realization: A laboratory-scale electrodialysis unit with a modular structure was designed and assembled, using accessible materials (PLA 3D printing, commercial membranes, galvanised steel electrodes) and reproducible technologies.
2. Control system: A two-level automated system based on Arduino MKR WiFi 1010 has been developed, with a user interface for manual management and automatic cycles (normal/wash). Integration with AWS IoT Core and the MQTT protocol enabled real-time remote monitoring of pH, TDS, and voltage via Grafana dashboards.
3. Experimental validation: The device demonstrated salinity reduction capabilities on 2400 ppm and 1400 ppm NaCl solutions, with desalination rates of 10 ppm/min and 5 ppm/min, respectively. The measured specific energy consumption (3.2 kWh/m³) exceeds the target of 2 kWh/m³, highlighting the need for scale-up.
4. Critical analysis: Post-experimental inspection revealed electrode oxidation, membrane deposits and structural failures in PLA spacers, providing valuable insights for future developments.

Future developments for the presented system can be the following:

- Material replacement (titanium electrodes, engineering polymers);
- Redesign of the sealing and compression system;
- Implementation of adaptive control based on sensor feedback;
- Scale up to reduce specific consumption;
- Integration with renewable sources in an agrivoltaic context.

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Abbreviations

The following abbreviations are used in this manuscript:

ED	Electrodialysis
TDS	Total Dissolved Solids
AWS	Amazon Web Service
PLA	Polylactic Acid
MQTT	Message Queuing Telemetry Transport

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