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Research Paper

Brackish water pre-treatment method: selection of the study area and water sample testing

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ABSTRACT

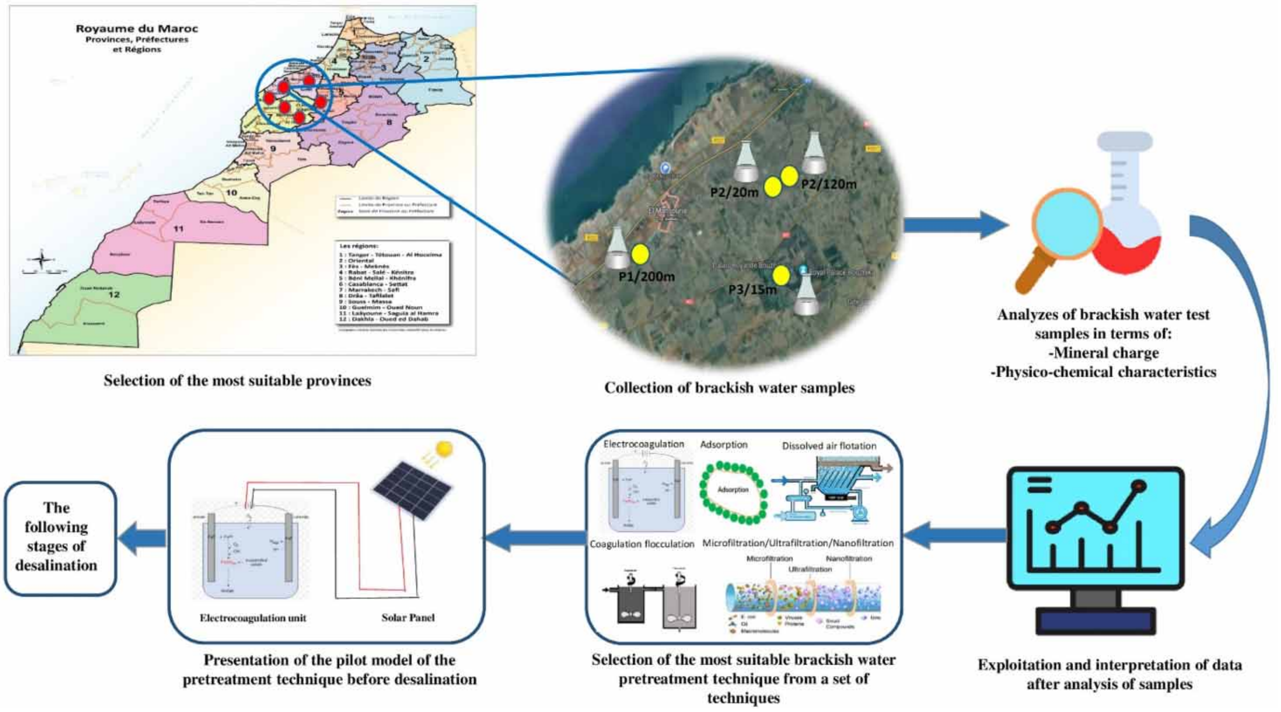
Climate change significantly disrupts the global water cycle, impacting rainfall and social and economic development in countries like Morocco. This has led to the need for alternative solutions like desalinating sea and brackish water. However, the efficiency of water pre-treatment operations depends on the characteristics of the raw water to be treated and affects the overall system's performance in terms of water quality and cost. The final objective of this study is to design a solar-powered brackish pre-treatment technique before desalination for remote rural populations. The primary task is to select the most suitable geographical area in Morocco for sampling and analysis of water characteristics and their compliance with drinking water standards. The results help identify the most appropriate provinces for our case according to certain selection criteria (distance, annual solar radiation, rural population, access to drinking water) and analyse the water's characteristics and compliance with national or international drinking water health standards. This provides a solid foundation for the next stages of desalination method development.

Key words: brackish water, climate change, decision support, desalination, health

HIGHLIGHTS

- Classify potential provinces for sampling brackish water.
- Analyse physico-chemical characteristics of water samples.
- Identify whether the mineral content of samples complies with national and international health standards regarding drinking water.
- Propose a technique for pre-treatment of brackish water before the desalination unit according to the characteristics of the water and the reality of remote rural populations.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is an essential element for human activities, and it is used for domestic, agricultural, and industrial purposes. The existing water on the earth is about 332.5 million cubic miles, but 96% is salty and only 2.5% is fresh (Gleick 1993). Faced with the demographic and economic development that humanity has experienced, this resource is becoming increasingly scarce; around 40% of the world's population, which is predicted to increase to 60% by 2025, currently has severe water shortages (Ibrahim *et al.* 2017). Thus, the endowment of water resources in the world went from 9,317 m^3/capita/year in 1980 to 5,500 m^3/capita/year in 2020 (Official website of the world bank).

Morocco, in particular, suffers from water stress. In fact, the endowment of water resources in Morocco has decreased from 2,560 m^3/capita/year in 1960 to 632 m^3/capita/year in 2020. In addition, Morocco will have a deficit of nearly 2.3 billion m^3/year by 2030 (Report by the Directorate of Financial 2020). Faced with this situation, the desalination of sea water and brackish water is among the solutions that have gained popularity in recent decades in several countries around the world (Jones *et al.* 2019). This technique remains a good alternative to conventional water supply (surface water, groundwater).

A major issue still remains to be resolved, that of access to water for rural populations in the most remote areas. In this sense the use of small desalination units based on renewable energy remains one of the most widespread solutions (Chafidz *et al.* 2016; Yoon *et al.* 2022). Their development requires, in particular, work in the field to locate sampling areas of the water to be desalinated and the analysis of these physio-chemical characteristics. This analysis constitutes an important step in characterizing water and then subsequently developing the appropriate pre-treatment methods (Maazouzi *et al.* 2013).

In this perspective, we will propose a brackish water pre-treatment method before desalination to serve the rural populations in Morocco who are suffering from lack of water. Considering the performance of this technique in terms of water quality (Hafez *et al.* 2009) and the importance of taking water characteristics into account before designing and validating the various techniques to be used, the choice of the deployment area for the desalination and analysis of water test samples reveals a crucial importance to be able to identify the populations to target, the analyses to prepare, and consequently the characteristics of the raw water that should be expected throughout the project (Gourai *et al.* 2015).

2. MATERIALS AND METHODS

Through this study, we were able to identify potential provinces and prioritized based on predefined criteria to optimize sampling locations and install brackish water pre-treatment units before desalination. Starting with analysing brackish water samples, we focus on mineral content and physico-chemical characteristics, crucial for validating pre-treatment techniques before desalination. This aids in proposing a pilot model for pre-treatment techniques later on.

2.1. Criteria for study area selection

The objective of this section is to determine the provinces in which samples will be taken to analyse brackish water and to be able to subsequently adapt the water pre-treatment processes. This is done first through the identification of the selection criteria by the research group: the geographical proximity to the greater Casablanca area, the accessibility of the population to drinking water, the number of the targeted rural population, and the solar energy potential of the area.

To determine the target area, we decided to choose among the provinces of Morocco. For logistical and financial reasons, it was also decided to eliminate provinces with a distance of more than 200 km from Casablanca (National portal 2023). The potential provinces are then presented subsequently (Figure 1).

Before proceeding to the stage of choosing specific provinces by setting the importance of each criterion, it is wise to detail the information on each criterion and the method of evaluation.

2.1.1. Geographical proximity of the Great Casablanca

We included this criterion because of the financial costs of travel and the costs necessary to carry out the sampling. To control the financial aspects of the project, a maximum distance of 200 km from Casablanca was set (Table 1).

2.1.2. Number of rural population by province

The number of rural populations in the study area is an important criterion as the project targets the largest possible rural population to ensure the impact of our solution will reach the maximum number of rural populations. Below is the number of rural populations in the provinces concerned. The data are taken from the general census established by the HCP (High Commission for Planning) in 2014 (HCP official website) (Table 2).

2.1.3. Population's access rate to drinking water

This accessibility rate measures the percentage of the population connected to the national drinking water network. It is of crucial importance since it designates a population that is open to solutions to guarantee their access to drinking water. The data from the HCP (High Commission for Planning 2014) (HCP official website) are collected. Figure 2 shows this rate at the provinces concerned.

2.1.4. Solar energy potential by selected zone

To have an idea of the solar energy potential of the potential provinces, we have resorted to the solar mapping of Morocco elaborated by IRESEN (Institute of Research in Solar Energy and New Energies) (IRESEN official website). Figure 3 shows solar irradiation throughout Morocco.

This mapping gives the global horizontal irradiation in kWh/m^2/year of Morocco. We have selected the concerned provinces, and we have been able to summarize their respective irradiation in Table 3.

2.2. The launch of sample analysis tests

Before embarking on the water quality analysis of the samples which will come from the selected provinces and for reasons of convenience, we decided to launch a test to collect and analyse some samples in the commune of Benslimane at the level of four wells with different depths in meters (P1/200 m, P2/120 m, P2/20 m, and P3/15 m). It was also decided, for comparative purposes, to include another source of brackish water in the Tissa area and a sample of seawater in EL Mansouria.

Twenty parameters were measured, five of which were carried out in the field after calibration and/or validation of the portable equipment: temperature, conductivity, pH using a multi-parameter analyser Type CONSORT – Model C535, and turbidity using a turbidity meter Type HACH-Model 2100P. Table 4 summarizes the method used and the unit of measurement for each parameter analysed.

For nitrogenous elements, water samples are fixed with concentrated sulphuric acid in a 500-mL polyethylene bottle and with concentrated nitric acid for Na$^+$ and K$^+$ cations in a 250-mL polyethylene bottle. The other unfixed parameters were

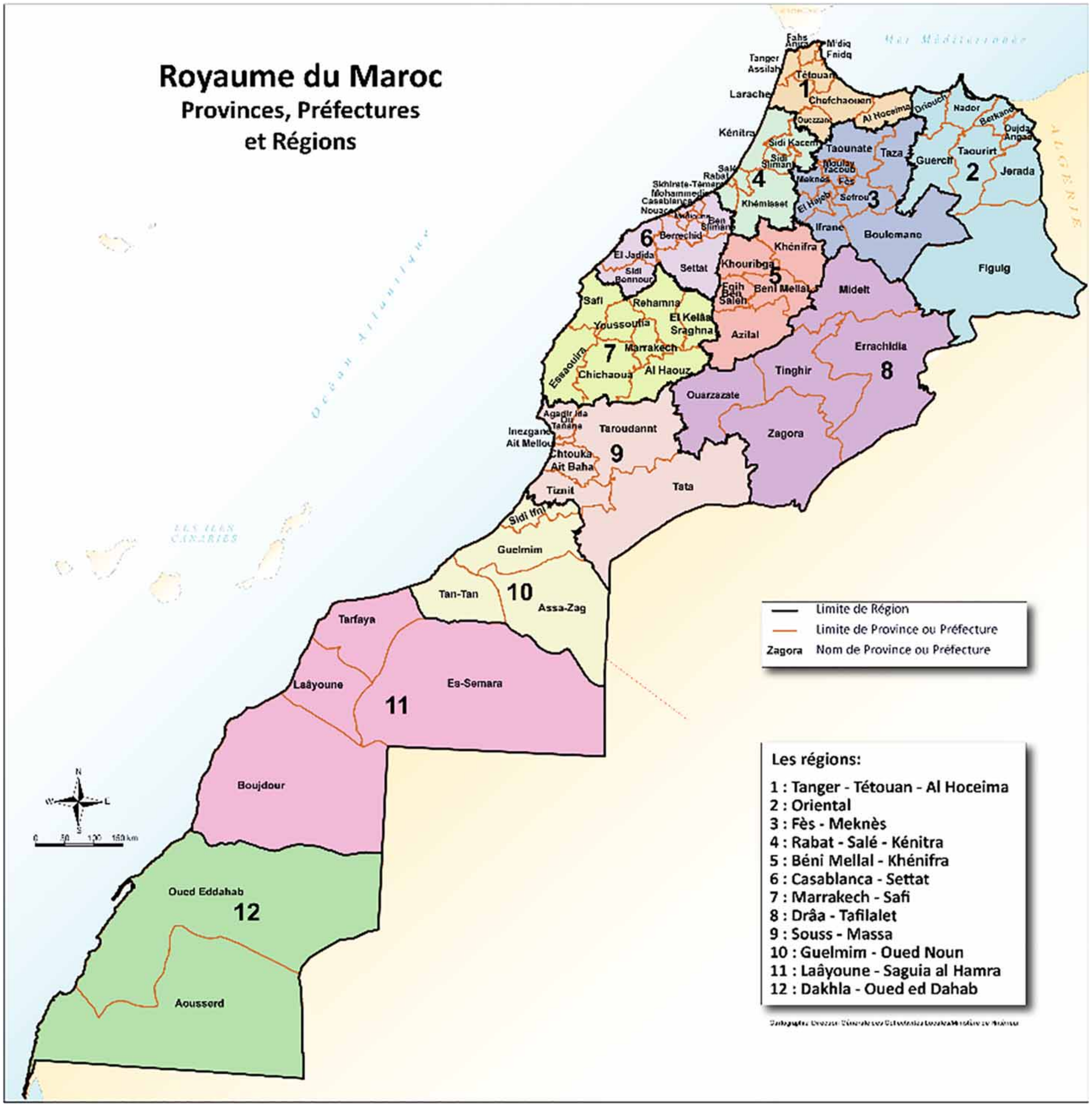


Figure 1 | Geographical map of Morocco with the different provinces.

sampled in a 1 L polyethylene bottle. The bottles of water taken, in accordance with Moroccan standard 03.7.059 (Moroccan standard 2020), are labelled and then sent to the laboratory in a cool box at a low temperature of ±4 °C, accompanied by a card bearing all the necessary information, in particular the origin, date, and time of sampling. Water samples are taken, transported, and stored in accordance with the protocol of national drinking water office (commonly called ONEP) quality control laboratory and standard norms (ONEP 2007; ONEP 2008).

The methods used in the Laboratory of Natural Resources and Environment (LNRE) of the Polydisciplinary Faculty of Taza (FPT) are as follows: volumetry for bicarbonates, chlorides (Cl^-), calcium, and magnesium (Ca^{2+} and Mg^{2+}); molecular absorption spectrophotometry for sulphates, nitrates, nitrites, ammonium ions, and orthophosphates; and flame spectrophotometry for sodium and potassium (ABOUZAID and DUCHESNE 1984; Rodier 2009).

Table 1 | Distances of the provinces from Casablanca

Province	Distance from Casablanca (km)
Sale	99
Khémissat	183
Skhirate Temara	92
El Jaddida	101
Benslimane	52
Berrechid	36
Sidi Bennour	165
Settat	75
Nouaceur	18.3
Mediouna	14
Mohammadia	30
Rhamna	187
Khouribga	124
Fquih Ben Salah	171

Table 2 | Number of rural population by province

Province	Rural population
Sale	66,505
Khemissat	261,142
Skhirate Témara	56,987
El Jaddida	474,546
Benslimane	119,033
Berrechid	210,669
Sidi Bennour	367,575
Settat	417,357
Nouaceur	55,166
Mediouna	52,402
Mohammadia	115,378
Rhamna	211,926
Khouribga	164,365
Fquih Ben Salah	297,107

3. RESULTS AND DISCUSSION

3.1. Study area selection

To summarize the results of each province by criteria, Table 5 represents an overview of the main statistics of our case study.

To show once again the deviation of each province value from the global variation of each criterion, we used the normalization technique to allow aggregation of criteria with numerical and comparable data.

In our case, we aim to select the provinces that have the best possible combination to minimize the distance to Casablanca and maximize the other criteria.

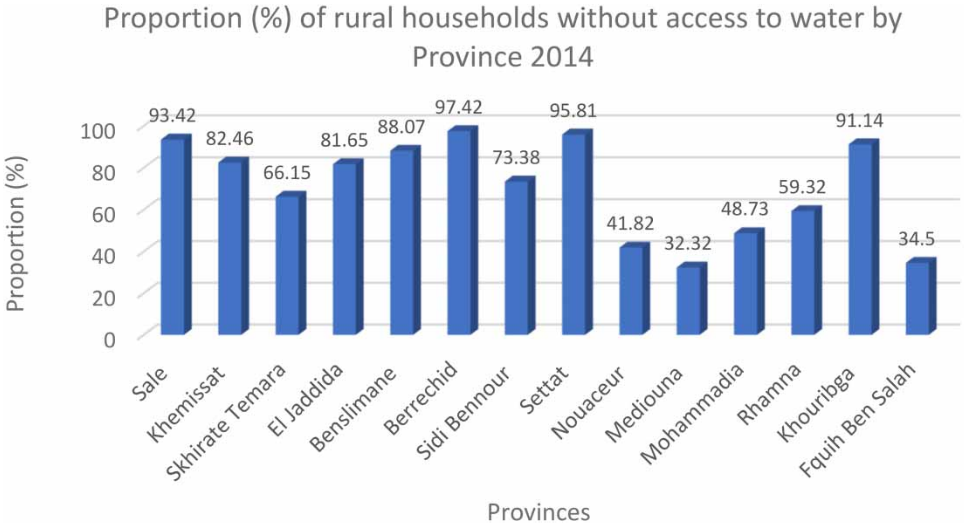


Figure 2 | Rate of rural population per province without access to water.

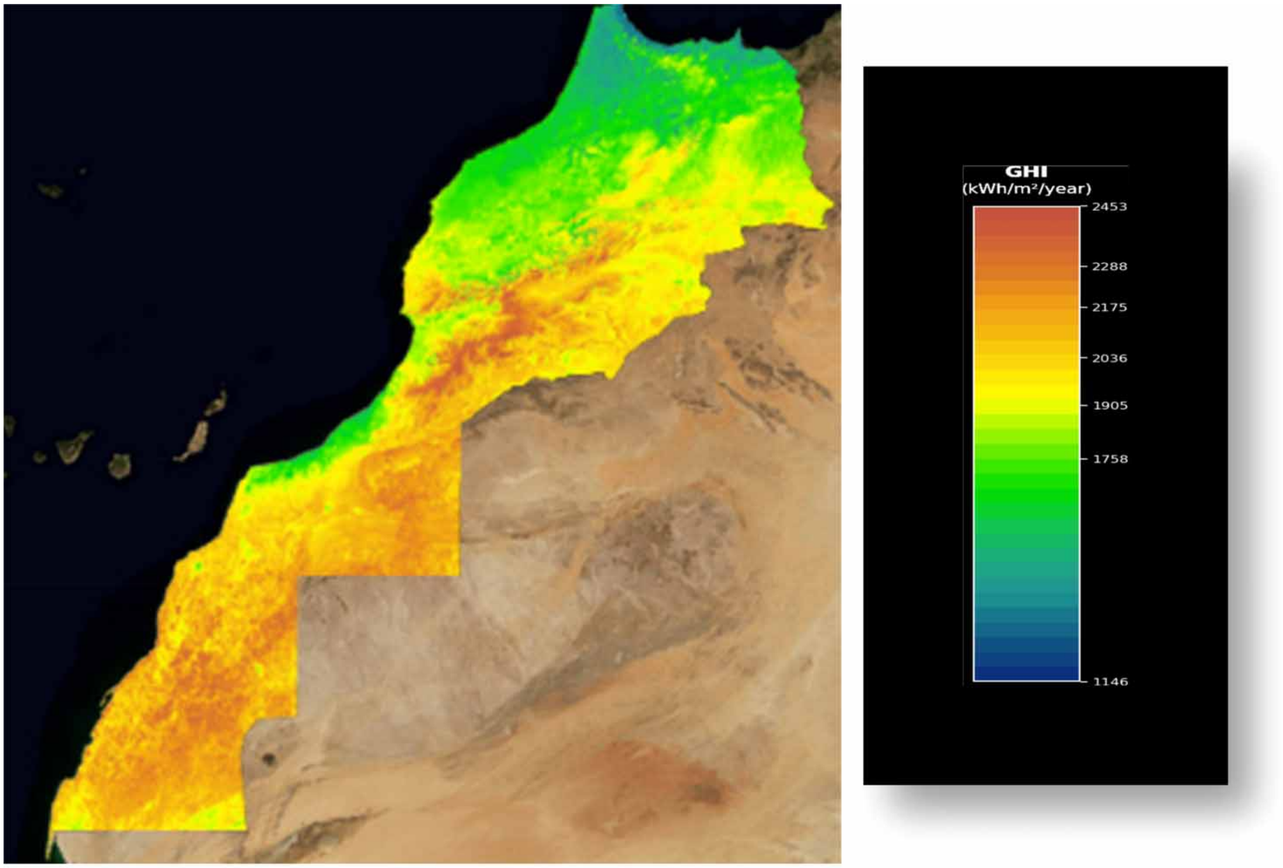


Figure 3 | Moroccan map of global horizontal irradiation in kWh/m^2/year.

To do this and considering the different scales we have, we will normalize the data using the Min-Max Scaler, which has the following mathematical Equation (1) (Izonin *et al.* 2022):

$$X_{\text{scaled}} = \frac{X - X_{\min}}{X - X_{\max}} \tag{1}$$

Table 3 | The global horizontal irradiation in kWh/m^2/year by province

Province	Daily horizontal solar radiation (kWh/m^2/day)
Sale	5.32
Khemissat	5.30
Skhirate Témara	5.32
El Jaddida	5.33
Benslimane	5.27
Berrechid	5.24
Sidi Bennour	5.41
Settat	5.37
Nouaceur	5.4
Médiouna	5.32
Mohammadia	5.31
Rhamna	5.47
Khouribga	5.50
Fquih Ben Salah	5.51

Table 4 | Methods for analysing physico-chemical components

Parameter	Analysis method	Unit
Conductivity	Conductivity meter Type CONSORT – Model C535	µs/cm
Turbidity	Turbidimeter Type HACH-Model 2100P	NTU
pH	CONSORT pH meter – Model C535	From 0 to 14
Temperature	Mercury thermometer/multi-parameter analyser Type CONSORT – Model C535	°C
Alcalimetric Title	Titrimetry with 0.1 N hydrochloric acid and phenophthalein	meq/L
Full Alkalinity Title	Titrimetry with 0.1 N hydrochloric acid and methyl orange	mg/L
Hydrotimetric Title	Complexometric titration with 0.02 M EDTA and eriochromic black T	meq/L
Calcic hardness	Complexometric titration with 0.02 M EDTA and HSN	mg/L
Magnesium	Deducted by the difference between total hardness and calcium	mg/L
Chlorides	Determination using mercuric nitrate in the presence of an indicator: diphenylcarbazone	mg/L
Nitrates	Sodium salicylate	mg/L
Nitrites	Zamballi reagent method	mg/L
Ammonium	Sodium phenol nitroprusside and chlorine solution	mg/L
Sulfates	Precipitation of barium sulphates in a hydrochloric medium	mg/L
Potassium	Flame spectrophotometry	mg/L
Sodium	Flame spectrophotometry	mg/L

Table 5 | Descriptive statistics of study criteria

Province	Distance from Casablanca (km)	Rural population	(%) of rural households without access to water	Daily horizontal solar radiation (kWh/m^2/day)
Average	96.24	205,011.29	70.44	5.36
Standard deviation	62.12	141,365.76	23.36	0.084

Table 6 | Values of the different normalized criterion values and scores by province

Province	Distance from Casablanca (km)	Rural population	(%) of rural households without access to water	Daily horizontal solar radiation (kWh/m^2/day)	Total score
Sale	0.51	0.03	0.94	0.30	1.78
Khemissat	0.02	0.49	0.77	0.22	1.51
Skhirate Témara	0.55	0.01	0.52	0.30	1.38
El Jaddida	0.50	1.00	0.76	0.33	2.59
Benslimane	0.78	0.16	0.86	0.11	1.91
Berrechid	0.87	0.37	1.00	0.00	2.25
Sidi Bennour	0.13	0.75	0.63	0.63	2.13
Settat	0.65	0.86	0.98	0.48	2.97
Nouaceur	0.98	0.01	0.15	0.59	1.72
Mediouna	1.00	0.00	0.00	0.30	1.30
Mohammadia	0.91	0.15	0.25	0.26	1.57
Rhamna	0.00	0.38	0.41	0.85	1.64
Khouribga	0.36	0.27	0.90	0.96	2.50
Fquih Ben Salah	0.09	0.58	0.03	1.00	1.71

Table 6 summarizes the calculation of the normalized values. For the criterion of the distance, the formula of the Min-Max Scaler will be preceded by 1 minus the value found by the formula to show the punishing aspect to have a big value for the distance. For the rest, we write directly the result calculated only by the formula, and the final score for each province will be the sum of its normalized values for all criteria.

We note after the calculations made above that we can select the main provinces that have the highest scores (the top 6) to carry out several samples in each province. According to our study, these are the following provinces: Settat, El Jaddida, Khouribga, Berrechid, Sidi Bennour, and Benslimane.

3.2. Analysis of the mineral load and the physico-chemical characteristics of the test samples

3.2.1. Analysis of the mineral load of the test water samples

Following the experimental protocol established in the material and method section, we were able to calculate the concentration of several elements that represent the mineral load of each sample from different sources. For visualization purposes, we have summarized the results in graphs. Figure 4 shows a summary of the mineral load of the four brackish water sampling points.

From these figures, we can extract the following observations:

- For the sample from P1/200 m, the elements Cl^- and Na^+ represent 73.31% with 2,128 and 1,686 mg/L, while SO_4^{2-} represents 9.95% (518 mg/L) and NO_3^- represents 3.13% (163 mg/L), exceeding World Health Organization (WHO) thresholds and recommendations of 200 mg/L, 200, 250, and 50 mg/L, respectively (Diouf *et al.* 2022). The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 5.09% and 7.07%, respectively, with a concentration of 265 and 368 mg/L, exceeding WHO thresholds ranging from [50–150 mg/L] to [75–200 mg/L], while the rest of the elements are less than 1.42%.
- For the sample from P2/120 m, the elements Cl^- and Na^+ represent 71.47% with 3,692 and 2,646 mg/L, while SO_4^{2-} represents 9.73% (863 mg/L) and NO_3^- represents 2.51% (223 mg/L), exceeding WHO thresholds and recommendations already mentioned earlier. The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 7.96% and 7.21%, respectively, with a concentration of 706 and 640 mg/L, exceeding WHO thresholds ranging from [50 mg/L–150 mg/L] to [75 mg/L–200 mg/L], while the rest of the elements are less than 1.1%.
- For the sample from P2/20 m, the elements Cl^- and Na^+ represent 61.83% with 989 and 789 mg/L, while SO_4^{2-} represents 12.48% (359 mg/L) and NO_3^- represents 10.05% (289 mg/L), exceeding WHO thresholds and recommendations already mentioned. The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 7.34 and 7.23%, respectively,

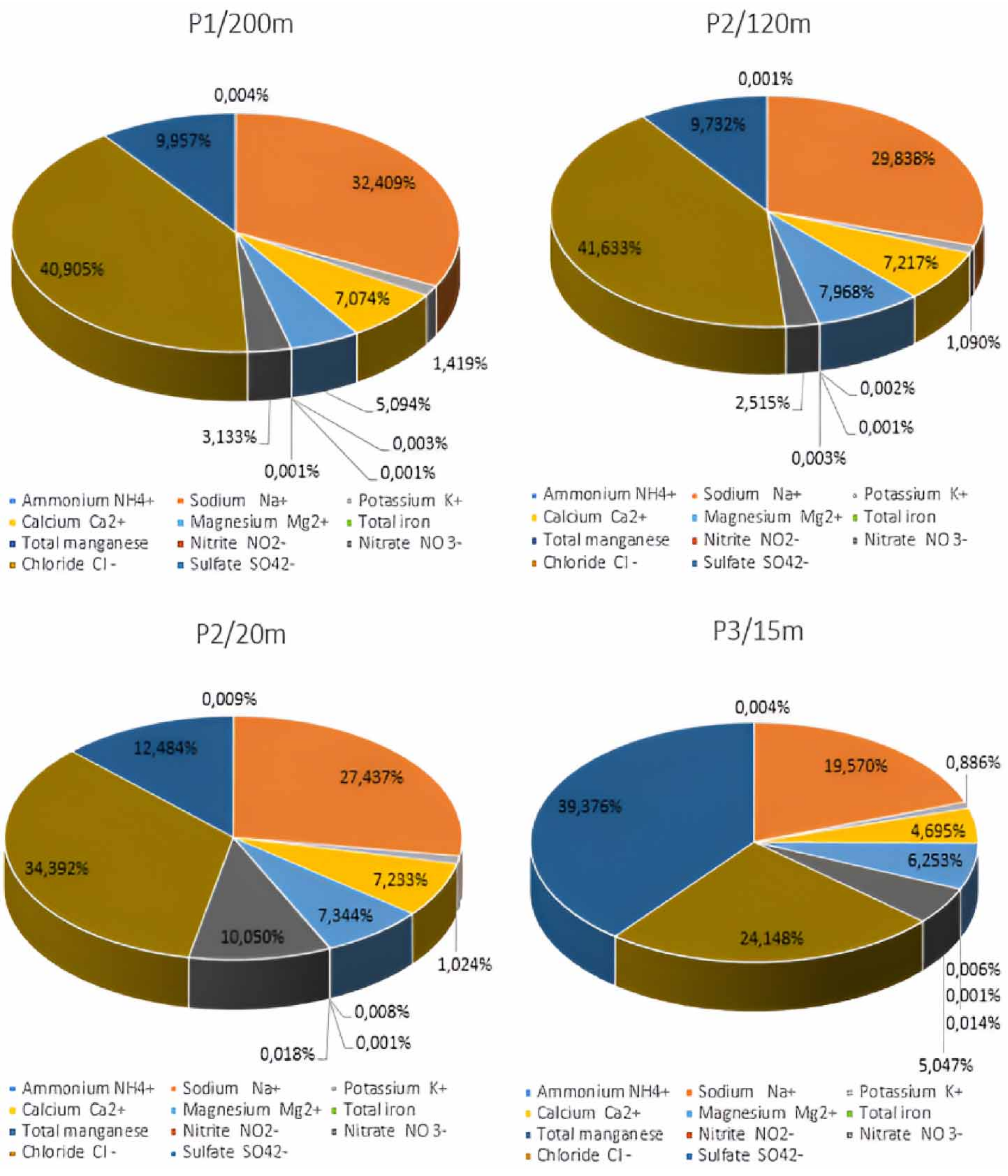


Figure 4 | Mineral load for the four brackish water samples.

with a concentration of 211.2 and 208 mg/L, exceeding WHO thresholds and recommendations already mentioned, while the rest of the elements are less than 1.03%.

- For the sample from P3/15 m, the elements Cl^- and Na^+ represent 43.71% with 823 and 667 mg/L, while SO_4^{2-} represents 39.37% (1,342 mg/L) and NO_3^- represents 5.05% (172 mg/L), exceeding WHO thresholds and recommendations already mentioned. The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 6.25 and 4.69%, respectively, with a concentration of 213.1 and 160 mg/L, exceeding WHO threshold ranging from [50–150 mg/L] for Mg^{2+}, while the rest of the elements are less than 0.89%.

The concentrations of the different components as well as their variations in relation to the depth of the wells can be justified by taking into account the location of the sampling zone and the following elements:

- A possible marine intrusion: As discussed by Diouf *et al.* (2022) and according to Bear *et al.* (1999) and Moujabber *et al.* (2006), based on the ratio of concentrations in mg/L of Ca^{2+} and Mg^{2+}, the enrichment of Ca is given by Equation (2):

$$\text{Ca Enrichment} = \frac{\text{Ca}}{\text{Mg}} \tag{2}$$

According to Bear *et al.* (1999), high ratios of Ca enrichment (>1) could be regarded as saltwater intrusion. After calculating this ratio, we can see that it varies between 0.75 and 1.38 (P1/200 m: 1.38, P2/120 m: 0.91, P2/20 m: 0.98, P3/15 m: 0.75). We can also see that this rate generally increases with depth, which gives an indication of possible marine intrusion in the deep layers of the ground.

- Agricultural activities in the region using fertilizers, which increase the concentrations of elements such as SO_4^{2-} and NO_3^- (Egboka 1984; Ju *et al.* 2006; Lwimbo *et al.* 2019)

For comparison purposes, it was decided to take another sample of brackish water away from the first sampling area and a sample of seawater close to the main sampling area. Their mineral loadings are summarized in Figure 5.

From Figure 5, we can extract the following observations:

- For the Tissa sample, the elements Cl^- and Na^+ represent 76.32% with 1,420 and 1,076 mg/L, respectively, while SO_4^{2-} represents 12.17% (398 mg/L) and NO_3^- represents 4.34% (142 mg/L), exceeding WHO thresholds and recommendations already mentioned. The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 3.31 and 2.78%, respectively, with a concentration of 108.5 and 91.2 mg/L, while the rest of the elements are less than 1.04%.
- For the seawater sample, orders of magnitude of concentrations vary greatly compared to brackish water samples. The elements Cl^- and Na^+ represent 85.40% with 20,620 and 10,089 mg/L, while SO_4^{2-} represents 8.17% (2,940 mg/L) and NO_3^- represents 0.6% (219 mg/L), exceeding WHO thresholds and recommendations already mentioned. The elements responsible for the hardness of the water (Mg^{2+} and Ca^{2+}) represent 3.97 and 1.11% respectively, with a concentration of 1,430 and 400 mg/L, exceeding WHO thresholds and recommendations already mentioned. The rest of the elements are less than 0.8%.

3.2.2. Analysis of the physico-chemical characteristics of the test samples

The analysis of the physico-chemical characteristics of the samples mainly concerned measurements of conductivity, turbidity, salinity, and pH. The details of the measurements are described in Figure 6.

The main information that can be drawn from the figure is as follows:

- For conductivity, all the samples are above the WHO threshold of 1 mS/cm or that recommended by the Moroccan standard of 2.7 mS/cm (Moroccan standard 2020). It is clear that the conductivity of the seawater sample is very high because of its high dissolved salt content, whereas that of the brackish water samples is relatively low compared with seawater. According to the samples we have, the relationship between conductivity and well depth is not trivial and depends very much on the specific characteristics of the sampling site. It is the same case for salinity which exceeds the desirable threshold for drinking water of <1 g/L
- For turbidity, which measures the opacity of the water due to the presence of suspended particles, all the samples were below the threshold recommended by the Moroccan standard, which is the limit value of 5 NTU (Moroccan standard 2020). The pH measurement is also compliant between 6.5 and 8.5.

3.3. Proposal of the brackish water pre-treatment technique

3.3.1. Selection of the pre-treatment technique

To validate the choice of our pre-treatment technique, we went through a set of pre-treatment techniques, and we were able to characterize them in terms of application and performance using the existing literature. Table 7 summarizes our relevant results.

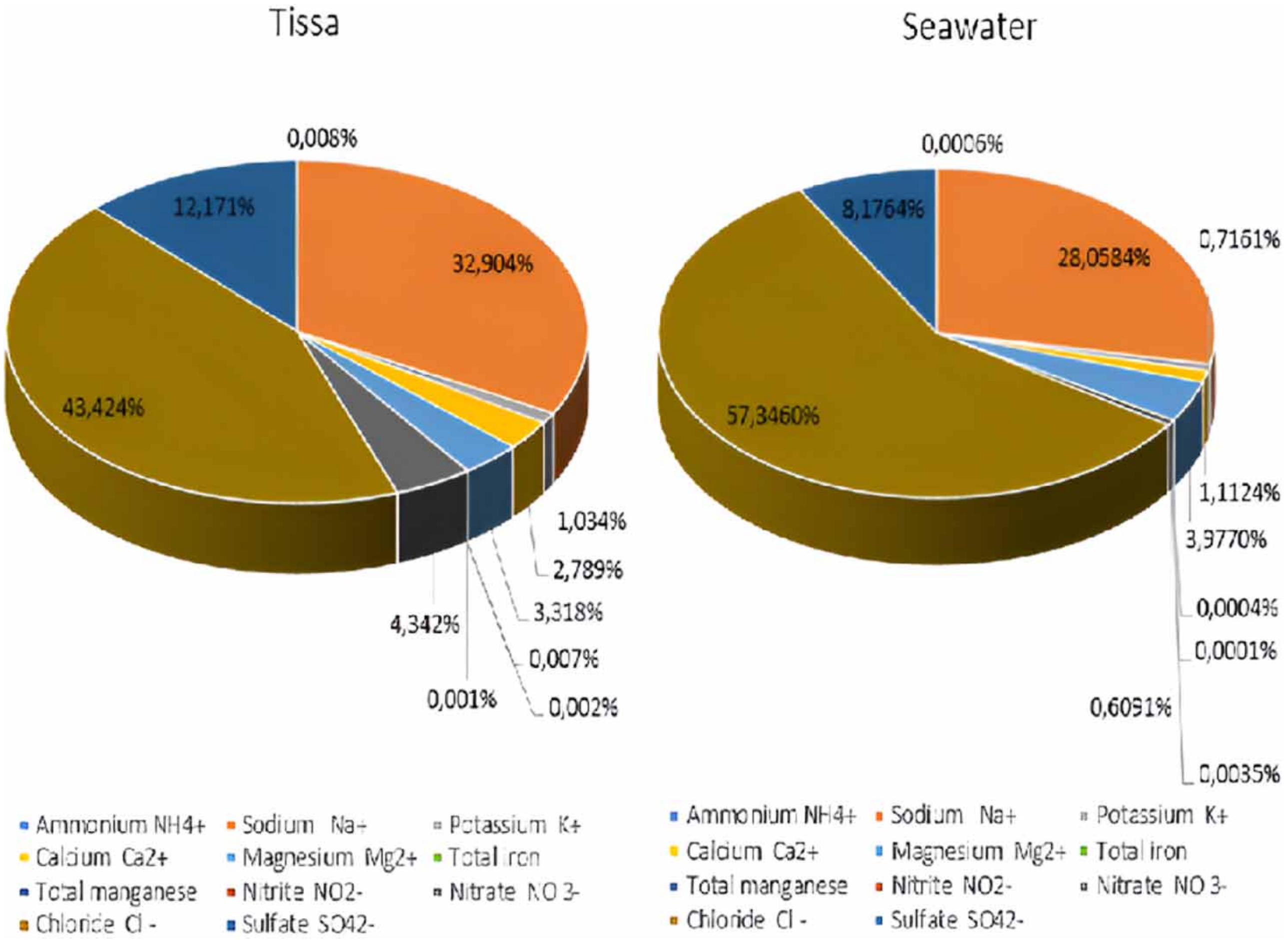


Figure 5 | Mineral load of samples from Tissa and seawater used for comparative purposes.

From Table 7, we can see that the electrocoagulation (EC) technique is the pre-treatment technique which has more advantages whether in terms of pollutant elimination (Hardness, Turbidity) or even lower energy consumption. In addition, the suitability of the technique for our project given that it uses electricity which will be supplied by solar energy will contribute to reducing the carbon footprint of our technique. In addition, this technique is more compact and requires less human intervention which is not the case for other techniques which require the addition of chemicals.

3.3.2. Development of the pre-treatment pilot model

3.3.2.1. Presentation of the technique. EC is a technique that has been used to treat many types of water, and this is especially the case for wastewater from different types of industrial or even domestic wastewater, groundwater, brackish water, and many other applications for the elimination of particular pollutants. Several possibilities exist for the design of EC, but in general, the basic scheme of EC is the following (Figure 7).

3.3.2.2. Simplified pilot model. Energy consumption of the EC unit: To assemble the EC unit with solar energy, particularly photovoltaic panels, it is essential to understand the operational cost and in particular the energy cost of this technique to be able to dimension our energy needs. The simplified operational cost calculation model which covers EC's electricity requirement. The operational cost of EC includes the cost linked to direct electricity consumption as well as the cost of the electrodes which will be consumed during the reaction (Geraldino *et al.* 2015). The mathematical equation which summarizes it is as follows:

$$\text{Operational cost} = \alpha.\ \text{Energy consumption} + \beta.\ \text{Electrode consumption} \qquad (3)$$

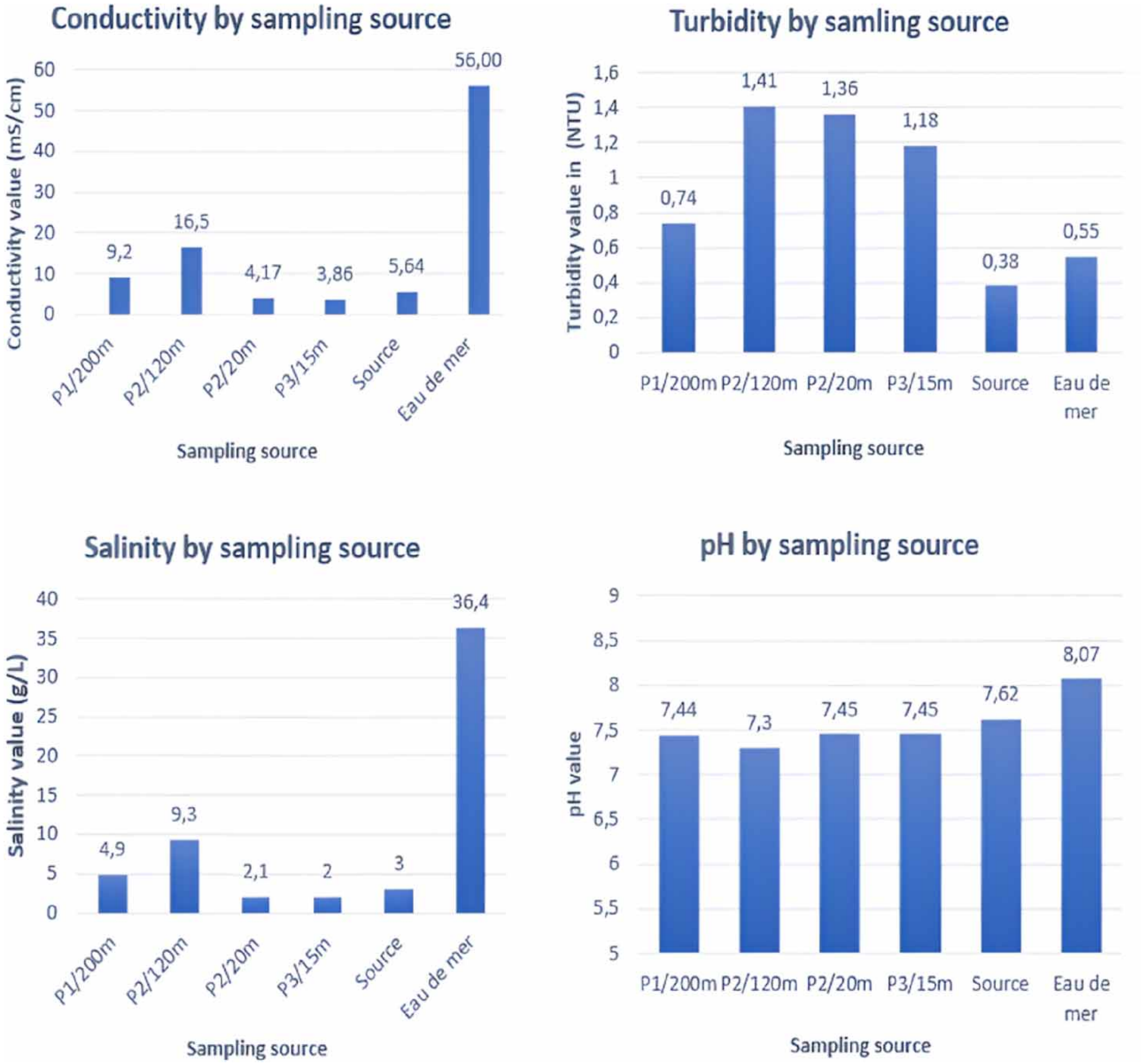


Figure 6 | Summary of the physico-chemical characteristics of the samples.

where α is the cost of energy and β is the cost of the electrode.

$$\text{Energy consumption} = \frac{U.I.t}{V} \tag{4}$$

where *i*th U is the electric tension (V), I is the current (A), t is time (h), and V is the volume (m^3)

$$\text{Electrode consumption} = \frac{I.t.M}{\text{F}.z} \tag{5}$$

where I is the current (A), t is the time (s), M is the molar mass (g), F is the Faraday constant, and z is the number of electrons.

Illustrative case study: In advancing the proposal for the simplified pilot model, it is imperative to establish operational hypotheses for the numerical application of this illustrative case study.

Table 7 | An overview of brackish water pre-treatment techniques

Technique	Applications	Performance
Coagulation-flocculation	Elimination of colloids and suspended particles responsible for turbidity (Cherif *et al.* 2016; Poirier *et al.* 2023)	- 70.87% reduction in turbidity (Cherif *et al.* 2016) - Generation of deposit from the addition of large quantities of chemical (Garcia-Segura *et al.* 2017)
DAF	Elimination of suspended solids/heavy metals (Yuan *et al.* 2008, Opedal *et al.* 2011)	- Reduction of OM (organic matter) (20–61%) (Shutova *et al.* 2016) - High operational cost (Garcia-Segura *et al.*, 2017; Hakizimana *et al.* 2017)
Adsorption	Elimination of organic matter (Shen *et al.* 2023)	- Reduction in hardness of around: 55% (Rolence *et al.* 2014) - Generation of deposit from the addition of large quantities of chemical (Garcia-Segura *et al.*, 2017)
Electrocoagulation	- Elimination of colloids, elimination of organic matter, and reduction of total dissolved solids and hardness (Poirier *et al.* 2023)	- Hardness reduction: 74% - Turbidity reduction: 90%(Aljaberi 2022) - 69.5% reduction in absorbance (Simanjuntak *et al.* 2011) - Ower deposit and operational cost (Garcia-Segura *et al.* 2017; Hakizimana *et al.* 2017)
Microfiltration (MF)/ ultrafiltration (UF)/ nanofiltration (NF)	- Do not allow particles that have a size larger than the pores of MF (0.1–10 μm) - Eliminate suspended particles, bacteria, and colloids - Do not allow particles that have a size larger than the pores of UF (10 nm to 1 μm) and eliminate macromolecules and viruses. - Do not allow particles that are larger than the NF pores (a few nm) and eliminate macromolecules and divalent ions (En CHIMIE G. D. D. 2019)	- MF: elimination of 100% of total suspended solid (Auliya *et al.* 2021) - UF: elimination of 98.95% of turbidity and elimination of organic matter (70–80%) (Arevalo *et al.* 2018) - NF: elimination of 97% de Mg^{2+} (Cheng *et al.* 2018) - Very frequent clogging and limited lifespan (Anis *et al.* 2019) - More energy consumption than non-membrane techniques (Anis *et al.* 2019)

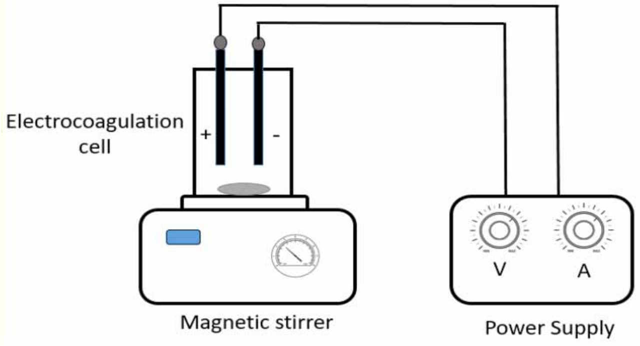


Figure 7 | Basic diagram of an electrocoagulation unit.

- For the energy requirements of the unit:
  - We admit an objective to produce potable water sufficient for a family, estimated at $V = 20$ L/day.
  - In addition, we presume that the maximum pollutant removal efficiency has been experimentally validated for a specific set of factors influencing EC (detailed in Section 3.3.2.1). In our context, we consider $U = 20$ V, $I = 3$A, and $t = 1$ h as the parameters for this experimentation. In this case, the necessary electrical energy will be calculated according to Equation (4) as follows: Energy required $= (20 \times 3 \times 1)/(0.02) = 3{,}000$ W h/m^3.day.
- Calculation of the size of the photovoltaic generator:

The calculation of the dimensions of the photovoltaic panels takes into account the initial energy requirement as well as factors linked to weather conditions and solar radiation of the area concerned by the installation (Soro *et al.* 2018). In this case, we will have the following calculation relations:

$$\text{Energy produced} = \frac{\text{Energy required for EC}}{K} \tag{6}$$

where K is the coefficient of meteorological uncertainty, generally [0.55, 0.65] and most often 0.65.

$$\text{Power consumed} = \frac{\text{Energy produced}}{\text{IR}} \tag{7}$$

where power is represented in Watts peak and IR represents the irradiation in kWh/m^2 per day. According to Table 5, the average value of $\text{IR} = 5.36\ \text{kWh/m}^2\text{/day}$. In our case, energy produced = 4,615 W h/m^3.day and power consumed = 861 W_{peak}.

Subsequently, the number of photovoltaic panels must be chosen by browsing a set of commercial products following the following equation:

$$N = \text{Number of panels} = \frac{\text{Power consumed}}{\text{Unit power of a panel}} \tag{8}$$

For a PHOTOWATT panel from the PX1650 DE range with a power of 165 W_{peak}, we will have $N = 6$.

- Simplified diagram of the pilot model:

We admit that our pilot model works without the direct use of energy from the solar panel without the need for a charge controller, and in addition, we will work with a parallel configuration for the panels since this will increase the current (given its importance for the reaction) without increasing the tension. The diagram of our simplified model is shown in Figure 8.

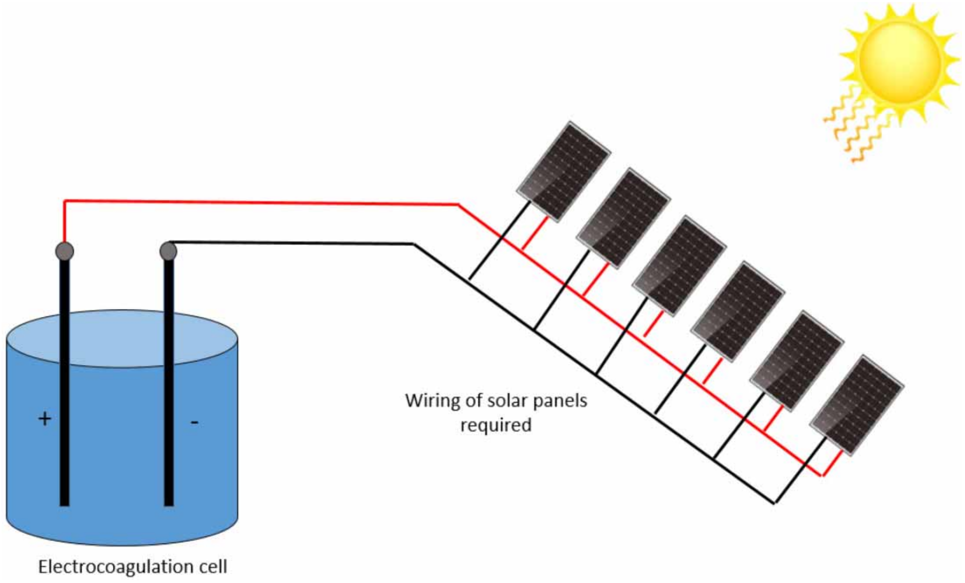


Figure 8 | Wiring of the simplified pilot model.

4. CONCLUSION AND PERSPECTIVES

This study focused on identifying candidate provinces in Morocco by considering various criteria, including distance, rural population, rates of non-access to drinking water, and solar irradiation. The selected areas were subject to brackish water sample collection to comprehensively understand their characteristics, essential for designing effective pre-treatment processes for water pre-treatment before desalination prototype. Analysing test samples revealed insights into mineral loads and physico-chemical characteristics, shedding light on the impact of soil location and human activities. Moreover, depth played a role in the presence of certain elements, such as SO_4^{2-} and NO_3^-. Notably, the elements contributing to water hardness exceeded drinking water standards, necessitating further exploration of appropriate pre-treatment techniques through a simplified pilot model. This is what was done by a simplified EC pilot model.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

ABOUZAID and DUCHESNE 1984 *Water Quality Control Department (Water Sampling and Analysis Manual)*. ONEP, Rabat.

AlJaberi, F. Y. 2022 Desalination of groundwater by electrocoagulation using a novel design of electrodes. *Chemical Engineering and Processing-Process Intensification* **174**, 108864.

Anis, S. F., Hashaikeh, R. & Hilal, N. 2019 Reverse osmosis pretreatment technologies and future trends: A comprehensive review. *Desalination* **452**, 159–195.

Arevalo, J., Sandin, R., Kennedy, M. D., Salinas Rodriguez, S. G., Rogalla, F. & Monsalvo, V. M. 2018 Membrane-based pretreatment to mitigate variations in desalination plants. *Water Science and Technology* **77** (12), 2858–2866.

Auliya, V. R., Marsono, B. D., Yuniarto, A. & Nurhayati, E. 2021 Brackish water treatment for small community by using membrane technology. In: *IOP Conference Series: Earth and Environmental Science* (Vol. 896, No. 1, p. 012073). IOP Publishing.

Bear, J., Cheng, A. H. D., Sorek, S., Ouazar, D. & Herrera, I. (Eds.). 1999 *Seawater Intrusion in Coastal Aquifers: Concepts, Methods and Practices* Vol. 14. Springer Science & Business Media, Dordrecht.

Chafidz, A., Kerme, E. D., Wazeer, I., Khalid, Y., Ajbar, A. & Al-Zahrani, S. M. 2016 Design and fabrication of a portable and hybrid solar-powered membrane distillation system. *Journal of Cleaner Production* **133**, 631–647. https://doi.org/10.1016/j.jclepro.2016.05.127.

Cheng, W., Liu, C., Tong, T., Epsztein, R., Sun, M., Verduzco, R., Ma, J. & Elimelech, M. 2018 Selective removal of divalent cations by polyelectrolyte multilayer nanofiltration membrane: Role of polyelectrolyte charge, ion size, and ionic strength. *Journal of Membrane Science* **559**, 98–106.

Cherif, L., Chiboub Fellah, A., Chiboub Fellah, F. Z., Boulefred, S. & Benadda, L. 2016 The effect of suspended matter concentration on the coagulation–flocculation and decantation process for low brackish water C (NaCl) = 3 g/L. *Desalination and Water Treatment* **57** (13), 6106–6115.

Diouf, O. C., Weihermüller, L., Diedhiou, M., Beltoungou, E. Y. T. B., Dieng, N. M., Faye, S. C., Vereecken, H. & Faye, S. 2022 Groundwater geochemistry and saltwater intrusion in the Dakar coastal area, Senegal. *Journal of Geoscience and Environment Protection* **10** (12), 45–64. https://doi.org/10.4236/gep.2022.1012004.

Egboka, B. C. E. 1984 Nitrate contamination of shallow groundwaters in Ontario, Canada. *Science of the Total Environment* **35** (1), 53–70. https://doi.org/10.1016/0048-9697(84)90368-1.

En CHIMIE, G. D. D. 2019 *Valorisation des ressources hydriques et production de l'eau purifiée par les procédés membranaires*. *Doctoral dissertation*, KU, Leuven.

Garcia-Segura, S., Eiband, M. M. S., de Melo, J. V. & Martínez-Huitle, C. A. 2017 Electrocoagulation and advanced electrocoagulation processes: A general review about the fundamentals, emerging applications and its association with other technologies. *Journal of Electroanalytical Chemistry* **801**, 267–299.

Geraldino, H. C. L., Simionato, J. I., de Souza Freitas, T. K. F., Garcia, J. C., de Carvalho Júnior, O. & Correr, C. J. 2015 Efficiency and operating cost of electrocoagulation system applied to the treatment of dairy industry wastewater. Acta Scientiarum. *Technology* **37** (3), 401–408.

Gleick, P. 1993 *Water in Crisis: A Guide to the World's Fresh Water Resources*. Oxford University Press, New York.

Gourai, K., Allam, K., El Bouari, A., Belhorma, B., Bih, L. & Cherai, N. 2015 AQUASOLAR-macro project: Brackish water desalination by coupling solar energy with reverse osmosis and membrane distillation process. *Journal of Materials and Environmental Science* **6** (12), 3524–3529.

Hafez, A., Khedr, M., El-Katib, K. & Gadallah, H. 2009 Pilot scale investigation of low pressure nanofiltration and reverse osmosis membrane techniques for the treatment of El-Salaam canal water, Sinai, Egypt. *Desalination and Water Treatment* **8** (1–3), 279–285. doi: 10.5004/dwt.2009.789.

Hakizimana, J. N., Gourich, B., Chafi, M., Stiriba, Y., Vial, C., Drogui, P. & Naja, J. 2017 Electrocoagulation process in water treatment: A review of electrocoagulation modeling approaches. *Desalination* **404**, 1–21.

HCP official website 2014 https://www.hcp.ma/Bases-de-donnees_r631.html

Ibrahim, A. G., Rashad, A. M. & Dincer, I. 2017 Exergoeconomic analysis for cost optimization of a solar distillation system. *Solar Energy* **151**, 22–32. http://dx.doi.org/10.1016/j.solener.2017.05.020.

IRESEN official website. http://gepmapping.ma/map?place=maroc&layer=ghi

Izonin, I., Tkachenko, R., Shakhovska, N., Ilchyshyn, B. & Singh, K. K. 2022 A two-step data normalization approach for improving classification accuracy in the medical diagnosis domain. *Mathematics* **10** (11), 1942. https://doi.org/10.3390/math10111942.

Jones, E., Qadir, M., van Vliet, M. T., Smakhtin, V. & Kang, S. M. 2019 The state of desalination and brine production: A global outlook. *Science of the Total Environment* **657**, 1343–1356. https://doi.org/10.1016/j.scitotenv.2018.12.076.

Ju, X. T., Kou, C. L., Zhang, F. S. & Christie, P. 2006 Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. *Environmental Pollution* **143** (1), 117–125. https://doi.org/10.1016/j.envpol.2005.11.005.

Lwimbo, Z. D., Komakech, H. C. & Muzuka, A. N. 2019 Impacts of emerging agricultural practices on groundwater quality in Kahe catchment, Tanzania. *Water* **11** (11), 2263. https://doi.org/10.3390/w11112263.

Maazouzi, A., Kettab, A., Badri, A., Zahraoui, B. & Khalfaoui, R. 2013 Physicochemical parameters of groundwater (Foggara) and sand dune (Timimoun) Algeria. *Desalination and Water Treatment* **51** (37–39), 7353–7358. https://doi.org/10.1080/19443994.2013.791765.

Moroccan standard on the quality of water for food use NM 03.7.001 2020.

Moujabber, M. E., Samra, B. B., Darwish, T. & Atallah, T. 2006 Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast. *Water Resources Management* **20**, 161–180. https://doi.org/10.1007/s11269-006-7376-4.

National portal for territorial authorities 2023 https://www.collectivites-territoriales.gov.ma/fr/la-prefecture-et-la-province.

Official website of the world bank. https://donnees.banquemondiale.org/indicator/ER.H2O.INTR.PC?end=2018&start=1962&view=chart.

ONEP 2007 Procedure for Sampling Natural, Treated and Waste Water. Water Quality Control Department.

ONEP 2008 Standard Operating Procedures. Water Quality Control Department.

Opedal, M. T., Stenius, P., Johansson, L., Hill, J. & Sandberg, C. 2011 Removal of dissolved and colloidal substances in water from compressive pre-treatment of chips using dissolved air flotation. Pilot trial. *Nordic Pulp & Paper Research Journal* **26** (4), 364–371.

Poirier, K., Lotfi, M., Garg, K., Patchigolla, K., Anthony, E. J., Faisal, N. H., Mulgundmath, V., Sahith, J. K., Jadhawar, P., Koh, L., Morosuk, T. & Al Mhanna, N. 2023 A comprehensive review of pre-and post-treatment approaches to achieve sustainable desalination for different water streams. *Desalination* **566**, 116944.

Report by the Directorate of Financial Studies and Forecasts 2020 Morocco in the face of climate change: situation, impacts and response policies in the water and agriculture sectors (official website of the Ministry of Finance of Morocco).

Rodier, J. 2009 *Water Analysis – Natural Waters, Waste Water, Sea Water*, 9th edn. Dunod, Paris, 1475 p.

Rolence, C., Machunda, R. & Njau, K. 2014 Water hardness removal by coconut shell activated carbon. *East Asian Science Technology and Society an International Journal* **2** (5), 97–102.

Shen, J., Yuan, Y., Duan, F. & Li, Y. 2023 Performance of resin adsorption and ozonation pretreatment in mitigating organic fouling of reverse osmosis membrane. *Journal of Water Process Engineering* **53**, 103688.

Shutova, Y., Karna, B. L., Hambly, A. C., Lau, B., Henderson, R. K. & Le-Clech, P. 2016 Enhancing organic matter removal in desalination pretreatment systems by application of dissolved air flotation. *Desalination* **383**, 12–21.

Simanjuntak, W., Ginting, I. & Pandiangan, K. D. 2011 Removal of natural organic matter using electrocoagulation as a first step for desalination of brackish water. *Indonesian Journal of Chemistry* **11** (1), 103–107.

Soro, D., Yapi, M., Fofana, B. & Yao, N. A. 2018 Dimensionnement d'une installation solaire pour la réalisation de travaux pratiques dans les lycées et collèges en zone isolée. *Afrique Science* **14** (5), 335–345.

Yoon, J., Kwon, H. J., Kang, S., Brack, E. & Han, J. 2022 Portable seawater desalination system for generating drinkable water in remote locations. *Environmental Science & Technology* **56** (10), 6733–6743. https://doi.org/10.1021/acs.est.1c08466.

Yuan, X. Z., Meng, Y. T., Zeng, G. M., Fang, Y. Y. & Shi, J. G. 2008 Evaluation of tea-derived biosurfactant on removing heavy metal ions from dilute wastewater by ion flotation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **317** (1–3), 256–261.

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