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Brine recycling impact on nitrate removal and electrochemical disinfection performances: a case study of Sidi Taibi desalination plant

Soufian El-Ghzizel[a], Hajar Zeggar[a], Fatima Elazhar[a,b], Mustapha Tahaikt[a], Mahmoud Hafsi[c], Azzedine Elmidaoui[a], Mohamed Taky[a,d,*]

[a]*Laboratory of Advanced Materials and Process Engineering, Faculty of Sciences, Ibn Tofail University, P.O. Box: 1246, Kenitra, Morocco, emails: mohamed.taky@uit.ac.ma (M. Taky), soufian.el-ghzizel@uit.ac.ma (S. El-Ghzizel), zeggar.hajar@uit.ac.ma (H. Zeggar), fatima.elazhar@uit.ac.ma (F. Elazhar), mustapha.tahaikt@uit.ac.ma (M. Tahaikt), elmidaoui@uit.ac.ma (A. Elmidaoui)*
[b]*National Higher School of Chemistry (NHSC), Ibn Tofail University, Kenitra, Morocco*
[c]*Water Technical Assistance, Rabat, Morocco, email: hafsi.mahm@gmail.com*
[d]*International Water Research Institute, Mohammed VI Polytechnic University, Lot 660, Hay Moulay Rachid Ben Guerir, 43150 Morocco*

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ABSTRACT

The groundwater in the region of Sidi Taibi (Kenitra, Morocco) is intended for human consumption and agriculture. However, this water is largely contaminated with nitrate, which poses a serious threat to human health. This situation is at the origin of the construction in 2014 of the first nitrate removal plant, using nanofiltration (NF) coupled to an electrochemical disinfection system, and supplied with renewable energies (photovoltaic and wind). The unit was installed at Al Annouar high school in Sidi Taibi to supply 1,200 students with potable water, with a production capacity of 500 L/h (3 L/d/student). The local groundwater is nitrated and slightly brackish. This work aims at studying the impact of recycled ratios of brine on nitrate removal and electrochemical disinfection performances. For this reason, two configurations are evaluated separately at a different recycled ratio of brine. The studied configurations are NF90-NF90 and NF270-NF90. The results show that NF90-NF90 configuration with brine recycling can only be technically feasible under the following conditions: brine recycling ratio of 70%, a recovery rate of 85% and a flow rate of 260 L/h intended to be blended with the nanofiltered water which is directed to the electrolytic cell (first mode). On the other hand, NF270-NF90 configuration presents two installations that are feasible to be combined with the electrolyzer. The first one is set for a recovery rate of 60% and a brine recycling ratio of 40% (second mode). The second one is optimized for a recovery rate of 75% and a recycled ratio of the brine of 10% (third mode). The three optimized modes present remarkable qualitative, quantitative, and energy performances.

Keywords: Nanofiltration; Electrochemical disinfection; Brine management; Brine recycling

1. Introduction

Brackish water (BW) is saline water that is not intended for human consumption. The total dissolved solids (TDS) of these waters vary from 1 to 10 g/L [1]. Generally, they are sometimes surface water but more often groundwater. Apart from the TDS problem, these waters can be also contaminated by nitrate representing a risk for human

* Corresponding author.

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health and exceeding the legal limit of nitrate concentration required by the World Human Organization (WHO) (50 mg/L) [2,3]. This particularity is generally detected in some groundwater cases intended for agricultural irrigation, so its TDS is relatively low [4–6]. Consequently, desalination of these waters is an essential alternative way to produce drinking water. So far, BW desalination represents over 21% of the total worldwide desalination capacity [7]. Despite the relatively lower production capacity, this alternative would solve the problem of water scarcity, especially in countries located in the Middle East and Nord Africa (MENA) region [1].

Besides ion-exchange (IX), electrodialysis (ED), biological denitrification, and catalytic denitrification processes, many publications indicate that nanofiltration (NF) and reverse osmosis membranes (RO) are promising technologies to treat groundwater with such nitrate contents and TDS in terms of high efficiency, easy operation, high effluent water quality, modularity and flexibility [6,8–12]. Unlike RO membranes, NF can operate with low energy consumption, because of the lower operating pressures applied. In addition, rejection of monovalent ions does not exceed 60% opening an opportunity to maintain the most favourable mineral content as required in treating waters [13].

Despite the progress made in membrane-based processes such as NF and RO, the brine production, as known as a concentrate, makes an obstacle for the application of these processes due to its high TDS [14–16]. The environmental impacts of brine discharges are manifold. The majority of studies associate this problem with the increase in salt concentrations in water bodies that receive the brine eliminated by desalination plants [15]. Brines with a high TDS negatively affect marine benthic communities living near brine discharges. Removing the brine is also aesthetically unpleasant. In addition, the chemical products used for pretreatment and membranes cleaning and corrosive metals are significant. TDS, temperature, and chemical composition of brine are reasons why brine poses a threat to the environment. TDS and temperature of the brine are entirely dependent on the membrane technology used. The salinity of the brine oscillates between 55 and 70 g/L, that is approximately 1.5–2 times higher than seawater [17]. Besides the quality of the water to be treated, the transmembrane pressure (TMP) applied and membrane used for the treatment, the recovery rate applied is a key parameter that determine the quality and quantity of the brine produced by desalination plants [18]. The typical water recovery of seawater reverse osmosis (SWRO) systems varies between 40% and 50% [19] and between 75% and 85% [18,20] for brackish water reverse osmosis (BWRO) desalination plants. Therefore, a cost-effective and environmentally friendly brine management system is required before their proper disposal. Currently, several disposal options have been used such as surface water discharge, deep-well injection, and evaporation ponds [7,18]. On other hand, new innovative and advanced research is being studied around the world which considers brine not as discharge but rather as a resource with high added value: use in aquaculture to increase fish biomass, irrigation of plants that tolerate high salinity (such as spirulina algae sold in drugstore as dietary supplement) [21]. Brine could generate electricity, and brine contains a diversity of precious metals of great economic interest (Li, B, Rb, Sc, V, etc.). Finally, brine is also a mine of nutrients (Mg, K, etc.) that are of high interest in terms of agronomic production [21]. All these aspects constitute a real research challenge for universities and research development in the near future.

Another option to minimize the brine problem is brine recycling. This method is technically usable in the case of BW desalination which is characterized by a lower TDS compared to seawater [22]. Sarkar et al. [23] tested this configuration on a small BWRO treatment pilot. The results of this study showed that the system requires an increase in temperature during processing to consistently maintain performance at a fixed product flow rate. In a simulation study, Sharma et al. [24] compared the performance of two RO configurations, with partial concentrate recirculation and open-loop without recirculation. The results of this study showed that the closed-loop design with recirculation of brine consumes between 70% and 95% less energy compared to the open-loop design. In addition, the implementation of recirculation with an optimal ratio (maximum recirculation) saves up to 95% of energy consumption. Another simulation study investigated the feasibility of implementing the brine recycle design on the original design of an industrial medium-sized multistage and multi-pass spiral wound BWRO desalination plant (1,200 m^3/d) of Arab Potash Company (APC) located in Jordan [22]. This study confirmed the possibility of increasing the production capacity of the plant by around 3% with 100% recycle percentage of the high TDS concentrate stream. Therefore, from a qualitative, quantitative, and energy consumption point of view, all these studies confirmed the feasibility of the brine recycling option for BW membrane-based desalination processes.

In this context, this study is based on the impact of brine recycling on the performance of an electrochemical disinfection system in a real desalination plant. Compared to other conventional disinfection processes (chemical and physical) [25], the electrochemical disinfection method (EDM) acts by means of electrochemical disinfectant generated on-site or in-line. This action is called the in-situ electrogeneration of disinfection. In addition, the disinfecting effect can be adjusted according to the on-site demand [26–29]. Apart from electrolysis medium (electric conductivity, pH, and temperature) and others factors like electrode potential, current density, and electrode material [30], the effectiveness of EDM depends mainly on the chloride concentration in the water to be disinfected.

In this perspective, the use of EDM as a basic step for the disinfection of the water produced by a desalination plant requires consistency and technical agreement between the quality of the water produced by the membrane process and the operating conditions of the EDM used, especially chloride concentration. In this context, to our knowledge, only one research work which was published by our laboratory in 2020 titled "Nanofiltration process combined with electrochemical disinfection for drinking water production: feasibility study and optimization" which studied the combination between desalination and electrochemical disinfection process [31]. More precisely, this work was carried out on a real desalination plant (Sidi Taibi desalination plant) which combines NF and an EDM to renewable energies system for potable water production. The results obtained showed that the main factors, which determined the electrolysis performance, respect clearly its technical requirements except for desalted water with a low content of chloride. This problem is corrected by an optimized blending of the permeate with raw groundwater.

This paper aims at studying separately the feasibility of two NF configurations installed in series before an EDM, NF90-NF90, and NF270-NF90. The purpose of these installations is two-fold; firstly, the objective is to correct the concentration of chloride ions at the inlet of electrolysis. Secondly, it is to a means prevent deterioration of the produced water quality (nitrate content in particular). The present work is carried out on two scales; at the laboratory and the Sidi Taibi desalination plant scales. Further term, this study examines whether the proposed design (recycling of brine) presents technically advantages in terms of quality, quantity of blending and energy consumption.

2. Materials and methods

2.1. Plant description

The Sidi Taibi plant is the concretization of collaboration between Belectric, Comodos, Firmus French Companies, and Ibn Tofail University. The plant marked the beginning of the use of a hybrid energy system (photovoltaic and wind) to power the NF desalination unit. It was installed in March 2014 at Al Annouar high school in Sidi Taibi (region of Kenitra, Morocco). The plant is designed to supply 1,200 students with potable water, with a daily production capacity of 12 m^3/d. The membrane is fed by groundwater which is slightly brackish and with nitrate content exceeding slightly the recommended standards [5,31–33].

After a brief pretreatment (cartridges 25 and 5 μm), the water is directed into the NF compartment, which consists of two spiral membranes (NF90 40*40) type: polyamide thin-film composite Filmtec Dow, installed in series with a total surface area of 15.2 m^2 (Table 1). Then, the nanofiltered water is routed to be disinfected by an EDM, called Sunpur developed by Belectric Company, for the in-situ generation of chlorine. This disinfection process is operated only with electrical energy and does not require any additives. The chloride in water is oxidized to free chlorine by an electrochemical reaction. In the final step, the produced water is stored in a storage tank and distributed. Table 2 gives the operating characteristics of the Sunpur EDM used and Fig. 1 shows the operating scheme of the Sidi Taibi desalination plant.

2.2. Characteristics of the feed water, permeate, and ions rejection by NF90 membrane

The main characteristics of feed water, permeate, concentrate, and rejections are summarized in Table 3.

2.3. Tested configurations

At the laboratory scale and the scale of the Sidi Taibi plant, two configurations are tested to correct the chloride concentration at the inlet of the Sunpur disinfection system. The first installation is a configuration containing two NF90 membranes with different ratios of recycled brine (Fig. 2a). This part of the study is carried out at the level of the Sidi Taibi plant. At the laboratory scale, a second configuration has been adopted in which the two membranes used in the series are different. In this configuration, the NF270 membrane is placed first followed by NF90. In this case, the experiments are performed on an NF/RO pilot plant (E 3039) supplied by TIA Company (Technologies Industrielles Appliquées, France) with the same operating conditions. The pilot plant is equipped with two identical spiral wound modules operating in

Table 1
Properties of NF90 and NF270 membranes

Membrane	NF90	NF270
Materials	Polyamide	Polyamide
Molecular weight cut-off (MWCO)	200–400	200–400
Area (m^2)	7.6	7.6
P_{max} (bar)	41	41
pH range	2–11	2–11
SDI	<5	<5
T_{max} (°C)	45	45

SDI: Maximum feed Silt Density Index, P_{max}: Maximum operating pressure, T_{max}: Maximum temperature.

Table 2
Operating characteristics of the EDM used (Sunpur)

Sunpur system	Recommended values	Data source
Power input	220V AC	Manufacturer
Required chloride of raw water	10–250 mg/L	Manufacturer
Minimum flow rate	400 L/h	Manufacturer
Maximum flow rate	Depends on the current supply	Manufacturer
Power consumption	100–700 W	Manufacturer
Water temperature	4°C–25°C	Manufacturer
Minimum conductivity of raw water	300 μS/cm	Manufacturer
Ambient temperature	Maximum 50°C	Manufacturer

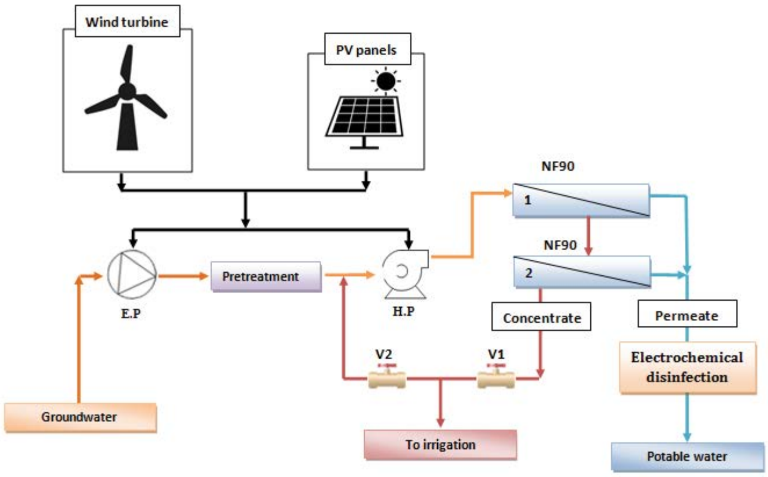

Fig. 1. Operating scheme of the Sidi Taibi desalination plant. V1: Pressure regulation valve; V2: Brine recirculation valve; H.P.: High-pressure pump and E.P.: Emerged pump.

Table 3
Composition of feed water, permeate, concentrate, and rejections of NF90

	Feed water (mg/L)	Permeate (mg/L)	Concentrate (mg/L)	Ion rejection (%)
K^+	7.04	1.5	23.64	78.6
Na^+	4.95	0.77	17.48	84.4
Mg^{2+}	36.01	1.3	140.12	96.3
Ca^{2+}	112.9	8	427.49	92.9
HCO_3^-	377.3	29	1,421.79	92.3
NO_3^-	68.7	14	232.60	79.6
Cl^-	25	2	93.97	96
SO_4^{2-}	35.01	1.2	136.42	96.5
TDS	660	60	2,459.15	89

series. Each module contains one element. Fig. 2b gives the scheme of the adopted configuration. The recycling ratio of the brine studied for the two configurations varies from 0% (without brine recycling) up to 70%.

2.4. Performance indicators

The performances of the plant are followed by rejection, specific energy consumption, recovery rate and Langelier Saturation Index (LSI) parameters, which are defined as:

- Rejection (R) [34]:

$$R(\%) = \frac{C_f - C_p}{C_f} \times 100 \quad (1)$$

where C_p and C_f are the permeate and initial concentrations, respectively.

- Specific energy consumption (SEC) [35]:

$$\text{SEC}\left(\text{kWh/m}^3\right) = \frac{\text{Pe} \times 100}{\left(\eta \times Y \times 36\right)} \quad (2)$$

where Pe, η, and Y are the pressure (bar), the global pumping system efficiency, and the recovery rate (%), respectively.

- Recovery rate (Y) is calculated using the following equation [36]:

$$Y(\%) = \frac{Q_p}{Q_f} \times 100 \quad (3)$$

where Q_f and Q_p are the feed and the permeate flow rates, respectively.

- Langelier Saturation Index (LSI) [37]:

$$\text{LSI} = \text{pH} - \text{pHs}\left(\text{TDS} < 10{,}000 \text{ mg/L}\right) \quad (4)$$

$$\text{p}H_s = \text{pCa} + \text{pHCO}_3 + \left(\text{p}K_2 + \text{p}K_s\right) \quad (5)$$

With:

pCa: log 1/[Ca^+].
$pHCO_3$: log 1/[HCO_3^-].
pK_2: log(1/K_2): (K_2 is the second dissociation constant of carbonic acid).
pK_s: log(1/K_s): (K_s is the solubility product of calcium carbonate).

LSI < 0: Water is undersaturated with respect to calcium carbonate. Undersaturated water tends to remove existing calcium carbonate protective coatings in pipelines and equipment.

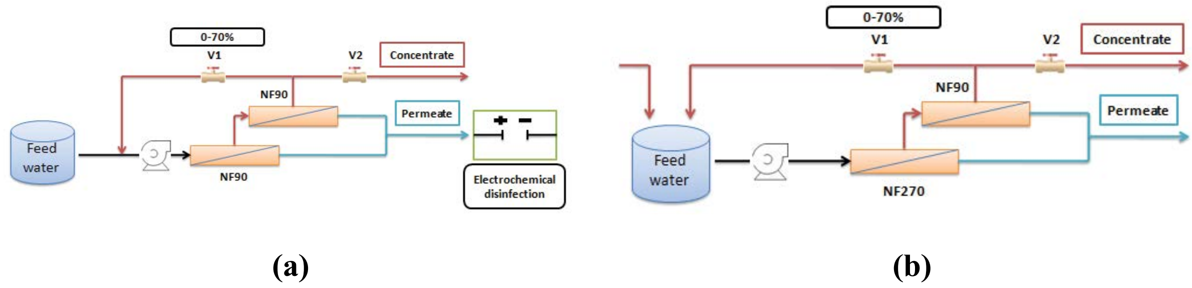

Fig. 2. Configuration with brine recycling. V2: Pressure regulation valve, V1: Brine recirculation valve. NF90-NF90 (a), NF270-NF90 (b).

LSI = 0: Water is considered to be neutral. Neither scale-forming nor scale removing.

LSI > 0: Water is supersaturated with respect to calcium carbonate ($CaCO_3$) and scale forming may occur.

Where pH, pHs, and TDS are the pH of the solution, the pH saturation of the solution, respectively.

3. Results and discussion

The performance of the two configurations, NF90-NF90, and NF270-NF90, are analyzed based on an experimental study (Fig. 2). In this part, both configurations are examined at different recovery rates by varying the ratio of brine recycling from 0% to 70%. Besides, this study focuses on investigating the performance of the treatment process for a step-change in the recycling of the brine flow. It is important to mention that the Sidi Taibi plant is currently operating with two NF90 membranes installed in series and without any brine recycling mode. The performance indicators of the treatment process include TDS, chloride concentration (Cl^-), nitrate concentration (NO_3^-), and LSI. In addition, this study focuses on the impact of brine recycling on the total productivity of the drinking water of the plant and energy consumption. The study is performed for a fixed feed flow rate of 850 L/h, a nitrate concentration of 68 mg/L, and TDS of 660 mg/L.

3.1. NF90-NF90 Configuration

Fig. 3 shows the influence of brine recycling on nitrate concentration, chloride concentration, and TDS for NF90-NF90 configuration at the Sidi Taibi plant scale.

Fig. 3a shows that nitrate concentration in the permeate varies from 15.4 to 25.6 mg/L. These results are still below the standards required by WHO. Thus, the results found in terms of TDS vary from 60 to 110 mg/L and from 68 to 138 mg/L for a recovery rate of 75% and 85%, respectively (Fig. 3b). These results confirm that increasing the ratio of brine recycling leads to an increase in the permeate concentration in terms of TDS and nitrate content. At the same time, it should be noted that the technical feasibility of these configurations depends mainly on the chloride concentration at the inlet of the electrolyzer. From Fig. 3c, it is noticed that the concentration of chloride varies progressively from 2 to 4 mg/L for Y = 75% and from 2.24 to 5.15 mg/L for Y = 85%. Depending on the operating conditions of the electrolyzer, the obtained chloride concentration is not satisfactory for safe production of free chlorine over the entire range of brine recycling ratios and the recovery rates applied.

Energetically, the energy consumption increases slightly from 0.29 to 0.4 kWh/m^3 for an NF90-NF90 without recycling (0%) to 70% of brine recycling, respectively for a recovery rate of 75%. In addition, the energy obtained for a recovery rate of 85% is not similar to that obtained for 75% (Fig. 4). This is mainly due to the resulting recovery rate and the pressure obtained during brine recycling.

In this regard, the configurations tested in this study have the advantage of increasing the daily water production and reducing the rate of brine discharged with slightly low energy consumption (E_{max} = 0.4 kWh/m^3). The only apparent drawback is the low chloride concentration obtained at the entrance of Sunpur, that is, just after the NF step. This behavior makes these configurations technically impossible to be applied at the scale of the Sidi Taibi plant. For this reason, another installation idea is adopted in order to correct the chloride concentration. This is done by setting the plant recovery rate and the brine recycling at 85% and 70%, respectively, and mixing the water intended to the electrolytic cell with raw water (bypass blending). This operation is carried out at different flow rates: 80, 260, and 340 L/h that correspond to an opening of the bypass blending valve of 20%, 30%, and 40%, respectively (Fig. 5).

In this case, it is noted that the configuration adopted in the treatment process (NF90-NF90) does not negatively affect the TDS of the produced water. TDS values varies respectively from 180 to 365 mg/L for an opening of bypass blending valve of 20% and 40% (Fig. 6a). Also, exceeding WHO standards are observed in nitrate concentration for a flow rate blending of 340 L/h, which corresponds to a 40% of bypass blending valve. In contrast, the results obtained in terms of nitrate concentration vary from 30 to 40 mg/L for an opening of bypass valve of 20% and 30%, respectively (Fig. 6b). These results limit the blending operation to the opening of bypass valve at 20% and 30% and studying its effect on chloride concentration and LSI. In this context, satisfactory results in terms of chloride concentration are achieved, the content of 9 and 13.5 mg/L for a bypass valve opening of 20% and 30%, respectively (Fig. 6c). From these results, it is clear that the chloride concentration produced at bypass valve opening

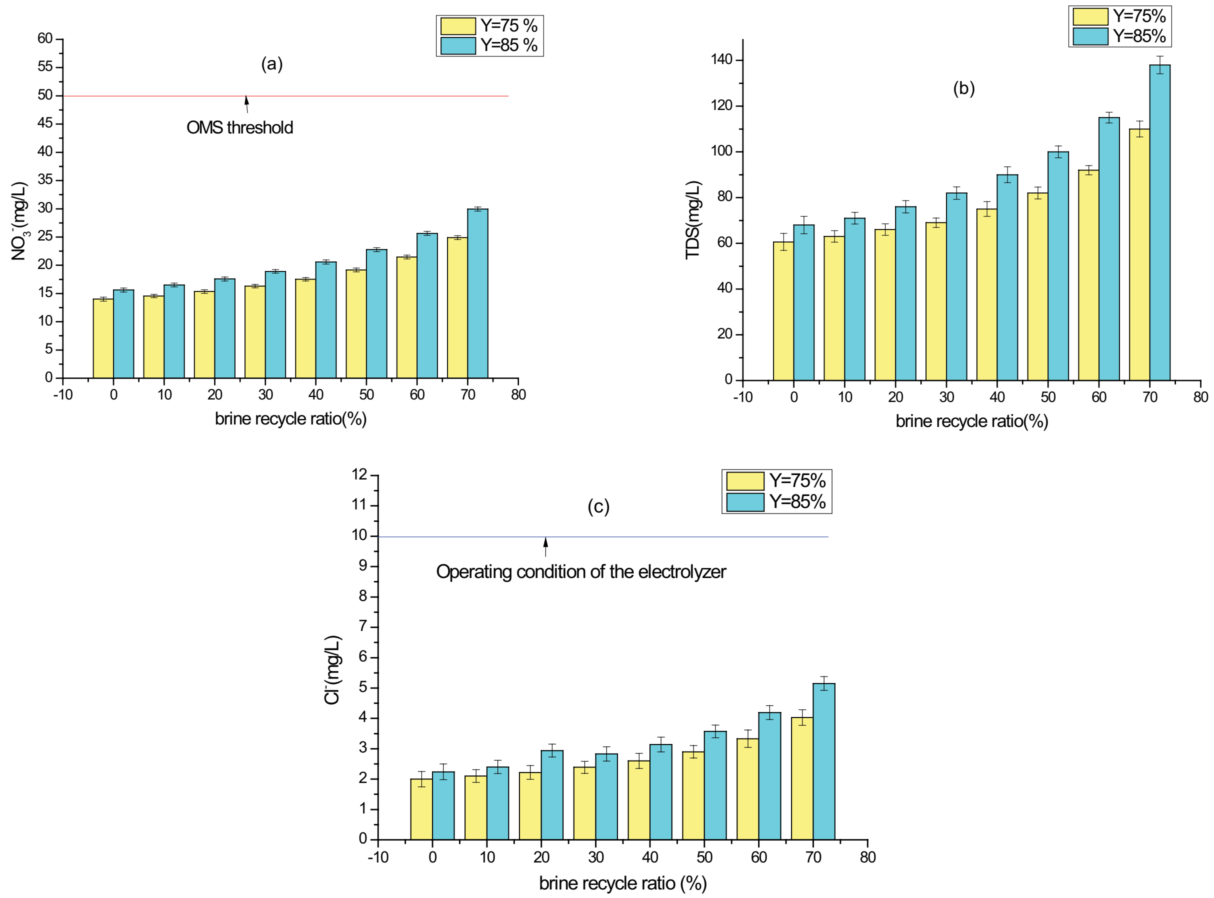

Fig. 3. Evolution of (a) nitrate concentration, (b) TDS, and (c) chloride concentration as a function of brine recycling ratio for NF90-NF90 configuration.

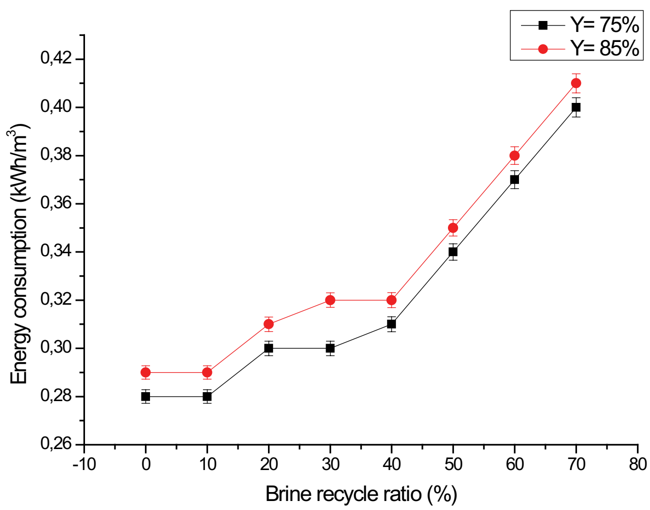

Fig. 4. Evolution of energy consumption according to the brine recycling ratio for NF90-NF90 configuration.

of 30%, unlike 20%, meets the operating conditions of the EDM. In addition, the calculated LSI values (−0.28) indicate that the water produced is non-scaling and slightly corrosive (Table 4). It should be noted that this parameter is mainly related to the pH and pHs of the water produced. The recorded pH value in this case (30%) indicates 7.4 (Table 4), which is satisfactory to limit the problems associated with the aggressive or encrusting tendency of water. Hence, this configuration is the most reassuring for producing disinfected water with TDS values that comply with drinking water norms. Also, the same configuration presents no risk to the equipment installed in the plant, more particularly in relation to the electrodes of the electrolyzer.

Hydraulically, the flow rate of the produced water by the configuration selected above is largely sufficient for the daily needs of the school (820 L/h that equals 19.6 m^3/d) (Table 5). Thus, the analysis of the energy results in the same configuration confirms that the recorded consumption is of the order of 0.21 kWh/m^3 (Table 5). This energy value remains similar to that obtained by the old NF90-NF90 installation but with better performance in terms of quality and quantity [5].

3.2. Configuration NF270-NF90

In this part, another hybrid NF installation is tested. It consists of two different NF membranes, NF270 and NF90 installed in series. For this configuration, the brine recycling mode is studied for two fixed recovery rates,

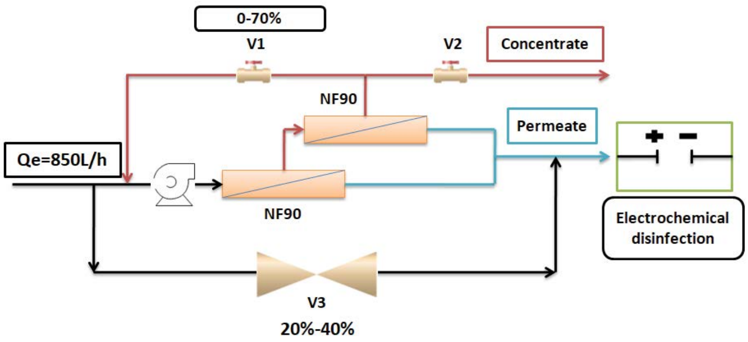

Fig. 5. NF9-NF90 configuration with brine recycling and bypass blending with raw water. V1: brine recirculation valve, V2: brine regulating valve, and V3: raw water bypass blending valve.

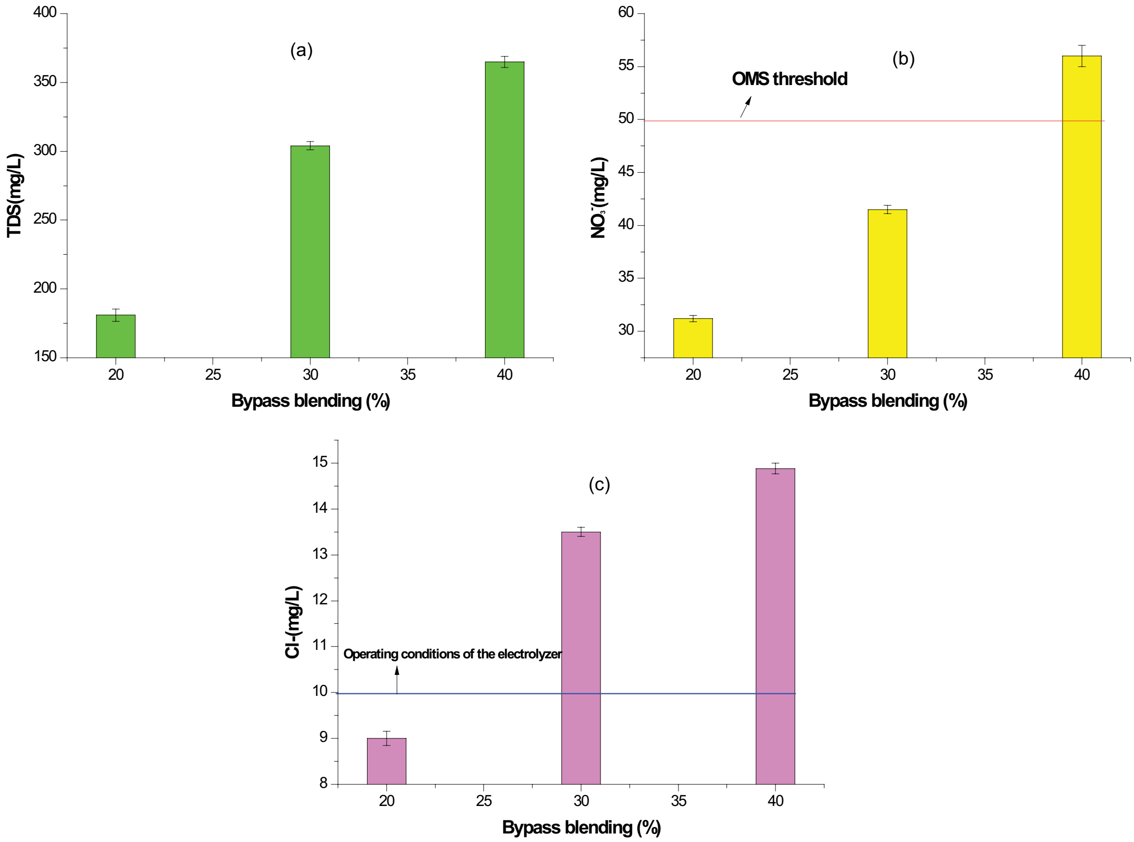

Fig. 6. (a) TDS, (b) nitrate, and (c) chloride content as a function of bypass blending valve for NF90-NF90 configuration.

60% and 75%. For Y = 60%, the results obtained show that the TDS of the water produced by the eight recycling ratios (0%, 10%, 20%, 30%, 40%, 50%, 60%, and 70%) does not show any great variation; TDS values vary between 210 mg/L for the mode without recycling (0%) and 308 mg/L for the 70% of brine recycling (Fig. 7a). Indeed, these results are below the standard required by WHO (500 mg/L). In addition, concentrations recorded in terms of nitrate show that from a brine recycling ratio of 50%, the nitrate content exceeds WHO guideline value relating to the quality of water intended for the production of drinking water (Fig. 7b). This result restricts the feasibility of the configuration NF270-NF90 (with brine recycling) between simple mode (brine recycling 0%) and brine recycling with a ratio of 40%. Within this range, the chloride values vary slightly between 10.75 and 12.3 mg/L for 0% and 40% of the brine recycling ratios, respectively (Fig. 7c). These results respect the technical requirements of the EDM (10 mg/L [Cl^-]). In this case, it is clear that in the eight recycling ratios studied previously, the first five meet both, the drinking water conditions required by WHO (especially nitrate) and the technical requirements of the EDM.

For this reason, the choice of the appropriate configuration focuses mainly on a recycling mode with a brine ratio of 40%. This choice turned out to be better because the quantity of water produced is largely sufficient for daily needs of the school and the flow rate of brine discharged by the plant has been minimized by 40%. In this regard, this configuration records an energy consumption of 0.26 kWh/m^3 which remains similar to that obtained by a simple NF90-NF90 configuration and lower than that found in the literature (Table 6) [38–41]. Hydraulically, the flow rate of drinking water produced by this configuration is stable at 610 L/h (Table 6). On the other hands, the main disadvantage noticed is the corrosive tendency of the produced water. This is mainly due to the difference between the pH and pHs of the produced water (Table 6). In this case, it is advisable to act via a preventive action aimed at reducing the corrosive potential of the water produced to reduce the corrosion rate and thus increase the residual life of the pipes. This operation must be carried out by controlling in real-time the aggressive potential of the water produced by adjusting the Calco-carbonic balance with a pH correction.

For Y = 75%, it is apparent that nitrate concentration exceeds the drinking water standard required by WHO from brine recycling ratio of 20%. Below this value, the recorded contents vary from 40 to 46 mg/L for the two modes, without recycling (0%) and 10% of brine recycling, respectively (Fig. 8a). This constraint limits the choice in this configuration to two technical possibilities: the first one is without brine recycling (0%), and the second is with recycling of brine with a ratio of 10%. In this perspective, it is judicious to select the second mode, which offers at the same time a good alternative to environmental and productive concerns. Indeed, it valorizes a brine ratio of 10% by the plant without being able to reject it and it improves the hydraulic potential of the plant by producing almost

Table 4
LSI and pH of the water produced according to the bypass blending for NF90-NF90 configuration

	Percentage of bypass valve opening		
	20%	30%	40%
pH	7.2	7.4	7.5
LSI	−0.93	−0.28	−0.041
	Corrosive	Slightly corrosive	Slightly corrosive

Table 5
Produced water flow and energy consumption as function of the bypass blending for NF90-NF90 configuration

	Percentage of bypass valve opening for NF90-NF90 configuration		
	20%	30%	40%
Produced water flow (L/h)	810	820	830
Energy consumption (kWh/m^3)	0.33	0.21	0.16

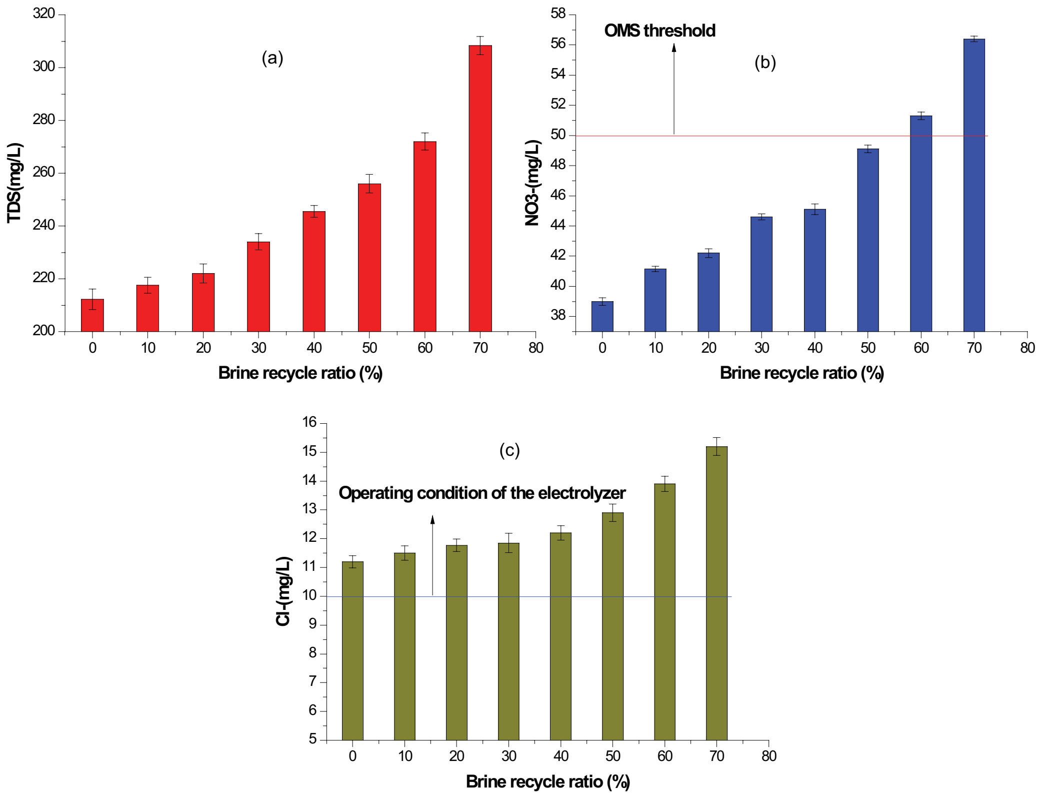

Fig. 7. Evolution of (a) TDS, (b) nitrate, and (c) chloride content as a function of brine recycling ratio for NF270-NF90 configuration (Y = 60%).

650 L/h (15.6 m^3/d) of drinking water (Table 7). In this case, it should be noted that at this brine recycling ratio (10%), TDS and chloride concentration display values in accordance with the standards required by WHO and the technical requirements of the EDM (Figs. 8b and c). In addition, the calculated energy is in the order of 0.25 kWh/m^3; almost similar to that found in the case of an NF270-NF90 installation applied for a recovery rate of 60% and an NF90-NF90 installation without recycling (Table 7). Likewise, as before, the quality of the water produced with this configuration (NF270-NF90 – 10% brine recycling) is characterized by a corrosive tendency, which presents a major risk to the plant equipment and to the electrodes of the EDM (Table 7).

3.3. Quality of brine by the three previously optimized modes

The quality of the rejected brine by the first optimized mode is characterized by a high nitrate content which is around 792 mg/L, and a high TDS which exceeds 10 g/L. The results found in this case are due to two main factors: the membrane used and the recovery rate fixed in the plant. In our case, the membrane used is an NF90. This membrane

Table 6
Permeate flow rate, energy consumption, and LSI as function of the brine recycling ratio for NF270-NF90 configuration (Y = 60%)

	0%	10%	20%	30%	40%	50%	60%	70%
Permeate flow rate (L/h)	510	530	550	580	610	640	670	710
Energy consumption (kWh/m^3)	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.27
LSI	−0.77	−1.1	−1.1	−0.95	−0.82	−0.73	−0.69	−0.62
	corrosive	corrosive	corrosive	corrosive	corrosive	corrosive	corrosive	corrosive

Table 7
Permate flow rate, energy consumption and LSI as a function of the brine recycling ratio for NF270-NF90 configuration (Y = 75%)

	0%	10%	20%	30%
Permeate flow rate (L/h)	640	650	670	690
Energy consumption (kWh/m^3)	0.23	0.25	0.26	0.27
LSI	−1.1	−1.1	−0.98	−0.82
	corrosive	corrosive	corrosive	corrosive

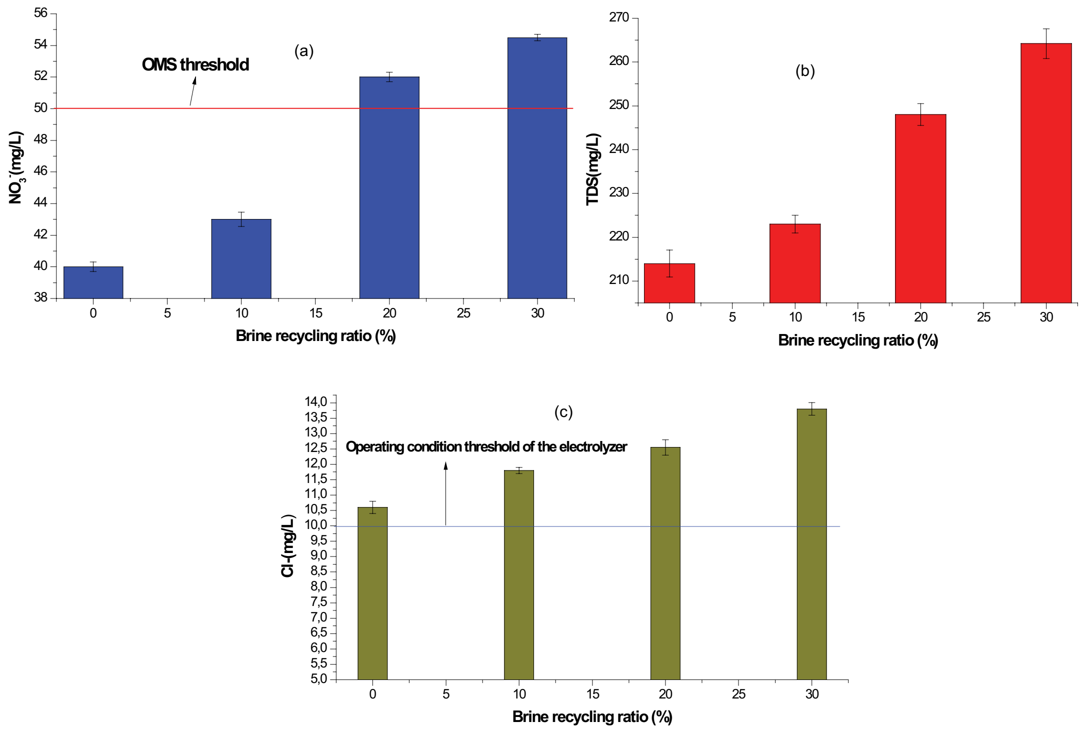

Fig. 8. Evolution of (a) TDS, (b) chloride, and (c) nitrate contents as a function of brine recycling ratio for NF270-NF90 configuration (Y = 75%).

Table 8
Quality of brine by the three previously optimized modes

	NF90-NF90 Y = 85%, P_{rb} = 70%, Q_{bw} = 260 L/h	NF270-NF90 Y = 60%, P_{br} = 40%	NF270-NF90 Y = 75%, P_{br} = 10%
	First mode	Second mode	Third mode
K^+ (mg/L)	86.77	11.42	13.40
Na^+ (mg/L)	66.74	8.86	10.60
Mg^{2+} (mg/L)	560.8	104.8	129.7
Ca^{2+} (mg/L)	1,771	273.9	340.7
HCO_3^- (mg/L)	6,018	1,014	1,259
NO_3^- (mg/L)	792.6	126.3	151
Cl^- (mg/L)	394	58.40	73.24
SO_4^{2-} (mg/L)	656.9	123.4	152
TDS (mg/L)	10,449	1,724	2,136
pH	7.5	7.4	7.4
LSI	2.3 (Scale forming)	1.0 (Scale forming)	1.2 (Scale forming)
Q_{br} (L/h)	30	240	200

Y: recovery rate; P_{rb}: percentage of recycled brine; Q_{bw}: flow rate of the blended water; Q_{br}: flow rate of the rejected brine.

rejects both monovalent and divalent ions with very reasonable values, rejection exceeding 80% [2]. In our case, the poor quality of the produced brine is compensated by its low flow rate, which is of the order of 30 L/h. This propriety limits and controls its negative impact.

In the other two cases, we notice a satisfactory quality of the concentrate in terms of nitrate content and TDS. The two installations are almost similar qualitatively and quantitatively in the brine released. The difference between the three installation modes is observed in the quality and quantity of the brine. The quality of the brine rejected by the first mode is deteriorated compared to the two other optimized modes (2 and 3). In terms of brine production, the first mode is not productive compared to the second and the third modes. Between the three modes, either the plant gains the brine quality and loses its quantity or the opposite. In terms of LSI, the quality of the rejected brine is scaling for the three modes. In this regard, the ultimate choice between the three modes directly depends on the operating conditions, the membrane used, the plant's production in potable water and brine, and finally, the quality of the rejected brine. However, these factors should be combined together for adopting the best decision. Table 8 presents the quality of brine by the three previously optimized modes.

4. Conclusion

In order to correct the chloride concentration at the entrance of the EDM and to avoid the quality deterioration of the produced water (nitrate in particular) in the Sidi Taibi desalination plant, two installations modes are tested. The tested configurations reveal attractive performances from a qualitative, quantitative, and energy point of view. The most important conclusions are as follows:

- The NF90-NF90 configuration with brine recycling is technically feasible only under the following conditions: a brine recycling ratio of 70%, a recovery rate of 85%, and a flow rate of 260 L/h intended to be mixed with the nanofiltered water which is directed to the electrolytic cell. The performance results obtained in this configuration are:
    - TDS meets the standards required by WHO;
    - Water quality respects both the operating conditions of the electrolyzer (chloride in particular) and the WHO guide standards relating to the quality of water intended for the production of drinking water (nitrate in particular);
    - Production of slightly corrosive water, which presents no risk to the installed equipment, more particularly to the electrodes of the electrolyzer.
    - Minimization of the brine rejected by the plant up to 70%;
    - Daily needs of the school are meet (820 L/h, which corresponds to 19.6 m^3/d).
    - Low energy consumption (0.21 kWh/m^3).
- The NF270-NF90 configuration offers different installation modes. Only two of them are technically feasible to be combined with the EDM. The first one is set for a recovery rate of 60% and a brine recycling ratio of 40%. The second one is optimized for a recovery rate of 75% and a brine recycling ratio of 10%. The performance results obtained in the two previously selected configurations (mode 1 and 2) are as follows:
    - TDS meets drinking water standards;
    - Acceptable chloride content for safe electrochemical disinfection of water;
    - Nitrate content in accordance with WHO standards;
    - Satisfactory drinking water production, 610 L/h (14.6 m^3/d) for the first mode of installation (recovery rate of 60%) and 650 L/h (15.6 m^3/d) for the second mode (recovery rate of 75%);
    - Energy consumption reduced, 0.26 kWh/m^3 for the first mode of installation (recovery rate of 60%) and 0.25 kWh/m^3 for the second mode (recovery rate of 75%);
    - Production of corrosive water requires preventive action aimed at controlling and adjusting the Calco-carbonic balance by correcting the pH of water.

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