Unlocking synergies: comprehensive analysis and challenges in the integration of reverse osmosis with reverse electrodialvsis.

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I. INTRODUCTION

Approximately 98% of the Earth's water exists in the saline form within seas and oceans. This prompts the exploration of desalination as a viable solution to the escalating water demand, exacerbated by population growth, environmental pollution, and the diminishing availability of surface water sources. [1], [2].

Desalination is the process by which salt water is treated to separate it from its salt content, thus making it suitable for human consumption [3]. Initially, the recognized techniques for this process were based on thermal sequences such as multi-stage flash distillation (MSF) and multi-effect distillation (MED), known to consume a large amount of energy (10 - 17 KWhel/m^3) [4]. However, membrane-oriented technologies have given rise to other desalination techniques which have lower energy requirements, as well as fewer chemicals, which have made them favored in new projects [5]. Considering the potential applicability of these membrane technologies, they are the most prominent on a large scale, specifically reverse osmosis (RO) [6]. This method has been implemented in a large number of desalination plants since the 1950s [7], currently having about 80% participation worldwide [2]. The study of RED has been increasing over the years due to the constant interest in its study and optimization focused on improving capital and operating costs as well as decreasing energy consumption [8]. For example, energy requirements average 3.1 KWhel/m^3 [9] compared to 13 KWhel/m^3 for thermal techniques. In addition, RO has recent advances in membrane materials, pretreatment technologies and system designs that lead to further reductions in operational costs [5]. However, these advances are still insufficient and further development is required.

Since the costs of Reverse Osmosis technology remain high, an approach aimed at coupling a salt gradient energy production (SGE) process to the desalination operation is emerging. [10]. SGE consists of mixing fresh river water with salt seawater, which due to a salinity gradient generates usable electrical energy, which can potentially decrease the power requirements that take place in membrane processes [11].

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It is important to highlight that SGE is considered one of the renewable energies with the highest potential; it is estimated that it can produce up to 23% of all the electrical energy required globally [12]. One of the most studied technologies for the extraction of SGE is electrodialysis reversal (RED), whereby mixing 1 m^3 of river water with seawater produces approximately 1.7 Mj, equivalent to the hydroelectric energy derived from a water height difference of 270-280 m [12], [13] [14].

According to the above, this research focuses its efforts on an evaluation of the feasibility and performance, in terms of energy efficiency and water quality, of an integration between Reverse Electrodialysis (RED) with seawater desalination by Reverse Osmosis (RO), in the context of the Colombian Caribbean region.

II. METHODS

A. *Pretreatment*

Pretreatment is a key factor in the design of desalination plants, as concluded by different authors [4]. Currently, the conventional one is the most used prior to the process of desalinating seawater by RO technique or producing energy through EDR [7]. Based on the results of the characterization of the treated samples and the study of the techniques in the literature, we proceed to evaluate a conventional pretreatment focused on the Multimedia Filtration and Coagulation units [8]. This proposal aims at removing the contaminants present; some of them are fine debris, plankton, detritus and silt [10], as well as colloidal particles of organic or inorganic origin, the most known, abundant and relevant in this case, silica and iron [11].

The initial characterization was taken as a starting point. Subsequently, the response variables were measured and, based on this result, the conventional pretreatment was started. Once the first stage was completed, a new physicochemical analysis was performed to check if the objective values were achieved, and if not, the optimal dose of the selected coagulant, previously found for the specific type of water to be treated, was applied and multimedia filtration continued.

During this filtration stage developed in experimental set up exposed in Fig 1, the literature indicates that if the proposed objectives are not achieved by adding the optimum dose of coagulant, a new filtration process should be carried out, this time using a Granular Activated Carbon filtration unit, it is expected that the medium will have the capacity to absorb the remaining contaminants, as stated by some authors [10].

Fig 1. Experimental set up for conventional pretreatment.

B. *Reverse Electrodialysis system*

Using the system presented in Fig 2. The experiments were developed varying the number of cells and the flow to see what configuration gives the best performance taking into account real samples of water from magdalena river and caribbean sea.

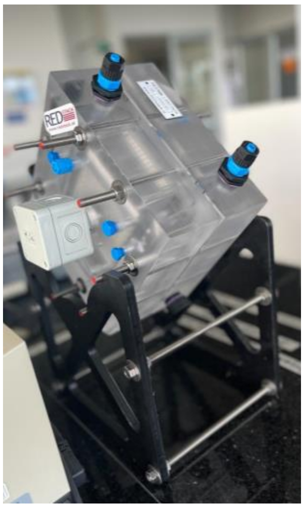

Fig 2. Cell from REDStack for Reverse Electrodialysis experiments at lab scale.

III. RESULTS AND DISCUSSION

For coagulation: A 1L stock solution of PCHS with a concentration of 1000 ppm was prepared from 4.3478 mL of PCHS at 23 % v/v, by volumizing with distilled water with the objective of extracting from it the doses of coagulant to be evaluated.

Initially, jar tests were performed evaluating doses of 10, 20, 30, 40 ppm of PCHS due to the high turbidity values (349-360 NTU) for the river water sample. These tests were performed with a fast mixing time of one (1) minute at 120 rpm, a slow mixing time of 20 minutes at 80 rpm and a settling time of 20 minutes following the instructions of ASTM D2035-19.

- Pretreatment:

In the Fig 3 and 4. it can be observed the results from the best conventional pretreatment used for river water from Magdalena River and Seawater from caribbean sea.

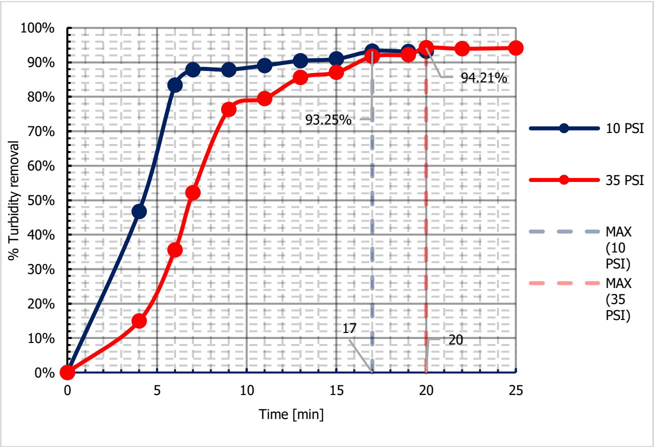

Fig 3. Stabilization curve FM (Multimedia Filter) with in line coagulation for river water.

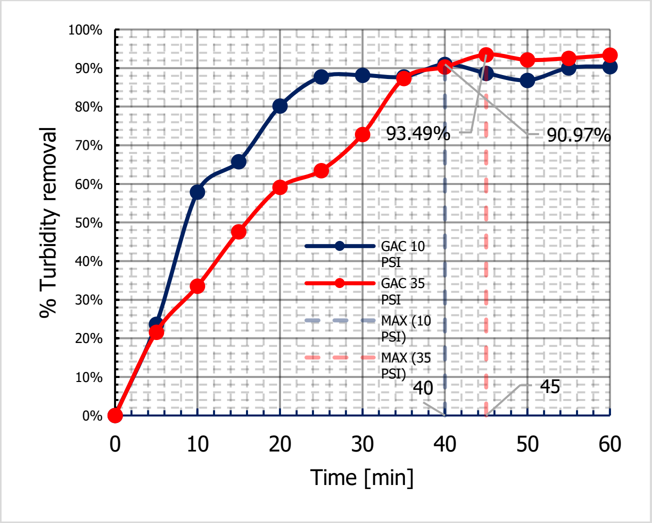

Fig 4. Stabilization curve FM (Multimedia Filter) with in line coagulation for river water

From the material balances, it is possible to simulate the coupling of the two technologies (RO-RED) and obtain the TDS that will enter the RO system based on the TDS that initially feed the RED stage, when comparing it with experimental values showed an error of 4%, which is considered acceptable.

Likewise, the quality of the water produced in the permeate (TDS) complies in terms of conductivity with what is required for drinking water according to resolution 2115 of 2015 in Colombia, being less than 1 mS/cm.

The simulation is carried out varying the recovery percentage in RO system between 0.5 to 0.8 and the recirculation percentage between 0 to 0.8.

Table 1. TDS initial RO.

	TDS RO inlet (g/L)							
	% Recuperación	0,5	0,55	0,6	0,65	0,7	0,75	0,8
An asum (% recirculation)	0	14,17	14,17	14,17	14,17	14,17	14,17	14,17
	0,1	14,17	14,33	14,48	14,64	14,80	14,95	15,11
	0,2	14,17	14,52	14,87	15,22	15,57	15,92	16,27
	0,3	14,17	14,77	15,36	15,97	16,56	17,16	17,76
	0,4	14,17	15,10	16,02	16,96	17,89	18,82	19,75
	0,5	14,17	15,55	16,94	18,34	19,74	21,14	22,55
	0,6	14,17	16,23	18,31	20,42	22,53	24,66	26,80
	0,7	14,17	17,36	20,60	23,90	27,25	30,66	34,13
	0,8	14,17	19,59	25,25	31,17	37,38	43,91	50,83

Table 2. TDS Permeado.

	% Recuperación	**0,5**	**0,55**	**0,6**	**0,65**
n asum (% Recirculación)	0	0,0425	0,0425	0,0425	0,0425
	0,1	0,0425	0,0429	0,0434	0,0439
	0,2	0,0425	0,0435	0,0446	0,0457
	0,3	0,0425	0,0443	0,0461	0,0479
	0,4	0,0425	0,0453	0,0480	0,0508
	0,5	0,0425	0,0467	0,0508	0,0550
	0,6	0,0425	0,0487	0,0549	0,0612
	0,7	0,0425	0,0520	0,0618	0,0710
	0,8	0,0425	0,0588	0,0757	0,0935

By graphing the above, expanding the interval to 0.01, Fig 5 is obtained, which shows that the TDS both in the inlet stream to RO and in the permeate increase as the % recirculation and % recovery increase. .

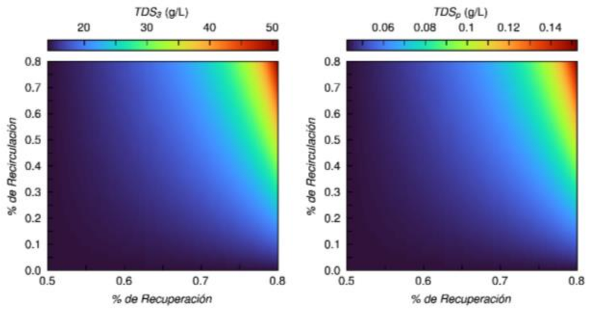

Fig 5. TDS acople.

It is observed that the values obtained for TDS of permeate up to less than 0.07 g/L comply with what is stated in resolution 2115 of 2007 for drinking water in Colombia, however, when they exceed this value in the region of % recirculation in 0.8 and % recovery of 0.65 to 0.8 will require post-treatment in order to reach the appropriate values according to the standard.

This must be contrasted with the results obtained in the energy balance since a higher concentration of salts represents a high energy consumption in RO.

Energy balances

The energy consumption of the RO stage was calculated using the equation:

$$SEC = 7{,}7 + 3{,}9x10^{-2}q_{rw} - 8{,}6x10^{-2}q_{pw} + \frac{1{,}7}{1-R} + 6{,}2x10^{-4}c_{rw} + 4{,}2x10^{-3}c_{pw} - 0{,}34P - 0{,}20T$$

Where:

$q_{rw}: Flujo\ de\ agua\ de\ alimentación\ (m^3/día)$

$q_{pw}: Flujo\ de\ agua\ producida\ (m^3/día)$

$R: Porcentaje\ de\ recuperación\ en\ OI$

$c_{pw}: Solidos\ disueltos\ totales\ del\ agua\ producida\ (mg/L)$

$c_{rw}: Solidos\ disueltos\ totales\ del\ agua\ de\ alimentación\ (mg/L)$

$P: Presión\ (bar)$

$T: Temperatura\ (K)$

Exposed in the article "Predicting the specific energy consumption of reverse osmosis desalination" (Stillwell & Webber, 2016)

Energy generation through RED was obtained taking into account the difference in salinity expressed in TDS and using the formula (Ortiz-Imedio et al., 2019):

$$P_{max} = \frac{(V^0)^2}{4AR_{stack}}$$

Where Vo is the voltage obtained when the current is zero, A is the effective area of the membranes and Rstack is the cell resistance calculated from the chosen membranes. Likewise, Table 3, Table 4 and Table 5 are obtained from the simulation, varying the percentage of recovery in RO and the percentage of concentrate recirculation.

Table 3. Energía consumida en OI.

	Energía consumida por RO (kWh/m³)							
	% Recuperación	0,5	0,55	0,6	0,65	0,7	0,75	0,8
A asum (% Recirculación)	0	11,744	12,121	12,593	13,199	14,008	15,141	16,840
	0,1	11,744	12,183	12,716	13,385	14,255	15,450	17,211
	0,2	11,744	12,260	12,870	13,616	14,563	15,835	17,674
	0,3	11,744	12,358	13,068	13,912	14,959	16,330	18,268
	0,4	11,744	12,489	13,330	14,306	15,486	16,990	19,062
	0,5	11,744	12,671	13,696	14,857	16,223	17,915	20,177
	0,6	11,744	12,943	14,242	15,684	17,334	19,315	21,869
	0,7	11,744	13,391	15,153	17,072	19,216	21,707	24,788
	0,8	11,744	14,280	17,004	19,967	23,248	26,984	31,437

Table 4. Energía generada en RED.

Energía generada en RED (kWh/m3) (30 cell pairs)								
% Recuperación		0,5	0,55	0,6	0,65	0,7	0,75	0,8
A asum (% Recirculación)	0	4,540	4,540	4,540	4,540	4,540	4,540	4,540
	0,1	4,540	4,563	4,586	4,609	4,631	4,654	4,676
	0,2	4,540	4,591	4,642	4,692	4,742	4,790	4,837
	0,3	4,540	4,627	4,713	4,796	4,877	4,955	5,032
	0,4	4,540	4,675	4,804	4,929	5,048	5,162	5,272
	0,5	4,540	4,740	4,927	5,103	5,270	5,429	5,579
	0,6	4,540	4,833	5,101	5,348	5,577	5,791	5,992
	0,7	4,540	4,981	5,369	5,717	6,033	6,323	6,594
	0,8	4,540	5,254	5,847	6,364	6,827	7,250	7,645

Tabla 5. Energía neta del acople.

Energía NETA (Energía generada en RED - Energía consumida en RO) (kWh/m³)								
% Recuperación		0,5	0,55	0,6	0,65	0,7	0,75	0,8
A asum (% Recirculación)	0	-7,204	-7,581	-8,053	-8,659	-9,468	-10,601	-12,300
	0,1	-7,204	-7,620	-8,130	-8,776	-9,624	-10,796	-12,535
	0,2	-7,204	-7,669	-8,228	-8,924	-9,822	-11,045	-12,836
	0,3	-7,204	-7,731	-8,355	-9,116	-10,082	-11,375	-13,236
	0,4	-7,204	-7,814	-8,526	-9,377	-10,438	-11,828	-13,789
	0,5	-7,204	-7,931	-8,769	-9,754	-10,953	-12,487	-14,597
	0,6	-7,204	-8,110	-9,141	-10,336	-11,757	-13,524	-15,877
	0,7	-7,204	-8,410	-9,784	-11,355	-13,184	-15,384	-18,195
	0,8	-7,204	-9,026	-11,157	-13,603	-16,421	-19,734	-23,792

And Fig 6, which summarizes what was found in the 3 previous tables, shows that as the recirculation percentage and the recovery percentage increase, more energy is consumed and generated. It should be noted that the optimal zone is where the lowest energy consumption occurs with the highest generation.

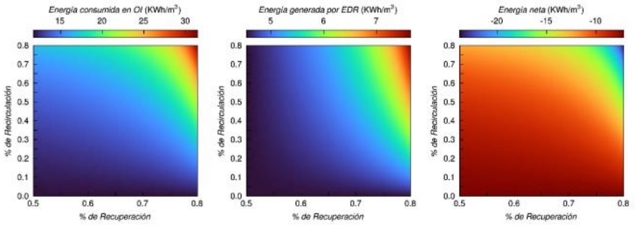

Fig 6. Balance de energía, acoples EDR-OI.

IV. CONCLUSION

In terms of conventional pretreatment, the effectiveness of the multimedia filter composed of anthracite and sand is confirmed, with a slight acidification until reaching a pH of 6.0-6.5, in the treatment of seawater, obtaining an SDI in a range of 3.4. For river water, the need for coagulant (PCHS) in line with a multimedia sand filter is highlighted. Both processes guarantee values of 0.89 and 1.20 NTU and SDI of 3.4 and 3.5 for sea and river respectively, fundamental parameters for the efficient operation of the RO and EDR membrane systems. In turn, it was proven that the absence of this initial stage could cause a minimum decrease of 20% in the reverse electrodialysis system.

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