Progress on Strategies to Maximize Reverse Electrodialysis Power Density Using Industrial and Municipal Effluents.

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***Abstract*—**High salinity wastewater disposal has adversely affected and degraded aquatic ecosystems. Furthermore, the current wastewater treatment technologies in the Sub-Saharan region are not designed to handle salinized wastewater, which has worsened the water scarcity challenge. Beyond environmental concerns, the agricultural sector is also negatively impacted due to its dependency on clean water for irrigation. Several developed technologies have been used to mitigate these challenges, including desalination as well as membrane, and thermal processes. On the other hand, their reliability when applied to large-scale industrial processes is limited by the high cost of routine maintenance and the intensive energy requirements of such methods. Therefore, scaling these technologies would increase their energy demand, undermining the sustainable development goals (SDGs) initiative taken by the United Nations (UN). The initiative promotes renewable energy while banning fossil fuel-based energy resources. Reverse electrodialysis has emerged as an alternative to treating salinized wastewater effluents. Increasingly, scientists are interested in this technology because of its advantage of harnessing electricity while reducing waste. This technology appears to be in positive alignment with UN SDGs based on studies by other researchers. However, this technology's maximum salinity gradient power is a concern that needs to be addressed. Hence, this paper proposes a critical review of the salinity gradient power production from industrial and municipal effluents. This aims to present the progress of this technology and the strategies used to increase its power-generating capacity.

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***Keywords*—:** Reverse electrodialysis; Salinity gradient power; Renewable energy; Wastewater; Effluent**.**

I. Introduction

Freshwater and energy are necessary elements for sustaining modern civilization; however, rising population growth and population density have put a strain on many local supplies to sustain water quantity requirements at acceptable water quality standards. The United Nations estimated that by 2025, 1.8 billion people will have a complete water shortage, and 2/3 of the world will be living under water-stressed conditions. Moreover, by 2030, high water stress will affect nearly half of the world's population [1]. This shortage of natural freshwater has promoted desalination to be a major source of freshwater worldwide. It is widely known that the treatment of water or wastewater consumes a large amount of energy, and that wastewater contains thermal energy as well as chemical energy [2]. Desalination, which is a component of treating water or wastewater is broadly categorized as thermal or membrane-based technologies [3].

Desalination has attracted a lot of attention recently due to its potential for recovering potable water from sewage and as well as brackish and seawater, which is why it is seen to be crucial in supplying the world's water needs [4]. Total global capacity to produce fresh water via desalination has increased from around 5 million cubic meters per day (m^3/day) in 1980, to 20 million m^3/day in 2000, to around 90 million m^3/day in 2020, with all major market forecasters anticipating that this tendency will persist over the next few decades [5]. The major drawback with most desalination processes is associated with cost, considering that a power plant is required to provide the energy requirements of the process (electricity may be provided by the national grid) [6]. Desalination is inherently energy-intensive, and energy consumption is a crucial contributor to the overall cost and is also related to environmental impacts. Hence, higher energy consumption also results in a proportional rise in greenhouse gas emissions (GHG) [3]. Therefore, the application of the desalination process such as electromembrane process is critical for lowering the cost of desalination and addressing environmental concerns about GHG emissions from the continuous operation of municipal and industrial desalination plants using conventional fossil fuels as their main energy source.

Environment-friendly production of power and clean water is one of the key objectives of the 2030 Agenda for Sustainable Development and can be achieved by emerging electro-membrane processes, such as reverse electrodialysis (RED) [7]. RED generates electricity from salinity gradient energy sources as well as treating wastewater [8-11].

The possibility of generating power from natural streams with different salinity was initially identified by Pattle in 1954 who obtained a power density of 0.2 W/m2 at 39 °C, by mixing salt and fresh water in a hydroelectric pile consisting of alternate 47 Anion Exchange Membranes and 47 Cation Exchange Membranes. Later RED was discovered and the huge majority of the studies performed so far have been carried out at a laboratory scale and using synthetic seawater and river water saline solutions [12] and pilot-scale RED studies employing real waters remain rare, however, opportunities for the use of concentrated brine are considered as well, driven by advantages for increasing power density and mitigation of adverse environmental effects related to brine disposal [13]. Consequently, the critical research direction to maximize power density by utilizing wastewater through RED is presented. Nevertheless, this paper provides insight that focuses on municipality effluent and industrial effluent for improving power density as compared to utilizing seawater/river water.

A. Municipality and Industrial Effluent

Many industrial wastewater (such as, from metal finishing, tanning, pulp, and paper processing) have a complex composition with contaminants and/or valuable components, containing heavy metal ions, acids, organic matter, etc. Similarly, treated wastewater from municipal or animal farming sources contains, for example, nutrients, as well as water. Finally, desalination plants reject brines that may provide water and/or salt [14]. RED methods can effectively treat these effluents, taking advantage of the ability to generate electricity to power the desalination process.

B. Pre-treatment strategies

Pre-treatment of wastewater before being fed to RED is considered to be one of the most promising approaches for increasing power density as it mitigates membrane fouling. Membrane fouling can be described as an unfavorable phenomenon caused by the substance's adhesion or a living organism to the surface of the membranes [15]. Even though RED is less prone to fouling than typical pressure-driven membrane processes, hence a proper pre-treatment unit in wastewater-seawater like that presented in Figure 1 is required to guarantee the RED system operates effectively. The kind of pre-treatment method depends on the nature of the wastewater to be treated. Therefore, the selection of a pre-treatment strategy for the wastewater is critical [16].

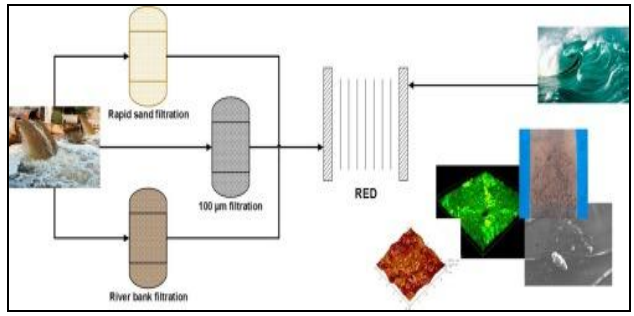

Figure 1 Pre-treatment before RED stack application [16].

II. LITERATURE REVIEW

A. Power density using Municipality Wastewater.

There aren't many articles that employ municipal wastewater as the RED feed that have been published so far [17]. A maximum of 0.38W/m^2 power density was reported by [18], whereby 1000 cell pairs and a total effective membrane of 250 m2 area using real seawater and municipal wastewater as the feed solutions without pre-treatment was used despite the fact that the effects of organic natural components were not well investigated in the study.

[17] undertook a study based on the effect of coagulation pre-treatment for RED power generation. At first, a synthetic solution was used and 0,53W/m2 power density was obtained. Secondly, municipality wastewater (real solution) was treated by (1) coagulation with 100-ppm PAC at pH 10 (type-(4)), (2) treated by coagulation with 10-ppm PAC at pH 7 (type-(3)) and (3). treated by filtration alone (type-(2)) and maximum power density of 0.43, 0.41, and 0.35 W/m^2 respectively were obtained. It was highlighted that the difference between the power generated with the model and real solutions is mainly due to the effects of NOM (natural organic matter), multivalent ions, and conductivity on both the stack resistance and OCV. Therefore, pre-treated wastewater showed that the efficient removal of chemicals from the wastewater can enhance RED power generation.

Discussion: The same study [17] reported that when using municipal wastewater as the feed under real conditions, the undesirable performance reduction and fouling potential should be taken into account and minimized to achieve higher and more stable RED performance. 13–77% reduction in RED power output over a short operating time when utilizing various types of wastewater including municipal wastewater effluent without pre-treatment was reported.

B. Power density using Industrial wastewater.

The use of concentrated brines and brackish water as feed solutions in reverse electrodialysis provides a worthwhile alternative to the use of river/sea water, allowing the enhancement of power output through the increase of driving force and reduction of internal stack resistance [19].

Audinos, R., and co-researchers [20] Discovered that brine can be fed to reverse electrodialysis stack for power production. The first experimental demonstration of using wastewater in RED was given by [21], 0.87 W/m2 was achieved by utilizing fresh and coal mine brine (see Table 1). As the research in the field of RED is ongoing, a significant improvement has been recently achieved regarding power density output through the utilization of wastewater but depending on the type (salinity)

The Power production from Produced Waters via Reverse Electrodialysis was studied by [22]. Wastewater generated by crude oil extraction processes was fed to a RED stack of 10 × 10 cm^2 units long-run continuous operations. Within the operation period of 25 days, anti-fouling actions were applied which included the use of chemical washes and physical counter washes to allow continuous operation. A power density of 2.5 W/m^2 was achieved on 25 days of continuous operation. However, negative values of net power density occurred after a few days of operation.

TABLE I

A list of power density obtained by several researchers indicates an increase in power density by utilizing wastewater adapted from [23]

Year	Authors	Power density (W/m^2)	Spacer thickness and experimental conditions	Solution
1955	Pattle	0.05	1mm spacers, 39°C	Fresh and seawater
1976	Weinstein and Leitz	0.17	1 mm spacers, 0.02 M – 0.57 M	Fresh and seawater
1983	Audinos	0.40	1 mm spacers, 4.3 M	Fresh and brine
1986	Jagur-Grodzinski and Kramer	0.41	250 µm spacers	Tap water and seawater
2007	Turek and Bandura	0.46	190 µm spacers, 0.01 M – 0.55 M	Fresh and seawater
2008	Turek et al.	0.87	190 µm spacers, 0.01 M – 1.9 M	Fresh and brine
2008	Veerman et al.	0.93	200 µm spacers, 0.017 M – 0.5 M	Fresh and seawater
2011	Vermaas et al.	2.20	60 µm spacers, 0.017 M – 0.5 M	Fresh and brine
2014	Daniilidis et al.	5.30	100 µm spacers, 0.01 M – 5 M, 40°C	Fresh and brine
2014	Daniilidis et al.	6.70	100 µm spacers, 0.01 M – 5 M, 60°C	Fresh and brine

Tedesco, M., and co-researchers [24] investigated the use of desalination brine for power production through reverse electrodialysis. Seawater (low concentration)and brine (high concentration) were used as feed solutions to a RED stack of 10 x 10 cm^2 membrane area with 50 cell pairs. Maximum power density of 7W/m^2 was observed in a lab scale at 40.4°C.

D'Angelo, A., and co-researchers [25] gave a study on the Evaluation of redox processes and simultaneous generation of electric energy and treatment of wastewater intending to investigate the influence of redox processes on energy production on a pilot plant scale. Researchers reported the performance of a RED stack with 500 cell pairs (44 × 44 cm^2) using artificial/natural brine and brackish water. A maximum power density of 1.76 W/m^2 and 1.61 W/m^2 were observed respectively. Researchers further mentioned that in the evaluation of RED stacks with 1000 cell pairs by **[18]** under natural conditions they achieved a gross power density lower than the anticipated value because of fouling and scaling on the membranes and electrodes.

In an experiment conducted by [23], 8W/m^2 and 12W/m^2 were reported to be the highest among all RED experiments due to a higher salinity ratio. Whereby 0.1 M NaCl (fresh water) and 5 M NaCl (brine) at 40°C were fed to RED with 50 cell pairs of 100 cm^2 membrane and with 100 cell pairs of 400 cm^2 membrane area respectively.

Tedesco, M**,** and co-researchers **[26]** emphasized that blending the dilute and the concentrated feeds before the stack entrance has been suggested as a method to enhance the system power output, by decreasing the stack resistance. Utilizing more concentrated solutions, such as saline water and brines is another option for reducing the internal resistance.

Cosenza, A, and co-researchers [**22]** highlighted that anti-fouling strategies still require careful integration and tuning. Researchers also suggested that the utilization of saline waste streams in RED systems may lead to new scenarios for the application of such systems in industries and treatment plants, expanding the potential of the salinity gradient power.

III. CONCLUSION

1. From the discussions above, it can be concluded that pre-treatment of wastewater is very crucial before it can be fed to the RED stack as this will enhance the power output.
2. The use of any brine for power harvesting in RED can improve the power density as compared to the use of seawater/river as a feed solution.
3. Because of the high salinity concentration in industrial wastewater than in municipality wastewater, more power can be obtained by utilizing industrial wastewater if it's properly treated.
4. Room for improvement still needs to be considered in terms of the selection of excellent pre-treatment strategies that will lead to higher power density.

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