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Recycling of polluted wastewater for agriculture purpose using electrodialysis: Perspective for large scale application

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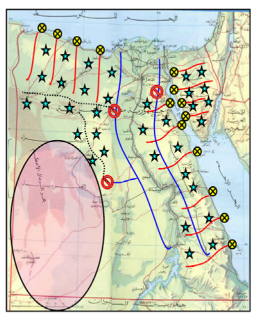
HIGHLIGHTS

- Drainage wastewater was treated to fit agriculture requirements.
- Electrodialysis steady state was more efficient to separate ions.
- Removal rate of cations is better than anions.
- The separation of associated heavy metals tended to oscillate.
- Perspective for further approaches and large scale application in Egypt is introduced.

GRAPHICAL ABSTRACT



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ABSTRACT

Water deficiency is a critical issue that faces many countries, particularly those located in arid and semi-arid zones. In Egypt, drainage wastewater (DWW) is used as an alternative source of irrigation directly or after it is mixed with Nile River water. Unfortunately, DWW is not suitable for irrigation directly or after being mixed with other water sources. In the present work, DWW was treated to meet the agricultural use requirements via electrodialysis (ED) based on agricultural water validity parameters, including removed Na^+, the sodium adsorbed ratio (SAR), and the Na^+ ratio. Our results indicate that a steady ED system (there is no flow in ED cell) is more efficient for DWW treatment in both regular ED and ED cation separation systems. For the regular ED steady system, removed Na^+ levels exceeded 99% after 100 min. The SAR levels were also reduced from a high value of 22 to an allowable limit of 0.34–0.4, and the Na^+ ratio decreased from close to 86% to 14.6–16.6%. The best salt removal results were obtained at an electrical potential level of between 65 V and 80 V over an operation period of 40 min. When cations alone were separated from DWW without anions, the applied electrical potential was remarkably decreased. Na^+ removal levels reached as high as 99.3% after 100 min, and the depletion of Na^+ reached 5.1 ppm–5.6 ppm from initial concentrations of 800 ppm. The SAR decreased from 22 to as low as 0.3–0.34, and the Na^+ ratio decreased from 86% to 13–19.5%. Finally, perspective for further approaches and large-scale application in Egypt would be introduced, which may be suitable for North Africa, and Middle East countries.

1. Introduction

A Lack of water, particularly in arid and semi-arid countries, has been one of most persistent issues through the ages that civilizations have had to address. Saline sea water accounts for 97% of all water on Earth, leaving only 3% potentially suitable for use. This 3% proportion of potable water is not suitable for direct supply, as 79% exists in glacial form and 20% exists as groundwater. Accordingly, potable fresh liquid water accounts for <1% of the Earth's water supply. The agriculture sector consumes the largest amount

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(75%) of this potable water. Issues of water scarcity can be divided into supply and demand problems. In heavily populated countries, particularly in those countries that are arid or semi-arid, water supplies are being challenged. The problem is especially significant in North Africa and West and Central Asia [1–4].

The Jordanian government has established a greenhouse-power plant hybrid system to generate water for irrigation and to eventually restore desert areas. In Egypt, such problems will become more catastrophic if the Nile Delta sinks by 2050 as a result of climate change. Another threat pertains to anticipated upstream dam construction effects as observed in Ethiopia. Due to high levels of water consumption in the agricultural sector, food production will be heavily influenced as a result, and starvation will eventually follow. Such problems are exacerbated by the annual increase in the global population of 80 million per year. Approximately 1.5 billion people suffer from limited access to potable water for domestic use. Processes that may solve such water supply problems include desalination and water reuse. Desalination and wastewater treatment are energy intensive processes, rendering them expensive to apply to irrigated crops, though they may be useful to apply to high-value cash crops such as vegetables and flowers grown in greenhouses [4–11].

Recently, the Egyptian government initiated five mega projects (Toshka, El Sallam Canal, Sharq Al-Owainat, Darb El Arbaeen, and New Villages) to develop desert areas and to create more agricultural land to support new communities. The Toshka project is heavily reliant on large volumes of dam water stored up to 187 m high. These volumes may be limited now, especially since conflicts between Nile countries on fair usage have erupted. The Al Sallam Canal project did not inspire significant progress in the agricultural sector owing to relatively high levels of water salinity generated since drainage wastewater and Nile River water have been mixed. Sharq Al-Owainat and Darb El Arbaeen are dependent on aquifer water, which is subject to salinity increases and limited supplies. Sustainable development in these areas should therefore involve water reuse and desalination. Other areas are dependent on rainfall for agriculture purposes (e.g., coastal areas) or on aquifer water (e.g., the Nile Delta, coastal areas, and desert areas) [12–16].

Several methods have been used to treat wastewater and to desalt brackish water and seawater. For wastewater, coagulation, floatation, chemical precipitation, ion exchange, adsorption, membrane filtration, and ion exchange methods have been developed and used. Desalination is carried out using membrane separation and thermal technologies. Membrane separation technology such reverse osmosis (RO) cannot be applied for agriculture due to their high unit costs [17–19].

Electrodialysis (ED) technology has proved satisfactorily helpful for the removal of various ions such as Cr^{3+}, Cu^{2+}, Mn^{2+}, Pb^{2+}, Fe^{3+}, Ni^{2+}, NO_3^-, and Cl^-, in addition to separation of organic acids and desalination of sea/brackish water [19].

A special issue on Desalination in the agricultural sector was published in 2015. The published literature shows that RO may be the most applicable in its current state for agricultural purposes. Unfortunately, RO separates total volumes of salt and does not take into account levels of specific elements such as boron and Na^+. Forward osmosis and membrane distillation, novel membrane separation technologies, have been used to improve upon this approach. To reduce the biofouling in RO, pre-treatments that use biologically activated carbon, phosphate, and nanofiltration have been applied. Generally, the process is still expensive and is only feasible when applied to valuable crops grown in green houses and to vegetables and flowers in particular [20–29].

Based on data presented in relevant literature there is only one article dealt with this issue (Chang et al., 2009) [30] using electrodialysis. In the present study, three main DWW sources are currently in use for irrigation purposes, namely, Bahr El-Bakar, Bahr Hadous, and El Serw. They vary in terms of salt content and have been treated for agricultural use. In the present study, agricultural water validity parameters including Na^+ removal levels, sodium adsorbed ratio (SAR) values, and Na^+ ratios were examined that did not take into consideration in previous studies. Salt was removed from each DWW using regular ED (through which cations and anions are removed simultaneously) and ED cation separation systems (through which cations alone are removed). The Taguchi approach was used to study the effects of the ED flow parameters, including dilute flows (L h^{-1}), cathode flows (L h^{-1}), anode flows (L h^{-1}), and applied voltage levels (V).

2. Materials and methods

2.1. Electrodialysis (ED)

The ED unit was constructed from 0.6-cm-thick acrylic, as shown in Fig. 1. The following two different designs were explored: a regular design consisting of cathode and anode compartments and a dilute compartment and a cation separation system consisting of two cathode compartments and a dilute compartment (anode compartment). The ED compartments had the following dimensions: (dilute) 25.2 cm long, 11.1 cm high, 7 cm wide; (cathode) 25.2 cm long, 11.1 cm high, 3 cm wide; and (anode) 25.2 cm long, 11.1 cm high, 3 cm wide. The cathode and anode compartments were separated by a cation exchange membrane (CEM) and anion exchange membrane (AEM), respectively, with the properties shown in Table 1.

The effective surface area each covered 85.5 cm^2 (19 cm $\times$ 4.5 cm). The CEM was positioned to face the cathode electrode, and the AEM was positioned to face the anode electrode. Titanium electrodes of 28 cm in length and 1.5 cm in diameter were used as the cathode and anode. Graphite anodes were tested through preliminary experiment, but as corrosion was observed, they were replaced with titanium. A variable alternating current (AC) transformer (0–250 V) was used to generate a direct current after connecting it to a bridge to change the AC to direct current (DC). An Avometer UT53 was used to control voltage levels and monitor the current passed. CEM and AEM were purchased from Membranes International Inc., Ringwood, NJ, USA. Titanium electrodes, pumps, and power supply were purchased from China.

2.2. Drainage wastewater (DWW) samples

Wastewater samples were collected from three main drainage sources: Bahr El-Bakar drainage $(DWW)_{1a\ and\ b}$, Bahr Hadous drainage $(DWW)_2$, and El Serw drainage$(DWW)_3$. The latitude of these drainage systems are (30° 43′47.30″N & 31°49′51.72″E), (31° 0′58.63″N & 32°12′10.23″E), (31° 06′21.29″N & 32° 00.24.73″E), and (31°15′23.27″N &31°48′40.21″E), respectively. Bahr Hadous drainage and El Serw drainage water are used for agriculture after it is mixed with Nile water at a ratio of 1:1 while Bahr El-Bakar drainage water can be used directly. Properties of the DWW are listed in Table 2. Primary experiments were carried out on samples collected from the opening of the Bahr El-Bakar drainage $(DWW)_{1a}$ system in July 2015. Additional samples were collected in October 2015 downstream of $(DWW)_{1b}$, $(DWW)_2$, and $(DWW)_3$. The DWW was generally characterized by a high concentration of Na^+, particularly in $(DWW)_{1b}$, in which levels reached 800 ppm, hindering its appropriateness for agricultural use. Electrical conductivity (EC) levels also exceeded the permitted level of 0.75 dS m^{-1} for all of the samples. EC values for the $(DWW)_{1b}$, $(DWW)_2$, and $(DWW)_3$ were measured as 3.8, 2.8, and 1.5, respectively. Wastewater pH levels exceeded a value of 7 in all of the samples, ensuring the auto