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Evaluating the reuse and recycling options of end-of-life reverse osmosis membranes in Tajoura desalination plant

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ABSTRACT

Least-developed countries such as Libya face many challenges regarding their water supply due to the reduction in the groundwater, especially around the coastal region. This problem is likely to create challenges for drinking water supply and for agricultural activities. Desalination and wastewater treatment technologies could provide a solution to the problem. In Libya, around 5% of the installed desalination capacity is based on reverse osmosis (RO) membrane technology. Seawater desalination accounts for more than 90% of the total installed capacity of all RO plants. The Tajoura desalination plant is one of the oldest RO desalination plants established on the west coast of Libya. The plant has been under operation for three decades with little careful attention to its environmental impacts. Membranes used in the Tajoura plant had to be replaced when fouling effect is irreversible. The overall objective of the present paper is to estimate by thermogravimetric analysis and Fourier-transform infrared spectroscopic analysis the remaining potential value of end-of-life RO membranes for proposing alterative reuse options for used membranes. Number of reuse options for some membrane elements have been observed. Converting the fiberglass of the outer casing into small pieces or powder for other production is highly recommended, while polypropylene spacers provide potential opportunities for [illegible] and agricultural applications.

Keywords: Desalination technology; Environmental impacts; Chemical recycling; Energy recovery

1. Introduction

Water resources in arid and semi-arid regions like Libya are scarce. Groundwater is the main water source in Libya, supplying more than 98% of the water consumed [1]. Rainfall is the main source of groundwater recharge. According to Brika [2], the annual rainfall in Libya ranges from 100 to 600 mm in the northern areas. The rainfall average is less than 100 mm/y over about 93% of the Libyan's land surface [3,4].

Groundwater mainly from upper aquifer, is the main water source for domestic, industrial, and agricultural activities. The excessive groundwater exploitation due to the expansion in agriculture and the growth of population have contributed to the severe water crisis in Libya. Consequently, there is an urgent need to look for alternative water sources to meet people's needs and compensate for the reduction in groundwater. As far as researchers and experts are concerned, desalination of seawater could be a sustainable option to solve the problem of water scarcity in Libya, especially in the coastal population cities, with growing increase in water demand and deterioration of groundwater availability quality. Given adequate attention by relevant authorities, seawater desalination plants

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could become highly competitive in comparison to current water supplies such as man-made river project (MMRP).

According to data obtained from the formal water authorities, there are currently 21 operating desalination plants in Libya, with a total capacity of 525,680 m^3/d, while another 13 are in approval stages for constructing, with a total capacity of 1,695,000 m^3/d [2]. It is worth mentioning that the new approved desalination projects are adapting desalination using membrane technology (reverse osmosis process) [3,4].

It has to be mentioned that the continuous growth in the use of desalination using membrane technology, creates a continuous build-up of the reverse osmosis membranes at the end of their life. Some sources indicate that the percentage of membrane replacement in reverse osmosis technology is about 10%–20% [5,6]. In general, the disposal of end-of-life RO membranes are dealt with according to the laws of each country, and unfortunately, these old membranes usually end up in landfills [7]. The current methods disposal of old membranes may result in significant negative environmental impacts. Therefore, to ensure sustainable and environmentally friendly use and disposal of old RO membranes, the construction of new desalination plants should be designed to take into account environmental considerations, including the process of safe disposal of end-of-life RO membranes. Moreover, old RO membranes should also be considered for potential reuse through recycling.

This study reviews the history of membrane usage in the Tajoura plant since its installation, specifically storage methods and the number of damaged membranes. Further, this paper proposes alternative options for reusing end-of-life membranes. The expected findings of this work will assist the people responsible for the plant and the operators to increase the life cycle of the membrane elements and safely disposal of old membranes. On the other hand, researchers, policy makers, environmentalists, and users are expected to learn lessons from the outcomes of this study for used in the design, installation and maintenance of future desalination plants using membrane technology.

1.1. Environmental regulations

Environmental impact assessment is a general and common technique used by industrialized countries, to preserve environment natural resources and to protect them [8].

In Libya, environmental impact assessment was established in July, 6th, 1982 under the name of Law No. 7 as a basic regulation on the protection of the environment, consists of 11 chapters divided into 75 articles, concerning all the environmental matters related to private and public projects.

Two years later further regulations were issued. These regulations included the establishment of the technical center for protecting environment, which was setup to focus on proposing, initiating plans, innovations that promotes the importance of the local environment as well as monitoring the conditions of ongoing construction projects and current operational private and public projects.

According to The Libyan Environmental General Authority (EGA) the environmental assessment adopted by Law No. 7 addresses the following aspects [9]:

- To all individuals and organizations, institutions and departments, companies and cooperatives and other entities, whether public or private, national or foreign make every effort to contribute to the reduction of pollution and through cooperation with the Technical Center for protecting environment and follow the instructions issued by it in this regard and adherence to implementation.
- The law expects that all stakeholders take into account environmental considerations when developing projects including housing, utilities, transportation, energy, industry, agriculture and other projects through the following schemes:
    - Prepare environmental impact studies for projects prior to construction and to provide these studies to the Technical Center for approval.
    - Consider the specifications and standards-based environmental standard in the design, implementation, operation, and maintenance of small and big projects.
    - Take preventive and remedial measure related to pollution as they may occur in the implementation and operation of the projects.
    - Write reports that demonstrate the environmental status of each project, and how the project conforms to environmental specification and standards.

Based on above-mentioned points, water desalination plants should be under the Law No 7 where an environmental impact assessment is mandatory. Nevertheless the Law No 7 is only the basic regulation for protecting the Libyan environment, other ministries such as agriculture, water resources, electricity and renewable energies should have further specific laws and regulations that protect the environment.

1.2. Specification and description of Tajoura RO desalination plant

The Tajoura seawater desalination plant, located approximately 25 km East of Tripoli, commenced operation in 1984. It is considered to be the first and the largest RO desalination plant in Libya, and has a designed capacity of 10,000 m^3/d. Due to the lack of consumers, the plant first started to operate at half of its capacity (5,000 m^3/d). The Tajoura reverse osmosis (RO) desalination plant was designed to be operated in two stages [10]: in the first stage, membrane modules with a 6-inch diameter were used, and sea water was used as raw water to be desalinated, while in the second stage, membrane modules with an 8-inch diameter were used. Water produced during the first stage was used as raw water in the second stage.

Ten years after the first operation of the Tajoura RO plant, new membranes (8-inches in diameter) were enhanced in order to desalinate sea water directly in only one stage. In this stage, 540 membrane modules were used in two rows.

Membranes used in the Tajoura RO plant used to be installed every 5–7 y. The estimated number of membrane modules in each period is 594 for each row (total rows = 4).

This number clearly shows that the total number of membrane modules changed in the first stage (6-inches in diameter) reached 1,188, while in the second stage (8-inches in diameter) 252 membrane modules were replaced by new ones. Fig. 1 shows membrane modules as currently used in the Tajoura desalination plant.

The lifespan of the Tajoura RO desalination plant is approaching its end, necessitating immediate action to dispose of the majority of the plant's systems (intake, high pressure pumps, membranes, and all the related equipment).

1.3. An overview of membranes used in Tajoura desalination plant

Old membranes in the Tajoura plant are replaced with new ones usually every 7 y. The number of membranes used and changed at the Tajoura desalination plant between 1984 and the end of this study is expected to be around 8,000 cells (membranes). Table 1 lists the membranes used and the specification for each membrane (supplied by the membrane manufacturer).

It has to be mentioned that recovery for membranes of 6-inch in the first stage reached 3[illegible]%, while for membranes of 8-inch in the second stage operated with a recovery of approximately 75%. Recovery for membranes of 8-inch during period from 2000–2013 reached 98%.

Fig. 1. Spiral wound membrane modules in the Tajoura desalination plant.

Based on data presented in Table 1 the total number of membranes that have been used is 8,136 units, divided into two stages (6,372 units in the first stage and 1,764 units in the second stage). Most of the membranes were 20 cm in diameter (8") and 1 m long. Consequently, a stock of used membranes has piled up over the years. These old membrane elements in stock are no longer appropriate for seawater desalination because they have lost their desalination properties (salts rejection lower than 99%) due to fouling, scaling, etc. These old membranes may constitute an environmental concern since they need to be disposed of in some way. Alternatively, it is suggested that these old unites mean an opportunity to recover some remaining value from the membranes if reused in another applications [11].

1.4. Present conditions of used membranes in the Tajoura desalination plant

Old membranes from the Tajoura RO desalination plant are currently being disposed of in landfills. These membranes may take a long time to reach their final destination, which is usually a land area packed with waste, due to the disposal and transport related issues.

When the membranes' lifespan has reached, the Tajoura plant's quality control department takes the appropriate and safe step by doing the essential analyses on the produced desalinated water. If the results of the analysis do not meet the Libyan Standards for drinking water, the plant's decision makers, in collaboration with the Tajoura Nuclear Research Center, must seriously consider replacing the used membranes with new ones. The plant unit supervisors will collect the old membranes and deposit them in containers brought particularly for this purpose, as shown in Fig. 2.

The container is locked for an unknown period, when the process [illegible]ading the old membranes is completed, as there is currently no safe way to discharge these old membranes. Workers and operators at the Tajoura plant indicate that the plant construction company has offered no recommendations on how to safely dispose of old membranes or repurpose them. Figs. 2a and b show some of the used membrane cells.

Table 1
Membranes used in the Tajoura RO desalination plant

Period	Membrane diameter	Number of units (elements)						Membrane model		Raw water source
		First stage				Second stage				
		R405	R406	R407	R408	R410	R411	First stage	Second stage	
1984–1989	6" + 8"	594	594	594	594	252	252	TFC 1501	TFC 8600	S.W*–Br.W**
1990–1991	6" + 8"	–	–	594	594	252	–	TFC 1501	TFC 8600	S.W–Br.W
1992–2000	6" + 8"	594	594	–	–	252	–	TFC 1501	TFC 8600	S.W–Br.W
2000–2005	8"	–	–	270	270	–	–	TFC 282255-360	–	S.W
2005–2013	8"	270	270	270	270	–	–	TFC 282255-360	–	S.W

*S.W is seawater;
**Br.W is brackish water.

Fig. 2. Old membranes as inst[illegible]d in a container.

It can be observed that the old membrane cells were placed randomly over each other. Old membrane cells were also found to be contaminated with deposit[illegible]uld have a harmful impact on both the human body and the environment

2. Materials and methods

2.1. Old RO membranes

RO membrane under study is thin-film composite spiral wound membrane consists of two membrane sheets glued together and spirally wound around a perforated central tube through which the permeate (product water) exits the membrane element. The first membrane sheet, is made of thin-film composite polyamide material and has microscopic pores. This membrane sheet is supported by a second, thicker membrane sheet, which is made of higher-porosity polysulfone material (PSf). In addition, the membrane element structure contains a feed spacer, made of polypropylene (PP), a permeate spacer made of polyester, a permeate tube and end-caps made of acrylonitrile butadiene styrene (ABS), an outer casing made of fiberglass and the glued parts containing proprietary epoxy-like components. Having named the materials of each membrane component, the authors believe that the chemical analysis can further help to suggest options to repurpose each part of the old membrane in a way that would be acceptable for the environment.

Two experimental analyses were performed during the development of this study to determine the chemical composition and thermal stability of the membrane's primary components. Membrane components were separated and cut into small pieces, which were then sent to the lab. Fig. 4 shows the image of the membrane component samples analyzed in this study.

The membrane components shown in Fig. 4 were analyzed by thermogravimetric analysis (TGA) and some of them, due to some difficulties, were characterized by Fourier-transform infrared spectroscopy (FTIR).

3. Results and discussion

3.1. Combustion and carbonisation

Thermogravimetric analysis (TGA) is a thermal analysis technique that measures the weight, and hence the mass of a sample as a function of temperature. TGA allows us to detect changes in the mass of a sample (gain or loss),

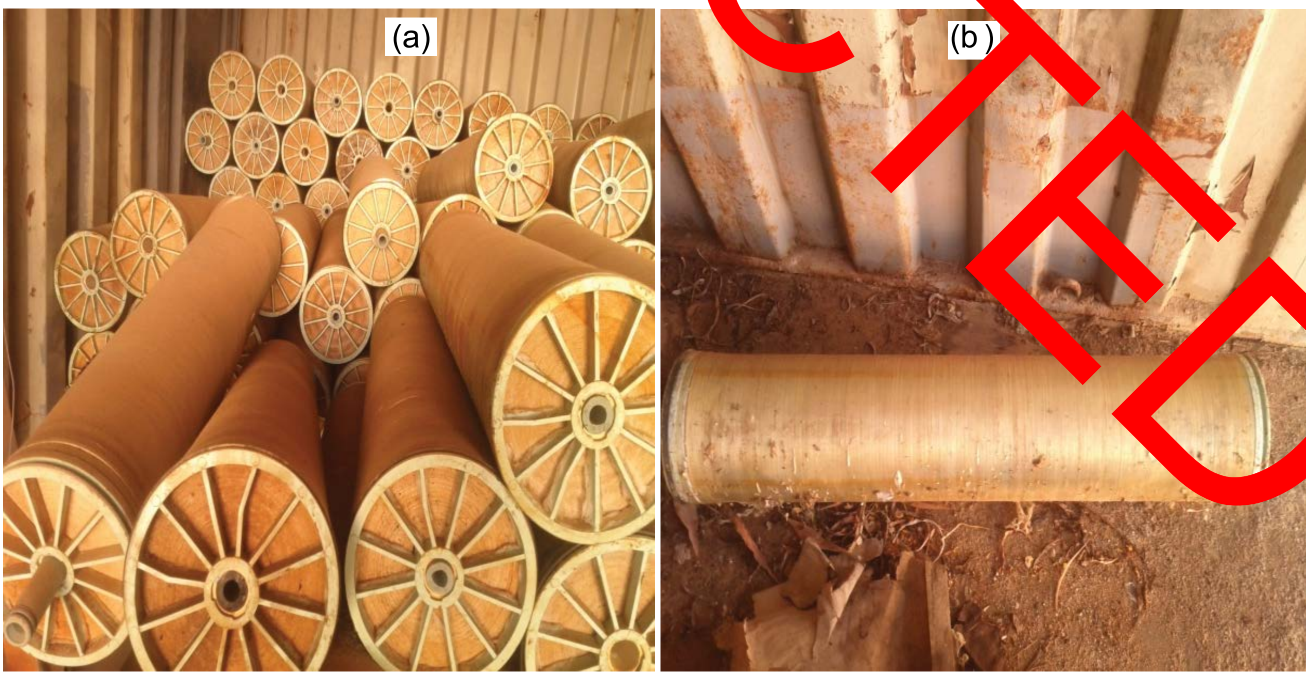

Fig. 3. (a and b) Old membrane cells.

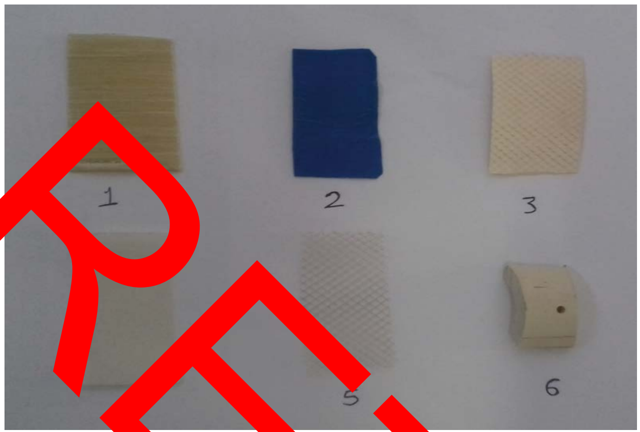

Fig. 4. Different membrane components that were tested in this study. From left to right: outer casing (1), glues (2), membrane sheet (3), permeate spacer (4), feed spacer (5), permeate tube (6).

evaluate stepwise changes in mass (usually as a percentage of the initial sample mass), and determine temperatures that characterize a step in the mass loss or mass gain curve.

TGA of membrane component samples was carried out using a HCT-5022 thermo-analyzer (Beijing Henven Instrument Company, China). Samples of 10–[illegible] mg were degraded under nitrogen atmosphere (flow rate [illegible] mL/min) at a heating rate of 10°C/min. Fig. 5 shows the results of the thermogravimetric analyses of the membrane components. The figure shows that sample number 2 (glues) is the least thermally stable component, showing almost complete degradation around 480°C, while sample number 5 (feed spacer) is the second least thermally stable component as it is completely combusted at 520°C, followed by the permeate spacer (4) and permeate tube (6). The remaining membrane components including outer casing (1) and membrane sheet (3) are much more thermally stable as their curves decrease slowly towards a zero weight. In the case of the outer casing, which comprised mainly fiberglass, an inorganic residue of about 67 wt.% remains after TGA combustion.

Based on the thermogravimetric analysis, it is possible to thermally degrade the polymer components to carbon using thermal treatments [12]. Except for the fiberglass outer casing, all membrane element components are suitable for combustion and carbonisation treatment to convert the polymer components into an energy source [13].

Furthermore, old membrane elements that have proven to be thermally degraded, particularly feed spacer, can be used as a substitute for coke in electric arc furnaces used in the steel fabrication process. The use of polymeric waste in electric arc furnaces offers several advantages, such as increased furnace efficiency, reduced energy consumption, lower coke consumption as well as reduced volume of waste in landfills [14,15].

3.2. Chemical composition

Identification of the raw material of each component of the membrane is a key step in polymer recycling. The authors believe that it might be possible to suggest more

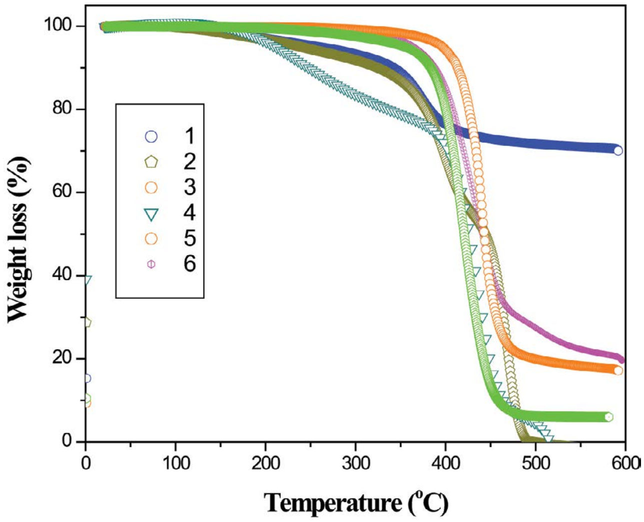

Fig. 5. Thermogravimetric analysis (TGA) of membrane element components.

recycling options of each membrane component individually. Based on this concept the Fourier transform infrared spectroscopic analysis (FTIR) was the only available technique to be used for identifying the polymer composition of the major membrane components.

FTIR spectra were recorded in the range 4,000–400 cm^{-1} with 2 cm^{-1} resolution on a Bruker Vector–22 Fourier transform spectrometer using the KBr pellet technique ([illegible] mg of sample in 100.0 mg of KBr). The FTIR spectra analysis confirms that the feed spacer is comprised of polypropylene and the permeate spacer is made of polyester. The permeate tube and end caps are comprised of an amorphous material such as ABS. The FTIR spectroscopic analysis further showed that the outer casing is clearly made of fiberglass. The detailed polymer composition of the membrane components is illustrated in Table 2.

4. End-of-life reverse osmosis membrane options

In general, waste plastic disposal has not yet become a big environmental issue in Libya. Furthermore, there are few government regulations that govern waste management. As a result, the city of Tajoura, where the desalination plant is located, has a limited number of small companies that collect plastic waste. However, only a small percentage of these companies participate in the plastic waste recycling process. Local companies collect plastic waste, compact it, and sell it to other local companies/factories or export it overseas for further processing and manufacturing.

In order to evaluate the potential value of recycled polymer materials membrane components were separated and taken to one of the local companies. Membrane components were observed and examined carefully by the plastic waste recycling company's management team, and the following comment was made:

Currently, and due to the lack of investment, advanced equipment and expert personnel, the only membrane elements that could be recycled are the ones comprising a single polymer component such as the outer casing, feed

Table 2
Composition of typical membrane components as it is exacted from FTIR analysis

Membrane component	Composition
Outer casing	Fiberglass
Feed spacer	Polypropylene (PP)
Permeate spacer	Polyester
Membrane sheet (thin-film composite)	Aromatic polyamide
	Microporous polysulfone (PSf)
Permeate tube/end caps	Acrylonitrile butadiene styrene (ABS)
Glue	Epoxy resin
Rubber o-ring	Ethylene propylene diene monomer (EPDM)

Fig. 6. Permeate tube for irrigation.

spacer and permeate spacer. Nevertheless, the local companies might not be able to recycle these components due to the lack of suitable separation technology equipment for such RO membrane cells.

Regarding alternative suggestions for the disposal and reuse of used RO membrane elements, the authors suggest the following:

- *Permeate tube*: an alternative reuse option is to connect a number of permeate tubes and use for irrigation (Fig. 6).
- Feed/permeate spacers for agricultural and domestic applications:
  - Feed spacer to prevent mosquitoes attack via house's windows (Fig. 7).
  - Permeate spacer as geotextile as reported in previous studies [13,16–18].
- Feed spacer is considered to be a single-polymer plastic that is clean and homogenous. Therefore, it has the ability to be directly recycled (mechanical recycling) and used as feed stock for the production of new products such as containers and packaging. This suggestion is in accordance with those stated in some previous investigations [15].
- Mechanical grinding can be done for some old RO membrane elements such as the outer casing, which is made of fiberglass. Grinding is the most obvious processing method used for recycling fiberglass. It leads to reducing material to small pieces or powder to be reused in other products. Grinding of fiberglass could provide a filler material or aggregate that could be used in concrete. Fiberglass powder could be used to make thermoforming molds or other structures. This suggestion is consistent with the recommendation of Garcia et al. [19].
- RO membrane elements which comprise mixed plastic materials such as the membrane sheet can be used as an energy source. Gasification and pyrolysis are preferable processes to incineration because they produce fewer emissions [20–22].
- Another process, known as the remembrane project, was recently introduced with the goal of extending the lifecycle of membranes used in RO saltwater treatments by through an innovative technology to improve membrane recovery and reuse. The goal of such innovative technology is to reduce waste, lower costs, and increase overall desalination efficiency [23].

Fig. 7. Frames with different sizes made for house's windows.

5. Conclusions and recommendations

The work reported in this paper represent a first attempt to assess the chances of reusing old RO membranes accumulated over the years at Tajoura RO desalination plant.

Amongst the results obtained, it was concluded that some membrane elements (the ones comprising a single polymer component) could be recycled and used effectively in other applications. Additionally, membrane elements that consis[illegible] plastic materials such as the membrane sheet can be used as an energy source. By utilizing these alternative end-of-life options, the volume of RO membranes sent to landfill can be reduced, eliminating the associated social and environmental costs.

Due to the lack of suitable separation technology equipment for such RO membrane cells, the authorized governmental authorities should make a huge effort to find potential international users for ex[illegible] membranes. In this regard, particular attention must be given to the reuse, recycling and disposal of used RO membranes when establishing new desalination plants.

The local authorities and decision makers should take the initiative to invest partly or entirely in new friendly desalination technology such as "the remembrane project".

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