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Food industrial effluent treatment for water recovery and reuse. Techno, economic and environmental analysis

Tratamiento de un efluente industrial alimentario para recuperar y reusar agua. Análisis técnico, económico y ambiental

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Abstract

The treatment of an industrial effluent was evaluated as an investment project for implementation at an industrial level to recover drinking water. The evaluation included a technical, economic, and environmental analysis.

The project was technically viable, fulfilling the following aspects. i) The effluent constitutes a source of drinking water production and a flow rate of 250 m^3/day is available. ii) Through effluent treatment, 50% of clean water is recovered. iii) The recovered water has drinking water quality; therefore, it can be used in industrial activities. iv) The treatment system for water recovery is scalable at an industrial level. v) The technology that integrates the treatment system to recover water is commercially available for implementation at an industrial level.

The environmental analysis of the water recovery project was also feasible, generating a positive impact. In turn, the negative impact index was low since the main emission is non-toxic sludge.

Also, the project was economically viable. The effluent treatment to produce drinking water at industrial level has a cost of $1.5 US /$m^3$. The initial economic investment is $565,569.00 US and the investment recovery period is 2.3 years.
Keywords: Effluent treatment, Water recovery, Environmental assessment, Technical assessment, Economical assessment.

Resumen

El tratamiento de un efluente industrial fue evaluado como un proyecto de inversión para su implementación a nivel industrial con el fin de recuperar agua potable, incluyendo un análisis técnico, económico y ambiental.

El proyecto fue técnicamente viable, satisfaciendo los siguientes aspectos. i) El efluente constituye una fuente de producción de agua potable y está disponible un caudal de 250 m^3/día. ii) Mediante un tratamiento del efluente se recupera el 50% de agua limpia. iii) El agua recuperada tiene calidad de agua potable, por tanto, se puede utilizar en actividades industriales. iv) El sistema de tratamiento para la recuperación del agua es escalable a nivel industrial. v) La tecnología que integra el sistema de tratamiento para recuperar agua está disponible comercialmente para su implementación a nivel industrial.

El análisis ambiental del proyecto de recuperación de agua fue también factible, generando un impacto positivo. A su vez, el índice de impacto negativo fue bajo ya que la principal emisión es de lodos no tóxicos.

También, el proyecto fue viable económicamente; el tratamiento del efluente para producir agua potable a nivel industrial tiene un costo de 1.5 dólares /m^3. La inversión económica es de $565,569.00 dólares, y el periodo de recuperación de la inversión es de 2.3 años.
Palabras clave: Tratamiento de efluente, Recuperación de agua, Evaluación ambiental, Evaluación técnica, Evaluación económica.

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1 Introduction

Water scarcity is a problem faced by several countries around the world, however, in a few years, this problem is expected to increase and cause serious threats to human life, ecosystems and global economic stability (UN-WATER, 2021). Extremely high levels of water stress are currently found in Middle East, North Africa, and America. Mexico ranks second with 5 well-located regions in the Northwest (Sonora-Sinaloa), Rio Bravo (Monterrey), Lerma-Santiago-Pacific (Jalisco), Valley of Mexico and the Balsas Region (Center of the country and Mexico City) (Hofste *et al.*, 2019). The main causes of water scarcity are drought, climate change and increased use by the growing population.

Among the main water consumers are the industries, generating contaminated effluents which are not incorporated in the water cycle and accumulate in natural and artificial reservoirs to be discharged to sewers.

To reduce the water scarcity problem, water recovery processes and reuse open different possibilities which also lead to the conservation of the environment because they increase available water resources (Hao *et al.*, 2015). However, to achieve this goal new processes, are required (Farago *et al.*, 2021). Together with their sustainability analysis, which include techno-economic and environmental impact studies.

Regarding water recovery from industrial effluents, there are different publications including inverse osmosis (RO) systems with pretreatments and post treatments to provide water with enough quality for most reuse purposes (Turek *et al.*, 2016; Ashraf *et al.*, 2021), as well as components recovery from effluents, as brines (Hernandez *et al.*, 2022; Wei *et al.*, 2021). For example, Khanzada *et al.* (2017) studied salt rejection from different brackish waters by an RO system, including ultrafiltration as pretreatment (UF-RO) to achieve 95% of salts removal efficiencies. Also, Hernández *et al.* (2019) treated an industrial effluent by UF-RO, producing water reuse for the food industry. In turn, effluent from the petrochemical industry was treated by RO and electrodialysis (RO-ED) to produce water for cooling towers (Venzke *et al.* 2018), and boilers by MF-RO (Ozbey *et al.* 2020). The removal of colloidal contaminants and metals by UF-RO was reported by Petrinic *et al.* (2015), whereas Dincer *et al.* (2021) reported Fenton oxidation-nanofiltration (FO-NF) for water recovery from industrial effluents treatment.

Other treatment processes for water recovery, such as, electrocoagulation, adsorption, and ozone also there are available in different publications; however, the water reuse is indicated for agricultural irrigation and other minor uses (Mendoza-Basilio et al (2017; Soto-Vázquez *et al.* 2023; Gonzales-Condori *et al.* 2023).

In turn, most economic studies on water recovery from effluents treatment come from investigations in municipal wastewater treatment plants (MWWTP), showing the economic feasibility of the processes. Ćetković, *et al.* (2022) exposed an Economic Internal Rate of Return (EIRR) = 16.38% and Benefit Cost Ratio (BCR) = 2.11 for water recovery, suggesting water reuse for agriculture. Kehrein *et al.* (2021) compared the net costs for three water reuse types (i.e. potable, industrial, agricultural); industrial reuse was the most economically interesting. Qi *et al.* (2020) determinate the operating costs for enhancing the processes of nutrient removal. The operating cost was high (\$ US 0.125 to 0.21/m^3); however, it was considered justifiable because the water bodies are enriched with treated water.

Economic analysis on water recovery from industrial effluents also are found in current reports. Li *et al.* (2020) proposed a membrane bioreactor (MBR) and NF (MBR-NF) process to treat textile effluents, showing the water recovery possibility and the economic benefits with a net profit of \$1.24 M US/year and a payback period of 3.11 years. Nazia *et al.* (2021) studied an integrated system consistent in UF with chemical coagulation for the treatment of an old industrial landfill leachate. The process exhibited economic advantages and environmental safety with simultaneous water reclamation of at least 70%. Shukla *et al.* (2022) studied the treatment of a complex pharmaceutical acidic wastewater in a pilot-scale plant, revealing that the project has a break-even period of 1.06 years with a return on investment of 94.28%. Bhargava *et al.* (2023) evaluated a batch-scale system of photochemical advanced oxidation processes to treat textile wastewater from a common effluent treatment plant, resulting in 0.77 US dollar or INR 59.75/m^3. Oke *et al.* (2023) showed the feasibility of the brewery wastewater treatment for water recovery. The total capital investment, NPV, IRR and PBT were \$2,416,358.62, \$2,790,608, 36% and 3.27 years respectively. Ankoliya *et al.* (2023) tested the ED-RO process for water recovery and its reuse within the same industrial plant. Economic analysis showed that the minimum cost of water recovery was \$ 0.77 US/L. Tripathi *et al.* (2023) studied the mineralization of Congo red dye from wastewater by ozonation for further mineralization by biodegradation. The coupling of processes saved 34% unitary expense in comparison to a single ozonation process. Zhou *et al.* (2023) used NF-ED hybrid system and single ED system for the flue gas desulfurization wastewater treatment. The total operating cost was \$ 0.41 US/m^3.

Additional information on effluents treatment for water recovery are found in reports of Life Cycle Assessment (LCA), which is a methodology to measure the environmental and economic impacts from the products and services (Pryshlakivsky and Searcy 2013; Pryce *et al.*, 2022); however, the information on this topic, also is scarce, and the investigation are restricted because mainly they are focused on MWWTP studies. In this case, Aldana-Espitia *et al.* (2017) assessed the environmental impact of a municipal solid waste and evaluated the use of landfill gas to generate electricity and reduce CO_2.

According to the latest studies, water recycling from industrial effluents has been promising because the effluents are seen as a source of water, contending the water scarcity. In turn, the costs of treatment effluents are economically and environmentally justifiably because the water recovery from industrial effluents treatment forms part of the circular economy. However, more information on water recovery process is required, including sustainable approach because their results depend on the effluent's treatment decisions.

In the present research, a water recovery process from an effluent from a food additive industry was evaluated, from a sustainability line, including a technical, environmental, and economic study.

The recollected information provides the methodological base for the evaluation of water recovery processes under a sustainability analysis, which is used for supporting the decision-making of the industrial process implementation.

2 Experimental section

2.1 *Technical evaluation of the water recovery process*

The technical feasibility of the project of water recovery included the study of the following aspects.

1. Industrial effluent status. The effluent is generated by an industry that produces food additives. The total flow was as 250 m^3/day, indicating an extraordinary source for water recovery.

   Currently, the effluent is transported for its treatment to an external wastewater treatment plant (WWTP) with primary and secondary treatment but does not include water recovery. The treated water is discharged into a waterbody (Lerma River). The total current treatment cost is \$1.6 US/m^3.

2. Physicochemical characterization of the industrial effluent. Samples from different schedules of production were provided by the industry.

   The quality parameters were colour, pH, Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), Total Suspended and Settleable Solids (TSS), Electric Conductivity (EC), Biological Oxygen Demand (BOD), Fats and Oils (F& O), Methylene Blue Active Substances (MBAS), Heavy Metals (HM), and Phenol (Ph).

   The effluent characterization was done according to Standard Test Methods for Wastewater (APHA, 2023). The equipment used were a Perkin Elmer UV/VIS Spectrophotometer (Lambda 35), HANNA benchtop multiparameter meter (HI5522-01) and a potentiometer with a pH HI 1131B electrode BNC, using five points of calibration.

3. Evaluation of the treatment process of industrial effluent for water recovery at laboratory level. The evaluation of the treatment of effluent was based on the investigation of Hernandez *et al.* (2022), including, operating conditions, flows of recovered water, the quality of recovered water and regulations of water and brine reuse and waste management.

4. Efficiency of water recovery process. The water recovery efficiency was measured by the membrane productivity of water recovery, including permeate and rejection flows, and membrane fouling, which involve the polarization phenomena.

5. Scaling of water recovery process from the treatment of industrial effluent. According to the effluent treatment, the established process of water recovery was scaled at industrial level. The scaling was by similitude theory and using a similar procedure indicated in Zaragoza *et al.* (2023). The operating conditions and water quality of recovered water were maintained in the scaled process at industrial level.

6. Plant design of water recovery from industrial effluent treatment. The plant of water recovery was integrated according to the treatment process of industrial effluent, indicating the required equipment in accordance with the existing technology on the market and the available area in the industry for its localization.

2.2 *Environmental impact assessment of the water recovery process*

The environmental feasibility was developed in accordance with the life cycle assessment (LCA)

Table 1. Physicochemical characteristics of crude sample of industrial effluent.

Parameter/ Sample	pH	EC (mS/cm)	COD (g/L)	SS (mL/L)	TSS (g/L)	TDS (g/L)	True color (m^{-1}) 436 nm	525 nm	620 nm
Range	8-9	70-90	3-5	5-10	0.25-0.6	40-65	600	492	114

methodology which is performed according to international standard ISO 14040 to evaluate the potential environmental impacts in water recovery using commercial technology (Arvanitoyannis, 2008; Pryshlakivsky and Searcy, 2013).

The environmental impact (EI) was calculated based on the environmental effect (R) that would be expected from the implementation and operation of the treatment process to recover water. Inventory analysis included the data collection of each process and the quantification of inputs and outputs of raw materials used and its emissions. The methodology used to calculate R was based on the identification and evaluation of the environmental impacts, through a cause-effect matrix (Ciobanu *et al.*, 2023; Peláez-León, 2010), adapting the data according to the water recovery project.

The environmental effect was evaluated using a quantity weighting of the magnitude, including hazard, reference limits, sensitivity to the environment and its regulations. The following scale was used to measure the magnitude of the effect: High = 3, Medium = 2 and Low = 1. The environmental effect (R) was calculated using equation (1) which is the ratio of the summation of effects of each component under normal, abnormal, and emergency situations, and the sum of the magnitude of the effects.

$$R = \frac{\sum \text{Efects}}{\sum \text{Effect size}} \quad (1)$$

2.3 *Economic feasibility evaluation of water recovery process*

The economic feasibility assessment of the project included the determination of the following indicators (Urbina Baca, 2010) and calculi (Doddapaneni and Kikas 2023).

1. Cash Flow (CF), including income or inputs (I) and costs or outputs (C) for activities derived from the water recovery project; equation (2) was used to calculate the CF.

$$CF = I - C \quad (2)$$

2. Minimum acceptable rate of return (MARR) represents the metric for evaluating potential investment (interest, i), including risk premium (between 10 and 15%) and forecasted inflation rate (f), MARR is calculated by equation (3).

$$\text{MARR} = \text{risk premium} + f + (\text{risk premium})(f) \quad (3)$$

3. Net present value (NPV) to describe the present value of CF by equation (4).

$$NPV = \sum_{t=1}^{t} \frac{CF}{(1+i)^t} - C_0 \quad (4)$$

Where t = 5 years, CF =Net cash inflow during the period t; i = Minimum acceptable rate of return (MARR); C_0 = Total initial investment costs; t=the number of time periods. CF, NPV and IRR were calculated iteratively through trial and error or by using Excel software.

4. The internal rate of return (IRR), which was used to estimate the profitability of potential investment and the time needed to recover the investment for the implementation of the project. IRR was calculated by equation (5),

$$IRR = NVP = 0 \quad (5)$$

5. Payback period is the length of time it takes to recover the cost of an investment, it is calculated following equation (6),

$$\text{Payback period} = \frac{\text{Cost of investment}}{\text{Average annual cash flow}} \quad (6)$$

3 Results and discussion

3.1 *Technical feasibility of water recovery process*

The technical feasibility evaluation of the water recovery process from industrial effluent treatment contains the following aspects.

1. Study of physicochemical characteristics of industrial effluent. Table 1 shows information on concentration ranges of the quality parameters of four samples of food industrial effluents, detecting high red coloration and presence of salts.

   In accordance with Mexican legislation NOM-001-SEMARNAT-2021, the red coloration shows that the spectral absorption coefficients

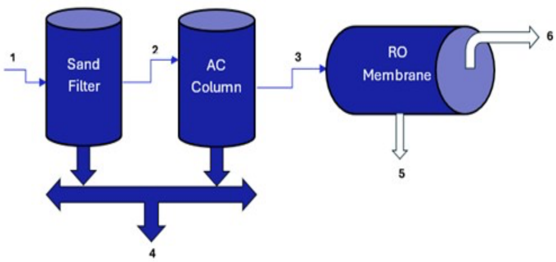


Figure 1. Process of water recovery from industrial effluent treatment 1. Effluent feed flow, 2. Treated effluent by filtration, 3. Treated effluent by AC adsorption, 4. Sludge, 5. Brine rejection from RO and 6. Treated effluent by RO (Drinking water).

at 436, 525 and 620 nm (600, 492, 114 m^{-1}) are higher than the permissible limits in water that can be discharged into bodies of water (7, 5 and 3 m^{-1}), indicating high pollution by colour. Therefore, the high COD was associated to colour content.

The high TDS and CE were linked to salts content, indicating a saline effluent, predominating sodium chloride salts, whereas pH revealed an alkaline effluent and SS and TSS showed low content of suspended and settleable solids. In turn, some parameters, such as, HM, Phenol, BOD, Nitrogen, Fats, and Oils were not detected in the effluent samples.

Consistent with the data of physicochemical characteristics, the industrial effluent was identified as saline and coloured wastewater with null toxicity by HM and phenol. Consequently, the industrial effluent could constitute a source of water recovery with drinking water characteristics.

2. Water recovery treatment process of the industrial effluent. The most effective process for water recovery at laboratory scale resulted in a RO membrane treatment, including two previous stages of effluent depuration. i) Filtration. (F), ii) Adsorption by activated carbon (AC), and iii) RO desalination. The treatment process was labelled as F-AC-RO and identified as an RO system.

   Figure 1 shows the process equipment of F-AC-RO consists of a sand filter in a packed glass column, a second packed glass column AC as a colour adsorbent, and a commercial RO membrane to remove salts.

   Continue flow was suggested as the running process for units F, AC and RO, resulting in 2 mL/min of flow rate.

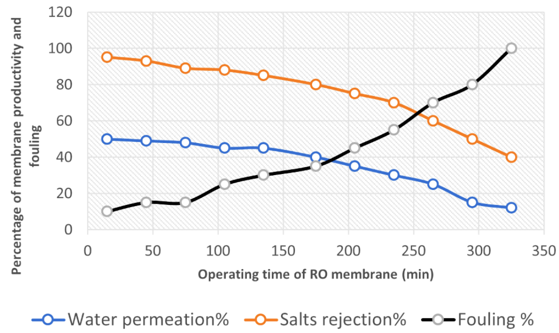


Figure 2. RO membrane efficiency during desalination of industrial effluent, including percentage of membrane fouling development and percentage of flow decline of water permeate and salts rejection.

The operating conditions in F and AC were the room temperature and atmospheric pressure, whereas in RO were 14 bar and room temperature without rejection recirculation. The membrane area at laboratory level is indicated as 0.5 m^2.

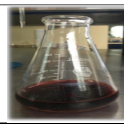
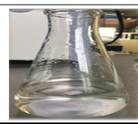
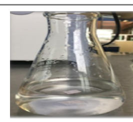
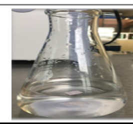
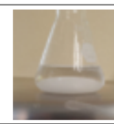
3. Quality characteristics of recovered water from industrial effluent treatment. Table 2 presents the average values of the quality parameters of the treated effluent and recovered water from each unit of treatment of F-AC-RO.

   TSS and SS were reduced in the sand filter; therefore, at the end of the filtration stage and the end of AC and RO the suspended and settleable solids were not detected (ND). The colour was removed during the adsorption with AC, resulting in colour not detected (ND) in the final of treated effluent, while COD was reduced by AC process, due to colour removal. In turn, salts were removed by AC (10%) and RO membrane achieved 95% of TDS rejection, whereas clean water was permeated, displaying high quality water for reuse with 99.9% of COD removal.

4. Efficiency of water recovery process. Figure 2 shows RO membrane behaviour during desalination of industrial effluent with 45-65 g/L TDS (equivalent to salts). Membrane behavior include membrane productivity of water recovery process, exhibiting flow decline percentage of water permeate, TDS rejection percentage and membrane fouling development.

   The permeation and rejection flows showed typical behaviour. The first step achieved 20 % of flow decline, indicating the dominion of the polarization phenomena. The membrane selectivity also is diminished, causing decrease in the efficiency of salts rejection. After, the membrane productivity was constant,

Table 2. Physicochemical characteristics ranges of the F-AC-RO process.

Water quality parameters		**Industrial effluent 1**	**Sand filtration 2**	**Adsorption by AC 3**	**RO membranes 4**	**Drinking water regulations USEPA/ NOM-127-SSA1-2021**	**Brine rejection 5**
Images of crude effluent and treated effluent by RO system							
F (mL/min)		2	2	2	2	1	1.9
pH		8-9	8-9	8-9	7-8	6.5-9	7-8
Conductivity (mS/cm)		70-90	70-90	75-85	0.25-1.0	NS	117
COD (g/L)		3-5	2-5	0.5-0.6	ND	NS	0.92
TDS (g/L)		40-65	39-65	25-55	0.30-0.50	0.50	109
SS (mL/L)		5-10	ND	ND	ND	NS	ND
TSS (mg/L		250-600	ND	ND	ND	NS	ND
True color (m^{-1})	436 nm	600	600	ND	ND	7.0	ND
	525 nm	492	492	ND	ND	5.0	ND
	620 nm	114	114	ND	ND	3.0	ND

NS = not specified
ND = not detected

maintaining 50% of the efficiency of water permeate and 95% of TDS rejection (salts). However, after 250 min, membrane fouling, was dominant (70%), causing drastic flow diminution in 80 and 50% of permeation and rejection respectively.

The membrane productivity behaviour is different for each process because it depends on membrane material, configuration, and permeation area; pressure and temperature of the operation; feed flux and feed composition. However, some similarities of the present results can be comparable with previous information from Dévora-Isordia *et al.* (2023a); Dévora-Isordia *et al.* (2023b). Authors showed the polarization effect on a RO pilot plant during desalination of seawater (35.52 g/L of TDS) and brackish water (13.34 g/L of TDS), using a membrane area of 2.8 m^2 and different operating forms of RO. The flows of water permeation were high, resulting in 0.75 and 3.5 L/min respectively. However, the membrane of salt rejection was comparable (98%) and the lower polarization effect was found when RO was run without recycling of salts rejection. In turn, authors showed that the application of temperature range in feed water (23-35°C with 5-10 g/L of TDS) could enhance the membrane productivity, decreasing the polarization by 3.1-3.6 % to prevent the salt scaling in the membrane layer.

5. Plant design of water recovery process. The laboratory data provided information to design the industrial process up the 250 m^3/day which this factory generates.

   Matching to laboratory level, the plant design to treat the industrial effluent contains two pre-treatment stages and a desalination stage using RO membranes. The equipment requires 2 filtration units, 4 AC adsorption columns and a system of seven RO membranes, including clean water storage tanks.

   Table 3 describes the process equipment of the water recovery process, dimensions, specifications, and number units. Equipment dimensions is according to industrial effluent emission (250 m^3/day).

   Operating in continuous flow without brine recirculation, the suggested RO system has the capacity to treat 250 m^3/day of industrial effluent (composition range 45-65 g/L TDS), producing two currents, 50% of clean water and

50% of brine, both supplying 125 m^3/day of drinking water and salts dissolution.

The characteristics of each product suggest its reuse. In line with the regulations of USEPA and NOM-127-SSA1-2021, recovered water from industrial effluents has high quality, showing drinking water characteristics with high possibilities of reuse in the industry. In addition, the brine from RO, also presented high possibilities of recycling because the brine contains sodium chloride (95%) and has no toxicity, since the brine is the result of a pre-treatment process of RO.

Thus, both products of RO membrane cover water industry necessities, reducing their discharge or disposal as contaminated water and brine. Recovered water is advocated for industrial processes application and in minor use, for washing of the filter, membranes, and cleaning of the factory, whereas brine could also be incorporated in industrial activities.

According to technical analysis, the water recovery project from industrial effluent treatment was qualified as technically feasible. The RO system was suitable for the water recovery requirements with drinking water quality, fulfilling this objective.

The efficiency of the process of water recovery was suggested as adept for effluent treatment, including sufficient steps to water recovery. The required equipment of the water process recovery is commercially accessible, and the materials involved in the pre-treatment can be replaceable and there are in the marketing.

The size of the RO system also was satisfactory for the industry, occupying a surface for the treatment plant of 136.3 m^2. Furthermore, the personnel requirement for the operation of the RO system is minimum, suggesting three people: a manager, a technician, and one plant operator.

Previous reports on the use of RO systems for water recovery show the design of RO systems to obtain drinking water. However, the studies are generally obtained from single desalination processes of seawater, brackish water, well water and groundwater, limiting the comparison from the RO systems for water recovery by industrial effluents treatment and other results; but the RO capacity for water recovery and salts removal is similar than the present research. For example, Robles-Lizarraga *et al.* (2020) designed a RO system to produce drinking water from desalination of seawater (33.97 g/L of TDS), using various membrane modules distributed in 473 pipes with six membrane modules each one to achieve 45% of water recovery and 98% of TDS rejection. Similarly, authors obtained high quality characteristics of recovered water, and it was comparable with drinking water on the base of the limits established by the Mexican Norm (NOM-127-SSA1-1994).

Table 3. Description of required units for 250 m^3/day water recovery process.

Stages	Instrument, equipment, and input required	Required units	Equipment characteristics and operating condition	Surface required
1. Effluent Storage	Tank	1	V = 300 m^3	60 m^2
2.Deep bed Sand Filtration	Centrifugal pump	1	P = 7.5 HP, V = 3F440V, P = 5×10^{-3} mbar, F = 505 m^3/h	1500 cm^2 = 0.15 m^2
	Fiberglass filtration unit	2	F_{max} = 12 m^3/h, T_{max} = 80°C, Filter dimension, d = 0.92 m y h = 1.83 m	3 m^2 include columns and supports.
3. Adsorption with activated carbon	Fiber glass columns	4	Includes Flow control measuring valve. Fmax = 200 L/min. Filter dimensions d = 1.26 m, h = 1.83 m	5 m^2 include columns and supports.

	Centrifugal pump	2	P = 7.5 HP, V = 3F440V, P = 5×10^{-3} mbar and F = 505 m^3/h	1500 cm^2 = 0.15 m^2
4. Desalination	Module of 7 RO membranes with active membrane area of 280 m^2	7	F_{max} = 1.2 L/s Pmax = 25 bar P = 70 HP	8 m^2 include membranes and support
	Permeate storage tank	1	V_{st} = 200 m^3	30 m^2
	Rejection storage tank	1	V_{st} = 200 m^3	30 m^2

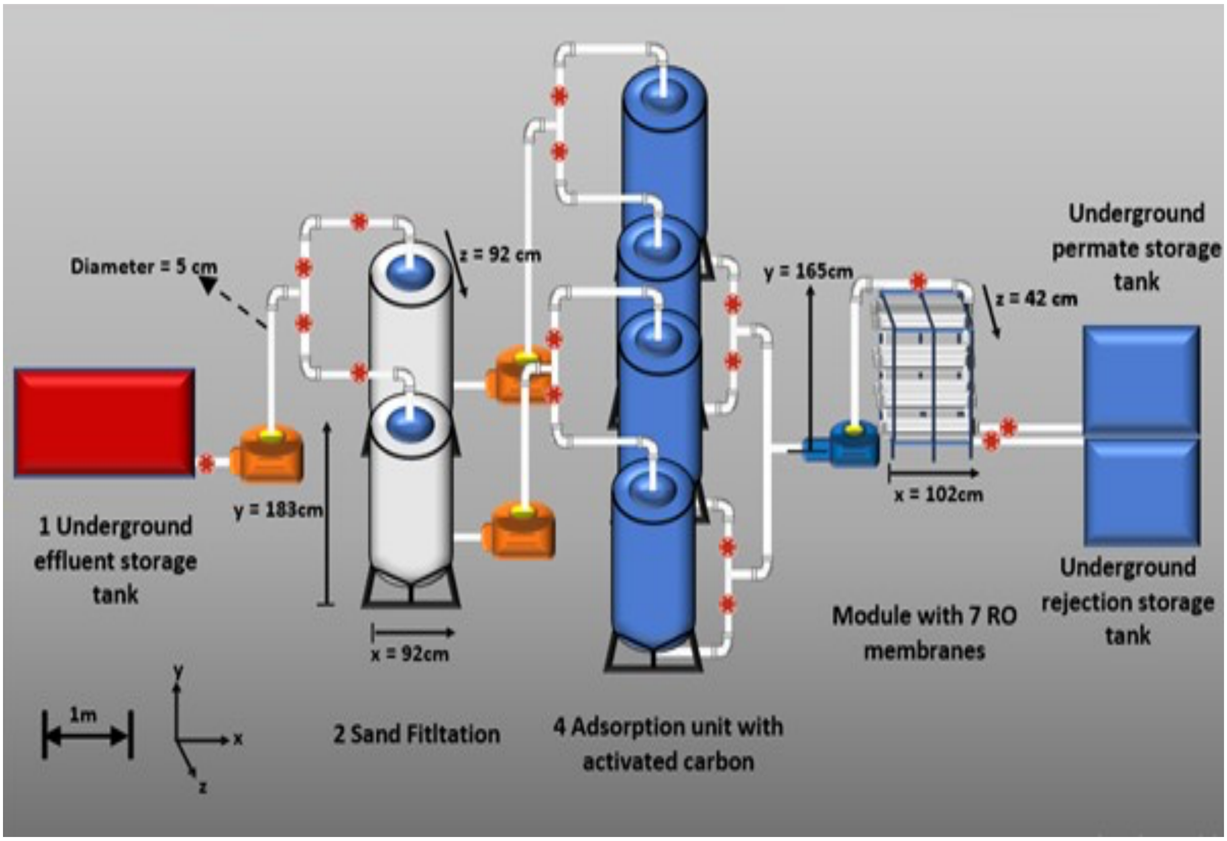


Figure 3. Plant design of a F-AC-RO water recovery process of 250 m^3/day at industrial scale.

3.2 Environmental feasibility of water recovery process

The environmental effect R (cause-effect relationship) resulted positive, since the input (cause) is referred to a polluted effluent and the outlet (effect) is a clean water, that in accordance with the provisions of the technical feasibility section of the project, the recovered water reaches up to 100-125 m^3/day with drinking water quality to be reused. Therefore, the water reuse has positive environmental impact, avoiding the use of well water and the exploitation of aquifers. Due to the quality of the reclaimed water, it can be used for washing equipment and material for finer uses such as boiler water. However, the cause-effect analyses showed that the operation of the water recovery process causes two negative impacts.

The affectations are derived from the activities of the washing and regeneration of filtration materials, adsorption, and desalination membranes since these activities generate wastewater and solids waste that would affect soil and water if they were discharged or would cause pollution due to the improper disposal of these waste.

Table 4 presents a concentrated matrix with the magnitude of the environmental effects of water recovery from the treatment of industrial effluent. Data include the operation of the process under normal, unusual, and emergency situations.

The frequency emission of liquid and solid waste from the washing and regeneration water of the materials and from the sludge generated from the cleaning of process the materials and equipment, would be every 3 months.

Table 4. Matrix of expected environmental effects of the water recovery process.

Environmental effect				Normal and unusual operating conditions					
Stage	Input	Operation	Output (effect)	Magnitude	Risk	Reference limit	Sensitivity to the environme nt	Regulation	Total effect
Sand filtration	Effluent	Filtration	Effluent free of TSS and SS Saturated sand	1	1	1	1	1	5
Effluent colour removal	Effluent from the sand filter	Adsorption by activated carbon	Effluent free of TSS, SS and colour Saturated carbon	1	1	1	2	1	6
Salt Removal	Effluent from activated carbon columns	RO membranes	Reclaimed drinking water and brine Fouling membranes	1	1	1	2	1	6
Total effects				3	3	3	5	3	**17**
Washing and regeneration of materials and membranes	Water for washing membrane s and materials	Cleaning and materials restoration and membranes	Contaminated effluent with retained molecules and chemical agents	1	1	1	1	3	7
	Chemical cleaning agents			1	1	1	1	3	8
Replacement of materials and membranes	New materials and membrane	Materials replaced	Depleted materials and membranes	2	2	2	2	3	11
Total causes				4	4	4	4	9	**25**
R				17/42 = **0.4**					

Solid waste from the filtration and spent activated carbon, as well as worn membranes, would have a semi-annual, annual and every 3 years respectively. However, due to the type of waste generated, and the fact that solids can be made available for incorporation into building materials, while the washing water for equipment and materials can be incorporated into the effluent treatment process.

Also, the desalination stage produces a brine product (TDS = 119 g/L) from the RO membranes, suggesting its reuse in industrial activities because brine did not contain toxic compounds and this product could cover industrial necessities of food scalded. However, the test on the reuse of brine was not carried out in this research.

The reuse of brine reduces its discharge, disposal, and treatment, which each strategy causes impact on the environment. In addition, the treatment of brine for salts and water recovery generates a cost of \$0.6 to 2.4 US/m^3 (Panagopoulos *et al.* 2019). Therefore, brine reuse is the best strategy to provide a positive effect to the environment and economy.

On the other hand, the residues obtained from activated carbon, filter sand and membrane cartridges can be valued for regeneration, however, they are considered as special waste which must be confined in specific places in accordance with the countries and current protocols. Within the U.S. regulation, a Plain English Guide to the USEPA part 503 for biosolids rule, is a guide that provides information about disposal of solids and biosolids generated during the process of treating municipal wastewater (USEPA, 2023).

Otherwise, the generation of minor residues from the treatment of industrial effluent are alienated in accordance with the document of reference number EPA-842-R-99-001 "Phase I Final Rule and Technical Development Document of Uniform National Discharge Standards (UNDS)" provides information about the technical background and regulations about national discharge standards provisions of the Clear Water Act, 33 U.S.C. (USEPA, 1999), and for Distillation and Reverse Osmosis Brine: Nature of Discharge (USEPA, 1999).

In addition, the residues from industrial effluent treatment could be supervised by Resource Conservation and Recovery Act (ACRA), which establishes regulations of basic hazardous waste management standards called hazardous waste generators, which are found in 40 CFR part 262, this standard aims to ensure the proper identification and safe handling of hazardous waste to protect human health and environment (USEPA, 2023).

Based on the previous analysis, the environmental feasibility of the proposed project showed that the cause-effect relationship expected by the operation activities that involved the stages of the water recovery process, presents a qualitative rating that categorizes the effects as "Simple". In the conditions it is highlighted that the sensitivity to the environment resulted in a rating equal to 5, indicating a low categorization, since the waste generated by the operation of the process is not dangerous, and there are alternatives for reuse of water and brine, causing low sensitivity to the environment.

Through the ratings obtained by each activity shown in table 4, a total of 17 effects were found with a total score of 42 applying equation 1 the total effects revealed a value of R=0.4 confirming that the project has a low environmental impact. In this way, the analysis of the implementation and operation of the proposed water recovery process establishes that it has environmental feasibility.

Studies involving environmental effects of water recovery process from industrial effluents treatment are limited in the literature. Environmental studies currently are approached on zero-residues or minimal-liquid discharge. The strategy comprises the treatment of wastewater for recovering the liquid fraction of freshwater and water components, constituting a sustainable and environmentally friendly process (Prado de Nicolás et al. 2023). The main application of this approach is found in the desalination process, involving brine treatment.

Other reports addressing environmental studies are included in LCA analysis, such as, Muñoz *et al.* (2007); authors analyzed photo-Fenton and ozonation-biological processes with granular activated carbon (GAC) adsorption for alpha methyl-phenylglycine removal. The results of the LCA showed that solar-driven photo-Fenton appears as the most environmentally friendly alternative. Rodríguez *et al.* (2016) evaluated the impacts associated to Fenton processes for the treatment of effluents from a pharmaceutical industry. Authors found that the recovery of the metallic sludge is the most contributing step to environmental impacts followed, as well as the use of chemicals and the heat requirements. Grisales *et al.* (2019) measured the environmental impacts of a photo Fenton process treatment on a synthetic mixture of azo dyes. The electricity, construction materials and reagents were the principal impact in the process.

Environmental analysis also is available in MWWTP. Specifically, Hao *et al.* (2019) found that thermal energy recovery has a significant role (40%). Chen *et al.* (2021) calculated the environmental impact in five full-scale MWWTPs in Kunming, China. The results indicated that the principal contribution is the secondary treatment (>68%) because the emissions and electricity consumption are high. In addition, the toxicity of sludge was high, due to excess of mercury concentrations.

3.3 *Economic feasibility of the treatment process to recover water*

The results of the economic feasibility analysis of the project indicated that the proposed treatment water recovery has high economic viability, since the investment is recovered in the short term, and once it is recovered, the project also generates profit which is derived from the savings for the expenditures that are due to the external treatment and disposal of the industrial effluent, as well as the savings for drinking water consumption, which is covered by 50% by the recovery of water through the treatment of the effluent. Currently, the industry that generates the effluent under study (250 m^3/day) has a considerable expense of $150,000.00 US/year for the transfer and treatment of the effluent in an external conventional type of plant (the effluent is treated together with other industrial effluent).

Table 5 presents the total fixed, deferred, and working capital investment required to implement and operate the proposed water recovery project, as well as the income and savings expected from the process.

The required fixed investment was $405,569 US, and $160,000 US is required for deferred expenses and annual working capital, with a total of $565,569 US.

The total expenses per year are estimated at $252,500 US, and the expenses for treating residues obtained in the treatment is $5,750 US, therefore, there will be an annual saving of $244,250 US.

In compliance with the above, the cost of water recovery from the integrated RO system resulted in 1.5 US/m^3. The production of the recovery period of the initial investment for savings from external effluent treatment is 2.3 years, with a minimum acceptable rate of return of 21%. The net present value (NPV) was positive $149,102.67 US, which indicated that the investment is recoverable with an internal rate of return (IRR) of 32.7%. Consequently, the process of water recovery was suggested as economically satisfactory.

Accordingly, the techno, environmental and economic analysis of the project of water recovery from industrial effluent treatment was feasible, and its implementation at industrial level is viable with high positive effect, since the investment is recoverable in a short period of time. Furthermore, the recovery and recycling of water and brine from industrial effluent constitute a viable process (Revollo-Fernández *et al.*, 2020).

Table 5. Economic investment analysis of the industrial effluent treatment project for water recovery.

Concept		Investment ($US)			Cash Flow ($US)		
		Fixed	Deferred	Working capital	Income	Expenses	Expected savings
Current industrial costs by consumption of potable water and treatment of industrial effluent	Annual drinking water consumption		75,000			75,000	
	Annual electricity consumption		2,500			2,500	
	Annual expenses for the transfer and treatment of the effluent by external parties		150,000			150,000	
	Annual manpower costs			25,000		25,000	
	Total, current expenses		227,500	25,000		252,500	
Proposal for the water recovery project, treating 250 m^3/day of industrial effluent	Civil Works	25,000				25,000	
	Piping and instrumentation equipment	367,265				367,265	
	Facility	10,804				10,804	
	Unpredicted	2,500				2,500	
	Inputs and direct services		7,500			7,500	
	Annual raw material		30,000			30,000	
	Annual manpower			100,000		100,000	
	Annual electricity consumption		17,500			17,500	
	Others		2,500	2,500		5,000	
	Total expected expenses	405,569	57,500	102,500		565,569	
Projected annual savings due to water recovery	Annual drinking water consumption		75,000				75,000
	Annual expenses for the transfer and treatment of effluent by external parties		150,000				150,000
	Annual manpower			25,000			25,000
	Current total savings		225,000	25,000			250,000
	Annual expenses to treat waste		5,750			5,750	
	Total savings					5,750	244,250

At present, there are several preceding works, showing different information on process costs of water and components recovery. Water sources include seawater, municipal effluents, and industrial effluents; thus, the costs are variable. However, these studies coincide in that the water production has high economic and environmental profitability because the recovered water has reuse possibilities and can cover several water necessities. In addition, the recovery of other products from effluents also has high economic remuneration.

The published information on this topic comes mainly from studies of desalination plants and the MWWP. For example, Wu *et al*. (2024) analyzed the cost of water recovery from desalination of seawater. Using an integrated system of RO, the water production cost reaches its minimum value of 0.64 US/m^3. Dévora-Isordia *et al*. (2016) analyzed the desalination costs by a RO plant and different operating forms. The RO system included a pretreatment for saline water with 6.6 g/L TDS. The best cost of water production resulted in the process without brine recirculation, achieving 0.31 US/m^3. However, the cost increases in agreement with TDS concentration.

Ćetković, *et al.* (2022) analyzed the water recovery costs from a MWWP for water reuse in irrigation. The Economic Internal Rate of Return (EIRR) resulted in 6.38% and the Benefit Cost Ratio (BCR) was 2.11. Authors suggested that water reuse in irrigation was not sufficient to justify the expensive investment. Kehrein *et al.* (2021) compared the net costs of treatment processes from a MWWP for the water production, ensuring three water reuse types (i.e. potable, industrial, agricultural reuse); industrial reuse was economically most promising. Qi *et al.* (2020) calculated the operating costs for enhancing the processes of nutrient removal. The investment cost was considered high ($0.12 to $0.21 US); however, it was considered remunerable because the water bodies are fed by clean water from treated water from MWWP.

In turn, viability studies on investment projects for water recovery from effluents treatment are scarce. Trotochaud *et al.* (2020) conducted a techno-economic analysis for the treatment of the liquid fraction of blackwater for water reuse. Authors tested an automated system at laboratory scale, which it was described as UF-A-ED. The cost was expensive, and flush volume and frequency of water production were identified as high impact factors on the total system costs. Oke *et al.* (2023) showed the economic feasibility of the brewery wastewater treatment. The total capital investment, NPV, IRR and PBT were $2,416,358.62, $2,790,608, 36% and 3.27 years respectively.

Bhargava *et al.* (2023) evaluated a batch-scale system of photochemical advanced oxidation processes to treat textile wastewater from a common effluent treatment plant, resulting in 0.77 US or INR 59.75/m^3.

Tripathi *et al.* (2023) studied the mineralization of Congo red dye from wastewater by ozonation for further mineralization by biodegradation. The coupling of processes saved 34 % unitary expense in comparison to a single ozonation process. Zhou *et al.* (2023) used NF-ED hybrid system and single ED system for the flue gas desulfurization wastewater treatment. The total operating cost was 2.95 ¥/m^3. Shukla *et al.* (2022) studied the treatment of a complex pharmaceutical acidic wastewater in a pilot-scale plant, revealing that the project has a break-even period of 1.06 years with a return on investment as 94.28%. In sequence, Nazi *et al.* (2021) studied an integrated system consistent in UF with chemical coagulation for the treatment of an old industrial landfill leachate. The process exhibited economic advantages and environmental safety with simultaneous water reclamation of at least 70%.

Conclusion

According to the characteristics of the effluent to be treated to recover reused water, the proposed treatment process consists of an RO system, including 2 pre-treatment operations and the desalination stage with RO membranes. Pre-treatment involves the retention of suspended solids (filtration through a sand filter) and the removal of colour (adsorption with activated carbon); while the final treatment is carried out to reduce the salts in the effluent through a set of seven RO desalination membranes.

Given that the technology involved in the proposed system to recover water is commercially available, that the indicated system can be integrated, and the process can be implemented and operated with an efficiency of 50% to recover potable type water and 50% of brine, it is established that the project is technically feasible, supporting that both products of RO system are recyclable. RO membrane also was efficient, providing 95% of salts rejection and a fouling increment after 250 min of membrane operation.

In addition, the space required to install and operate the system (136.3 m^2) is available in the industry, as well as personnel necessary to operate the units (3 workers).

Within the legal framework, the existing regulations related to the quality of reused water and the brine can be met in the implementation of the process, therefore, in this area, the water recovery proposal was also declared as technically feasible.

Regarding the results of the environmental effect study, the objective of recovering water in the project adds sustainable value to the company. In addition, brine also could cover industrial necessities, causing a positive environmental effect. However, derived from the operation of the proposed system, it is expected that the environment will be affected by the generation of waste, highlighting the solids due to the filtration materials, activated carbon, membranes and brine reuse. Nonetheless, the evaluation of environmental impact is low because the solids can be incorporated into construction materials and the liquids into the treatment effluent, obtaining only non-hazardous sludge weekly that can be disposed of.

The economic study of the water recovery treatment proposal also showed financial feasibility, with an initial investment of $565,569.00 US and 2.3 years of investment return. The expected utility after that time is derived from the savings for the external treatment that is currently paid for, and the cost of drinking well water consumption.

Overall, a comprehensive analysis of the investment feasibility of the water recovery project from the treatment of an industrial effluent from a company in the State of Mexico, showed that the project has technical, environmental, and economic feasibility for its implementation and operation. In addition, the analysis of the water recovery process provided tools for decision-makers for future investment and water management decisions.

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Nomenclature

AC	Activated carbon
ACRA	Resource Conservation and Recovery Act
BCR	Benefit Cost Ratio
BOD	Biological Oxygen Demand, mg/L
C	Costs or outputs, $
C_0	Total initial investment costs, $
C_t	Net cash inflow during the period, $
CE	High conductivity, mS/cm
CF	Cash Flow, $
COD	Chemical Oxygen Demand, mg/L
ED	Electrodialysis
EI	Environmental Impacts
EIRR	Economical Internal Rate of Return
F	Filtration
FO	Fenton oxidation
GAC	Granular Activated Carbon
I	Income or inputs flows, $
IRR	Internal rate of return, %
LCA	Life Cycle Assessment
MBR	Membrane bioreactor
MF	Microfiltration
ND	Not detected
NF	Nanofiltration
NPV	Net present value, $
NSDWRs	National Secondary Drinking Water Regulations
R	Environmental effect
RO	Reverse osmosis
T	Time, years
TDS	Total Dissolved Solids, mg/L
TSS	Total suspended and settleable solids, mL/L
UF	Ultrafiltration
UF-A-ED	Ultrafiltration-Adsorption-Electrodialysis
UNDS	Uniform National Discharge Standards
USEPA	United States Environmental Protection Agency
WWTP	Wastewater Treatment Plants

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