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Assessment of Municipal Effluent Reclamation Process Based on the Information of Cost Analysis and Environmental Impacts

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Case Study

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ABSTRACT

Water shortage has now become a global issue. Reclamation of the effluent from municipal wastewater treatment plant is feasible for supplying the quick growth of water requirement. The objective of this study was to conduct both the cost analysis and environmental impact evaluation of two reclamation processes: sand filter – ultrafiltration - reverse osmosis (SF-UF-RO) and sand filter - electrodialysis reversal (SF-EDR). The results will serve as a reference for selecting the process in the scale-up construction works. Two processes were installed in a reclamation pilot plant in Futian Water Resource Recycling Center (Taichung City, Taiwan) and operated in parallel to evaluate their stability and product quality. The cost analysis was conducted to estimate the capital requirement of building large-scale plant for reclaiming the effluent. The cost of land construction, mechanical with electronic equipment and operation with maintenance were all considered in the analysis. On the other hand, the environmental assessment of these processes has been realized by Life Cycle Assessment (LCA). The software Sima Pro 7.3 was used as the LCA analysis tool. Four different evaluation methods, including Eco-indicator 99, Ecopoints 97, Impact 2002+ and CML 2 baseline 2000, were applied. The results show that the water quality of SF-EDR has similar potential in reclaiming the effluent from municipal water resource recycling center as SF-UF-RO. The cost of SF-EDR is lower than that of SF-UF-RO. In the environmental analysis, the LCA demonstrates that SF-EDR may create more impacts on the environment due to more

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consumption on electricity and chemicals than SF-UF-RO. Using SF-UF-RO as the effluent reclamation process may be an option causing less impacts on climate change.

Keywords: Reverse osmosis (RO); Electrodialysis reversal (EDR); municipal wastewater reclamation; cost analysis; environmental impact comparison.

1. INTRODUCTION

In the recent decades, water consumption in Taiwan has gradually increased due to population growth, urbanization and the rapid development of industries. However, the construction of reservoirs and groundwater wells has become increasingly difficult because of the strong public concerns. Reclamation of effluent from municipal wastewater treatment plant has been considered as a feasible solution as the effluent quality is usually stable and acceptable [1,2]. The reclaimed effluent can then be used to supply the requirement, especially for those from industries with enormous water consumption [3,4]. Successful experiences of the large cases also show that this solution is feasible, such as "NEWater" in Singapore (microfiltration-reverse osmosis-ultraviolet), "Groundwater Replenishment System" in Orange County, California, USA (microfiltration-reverse osmosis-advanced oxidation), and "Water Reclamation and Management Scheme" in Sydney, Australia (microfiltration-reverse osmosis-chlorine disinfection). Furthermore, the quick growth of public sewer construction and connection in urban areas of Taiwan provides an appropriate environment to promote this idea.

In the previous cases, the combination of ultrafiltration (UF) and reserve osmosis (RO) is a widely accepted process to reclaim the effluent from wastewater treatment plants. This is called the "dual membrane process". In Taiwan, a variety of local studies also showed its feasibility and the performance stability [3,4]. On the other hand, electrodialysis reversal (EDR) has been less applied in this field. Due to the structure of flowing channels, it requires less pre-treatment than that of RO. Compared to RO, EDR has a tolerance to colloids, microorganisms and silicate, and thus it allows the SDI of inlet up to 12, while the SDI requirement of RO inlet is less 3. The total cost of using EDR to desalinate the municipal wastewater may be reduced. In UF-RO process, the permeate flow is driven by pressure drop across the membrane. For EDR, electric current forces dissolved salt ions in the wastewater through an electrodialysis stack consisting of alternating layers of cationic and anionic ion exchange membranes. The direction of ion flow is periodically reversed by reversing the polarity of applied electric current to prevent the scaling on the membranes. More power consumption is possibly required for EDR than UF-RO. For the water quality, UF-RO usually gives better permeate than EDR, especially in turbidity, total organic carbon and conductivity. The removal rate of the multivalent ions is worse in the case of EDR than RO [5]. In case that the requirement of production conductivity is less stringent, EDR is a suitable application, such as replenishing water in the recirculation cooling system [6].

In general, capital investment and operation cost is the main factor for choosing reclamation process. From some other angles, in Taiwan, carbon emission inventory has gradually become a necessary step in the planning stage. Other environmental impacts induced by the electricity and chemicals, including the greenhouse effects and other pollutions, should also be considered in the evaluation from the aspect of whole life cycle analysis (LCA). LCA is a method to study the environmental aspects and potential impacts throughout a product's life cycle starting from raw material acquisition, manufacture, use, recycling and disposal. LCA is helpful in measuring the ecological aspects of products composed of different raw materials though used for the same purposes. In 1990s, The Society of Environment Toxicology and Chemistry (SETAC) has drafted a series of handbooks for conducting LCA. In June 1997, "ISO 14040 Life cycle assessment - Principles and framework" has been announced. After that, LCA is more widely applied in the environmental management strategies of enterprises. When selecting environmentally friendly raw materials, products, and production processes, the results of a comparative LCA study provide reference value for decision makers [7].

Sima Pro (PRé Consultants bv, the Netherlands) is a widely adopted LCA software based on ISO 14040 and has been applied in the decision making. It was first developed by Leiden University, the Netherlands in 1990 and includes a variety of databases. Using the information in the database, the input of raw materials and output of pollutants can be transformed into the impacts on the ecology and environment. Using the function of normalization, the impacts of different processes or using different raw materials can be quantified and compared.

In many cases for selecting proper water or wastewater treatment processes, Sima Pro has been applied to analyze the environmental impacts raised from the consumption of chemicals and electricity, as well as the waste generation. The assessment usually focuses on the fields such as greenhouse effect, resources depletion, acidification, eutrophication and human toxicity [8]. Ortiz et al. [9] conducted environmental analysis on the conventional activated sludge process and the additional tertiary treatment units, and evaluated whether the additional tertiary units increased the environmental impacts. Bonton et al. [10] conducted a comparative life cycle assessment of two surface water treatment plants, using enhanced conventional process and nanofiltration membrane, respectively. Barrios et al. [11] compared the financial cost and environmental costs of individual units in a water treatment plant, and quantitatively assessed if any more environmentally friendly alternative could be applied. Muñoz et al. [12] compared the environmental impacts between the homogeneous and heterogeneous advanced oxidation processes (AOP) on treating industrial wastewater. Nijdam et al. [13] evaluated the impacts between two processes, granular activated carbon (GAC) and ozone/UV, on treating leachate from the landfill. Chatzisymeon et al. [14] assessed the environmental analysis among three AOPs, UV heterogenous photocatalysis (UV/TiO_2), wet air oxidation (WAO) and electrochemical oxidation (EO), on treating olive mill wastewater. The main difference of these processes not only came from the electricity consumption, but also the catalyst amount used during the treatment. In these studies, multiple evaluating methods are applied so that we may give credits to the individual process from different aspects. Based on the results, it can give a full picture regarding which process is more suitable and impacts the environment less.

Using desalination units like RO or EDR to produce clean water from the discharged effluent certainly consumes more energy than the traditional water treatment plants. When the scale of effluent reclamation plant gradually becomes larger since the last decade, say, over 100,000 m^3 per day, it raises more concerns regarding the greenhouse gas emission. In the literature, to the best of authors' knowledge, the studies on EDR and RO mainly focused on the production quality and the cost [6,15,16]. The comprehensive analysis on the environmental impacts of the two processes however is still lack. In this study, we conducted both the cost analysis and environmental impact assessment of two reclamation processes: SF-UF-RO (sand filter – ultrafiltration - reverse osmosis) and SF-EDR (sand filter-electrodialysis reversal). A variety of environmental impacts, including global warning, human toxicity, eutrophication, acidification, ozone layer depletion and so on has been considered. The results would serve as a reference for the decision making for the full-scale construction of an effluent reclamation plant in the near future.

2. MATERIALS AND METHODS

2.1 Futian Municipal Wastewater Treatment Plant

In this study, the chosen wastewater treatment plant is Futian Water Resource Recycling Center, located in Taichung, a large city in central Taiwan. Quick growth of industries in this region is the main reason leading to its water shortage. To relieve the shortage, Futian Water Resource Recycling Center has been considered as a feasible site for upgrading and reclaiming the effluent for industrial use (Fig. 1). The effluent is of good quality and the reclaimed effluent can be supplied to the steel-making industries as coolant water.

Fig. 1. The location of Futian water resource recycling center and the industrial parks in Taichung City

Futian Water Resource Recycling Center is located in the southern district of Taichung City, which currently applies activated sludge process to treat 55,000 m^3 of sewage daily (the first phase). The footprint of this plant is 13.6 hectares. After being treated by secondary clarifier and chlorine disinfection, the effluent has been discharged to the Green Stream in the neighborhood. The sludge is treated by gravitational thickening, anaerobic digestion, and belt dewatering. In year 2030, the capacity will increase to 295,000 CMD in its fourth (final) phase.

To evaluate the feasibility to reclaim the effluent, a full survey has been commenced since 2006. In its effluent, the suspended solids was 5.5 mg/L on average, biochemical oxygen demand was 2.4 mg/L on average, chemical oxygen demand was 10 mg/L on average, and pH ranged from 7.0 to 7.5. For the salty items, the hardness ranged from 100 to 170 mg/L, and the total dissolved solids (TDS) ranged from 250 to 350 mg/L. The effluent quality is acceptable for many industrial uses if it is further purified.

2.2 Pilot Plant for Effluent Reclamation

To evaluate the feasibility and to select the proper process, a pilot plant has been installed in Futian Water Resource Recycling Center to continuously reclaim this effluent. It included two processes, "Sand Filter - Electrodialysis Reversal" (SF-EDR) and "Sand Filter - Ultrafiltration - Reverse Osmosis" (SF-UF-RO) in parallel (Fig. 2). The pilot plant installed in Futian Water Resource Recycling Center continuously reclaims this effluent using the two processes. The operation began in October 2008. The performances of the two processes were compared to reveal if they were efficient in reclaiming the effluent, how much they cost, and how stable they performed. Table 1 compares the design parameters and the actual parameters after long-term operation.

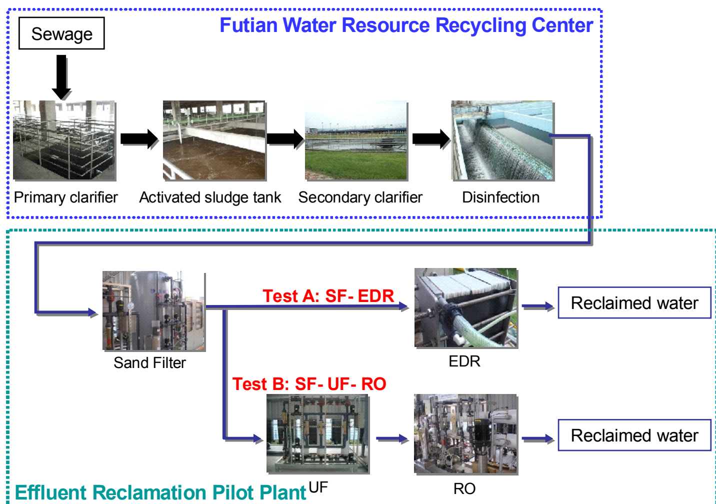

Fig. 2. The process of effluent reclamation pilot plant (SF-UF-RO and SF-EDR)

Table 1. The design and operation parameters of sf, uf, ro and edr in the pilot plant

Process Unit	Parameters	Operation Values
Sand filter	Capacity (CMD)	120
	Flux (m^3/m^2-hr)	8.68
Ultrafiltration	Capacity (CMD)	120
	Flux (m^3/m^2-hr)	0.072
	SDI15 of product	1~1.5
Reverse osmosis	Capacity (CMD)	60
	Flux (m^3/m^2-hr)	0.037
	Recovery (%)	55
	Desalination efficiency (%)	90~94%
Electrodialysis reversal	Capacity (CMD)	4
	Desalination efficiency (%)	80
	Recovery (%)	50
	Operation voltage (V)	84
	Circulation rate (L/min)	18
	Electrode reversal period (hr)	1

2.3 Evaluation I: Cost Analysis

The detailed items of cost analysis were composed of three parts [16]:

1. Land construction (L), including the plant building for installing the relevant facilities, piping systems and storage tanks.
2. Mechanical and electronic equipments (M), including the membrane modules, pumps, blowers, and the monitoring meters.
3. Operation and maintenance (K), including the consumables (chemicals, prefilters and membrane elements), electricity consumption, personnel expenses and the insurance during the operation.

One may obtain the cost to produce one ton of filtrate from the two processes of filtrate production scale Q (in unit of m^3/day), denoted as c, using the following equations:

$$c = \frac{Y + K}{Q * 365} \tag{1}$$

$$Y = (L + M) \times \left\{ (1 + r) \left[i + \frac{j}{(1 + j)^{t} - 1} + x \right] + f \right\} \tag{2}$$

The parameters are defined as:

r: the safety factor of public works budget in Taiwan, 47% in this study
t: the depreciation period, 20 years in this study
i: annual loan interest rate, 6% in this study
j: annual deposit interest rate, 3% in this study
x: the tax rate and relevant insurances during the construction, 0.62% in this study
f: percentage of annual facility renewal, 1.36% in this study

2.4 Evaluation II: Environmental Impact Assessment

Comparisons of environmental impacts of two processes were performed using the software SimaPro 7.3 (the registration name of SimaPro 7.3 which used in this study is Sinotech). The environmental impacts of reclamation processes are intrinsically related to its direct discharge of pollutants in the retentate (from RO or EDR), electricity consumption, consumables (like membrane, prefilters and chemicals), the piping works of reclaimed water, and disposal of waste. In order to quantify the aforementioned environmental impacts of different process as possible, a variety of methods have been applied in this study. The four methods, Eco-indicator 99, Ecopoints 97, Impact 2002+, and CML 2 baseline 2000, mainly consider the overall impacts on the ecology and human health. Table 2 lists the characteristics of the four methods.

Table 2. Characteristics of methods used in this study

Method	Introduction	Impact Categories
Eco-indicator 99	The damage-oriented approach. It is to assess the seriousness of three damage categories: 1. damage to human health; 2. damage to ecosystem; 3. damage to resources.	Carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/ eutrophication, land use, minerals
Ecopoints 97	Based on actual pollution and critical targets that are derived from Swiss policy. The following data are necessary in calculating a score in ecopoints for a given product: 1. quantified impacts of a product; 2. total environmental load for each impact type in a particular geographical area; 3. maximum acceptable environmental load for each impact type in that particular geographical area.	It assesses impacts, such as air pollution (NOx, SOx, PM10, etc.) , water pollution (COD, P, heavy metals, etc.) and solid waste, individually
Impact 2002+	Proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories.	Ionizing radiation, Carcinogens, Non-carcinogens, Respiratory organics, Ozone layer depletion, Global warming, Respiratory inorganics, Aquatic eutrophication, Terrestrial acid/nutrients, Aquatic acidification, Terrestrial ecotoxicity, etc.

Table 2 Continued ……

CML 2 baseline 2000	The CML 2 baseline method elaborates the problem-oriented (midpoint) approach. The CML Guide provides a list of impact assessment categories grouped into: 1. obligatory impact categories; 2. additional impact categories; 3. other impact categories	Depletion of abiotic resources, Climate change, human toxicity, fresh-water aquatic eco-toxicity, eutrophication, acidification, etc.

3. RESULTS AND DISCUSSION

3.1 Cost Analysis on SF-EDR and SF-UF-RO

The pilot testing provides the results including permeate flux of individual units, requirement of chemicals and consumables, and electricity consumption. More information was given in the studies of Hsu et al. [16,17]. By referring to the inquiry from the membrane module manufacturers, cost analysis was conducted to estimate the capital requirement of building large-scale plant for reclaiming the effluent. From the preliminary plans, the supply of reclaimed effluent from Futian to the industrial parks in neighborhood is 30,000 CMD. Thus the subsequent evaluation is based on this production scale. For a 30,000 CMD plant, our estimation shows that it costs US$ 0.65 to produce one cubic meter of filtrate from the SF-UF-RO process, including building cost of US$ 0.35 (land construction + mechanical and electrical equipments, depreciation period 20 years) and the operation/maintenance cost of US$ 0.30. On the other hand, SF-EDR costs US$ 0.57 to produce one cubic meter of filtrate, including building cost of US$ 0.33 and the operation/maintenance cost of US$ 0.24. From this angle, wastewater reclamation using SF-EDR costs less than using SF-UF-RO, though SF-UF-RO produces filtrate of better quality. The main reason that SF-EDR is cheaper than SF-UF-RO is that EDR does not require an expensive pretreatment like UF. On the other hand, EDR requires more frequent cleaning (once every month) than that of RO (once every three to four months). The high cost in chemicals and staffs for maintaining EDR offsets the advantage that EDR does not need UF as pretreatment.

3.2 Environmental Impacts Assessment on SF-EDR and SF-UF-RO

We used the four methods (or the “index system”), Eco-indicator 99, Ecopoints 97, Impact 2002+, and CML 2 baseline 2000 to quantify the aforementioned environmental impacts of two reclamation processes. Using different index systems usually gives inconsistent rankings. It also provides more comprehensive view for evaluating the potential impacts of the two processes [8].

Using Eco-indicator 99 gave the results in Fig. 3 (percentage characterization chart). The process “SF-UF-RO” had fewer impacts on the counted impact categories than “SF-EDR” to produce one ton of pure water, especially regarding climate change, adsorbed inorganics, and acidification/ eutrophication. The percentage characterization charts of Ecopoints 97 and Impact 2002+ are illustrated in Fig. 4 and Fig. 5, respectively. Both methods show similar results to that of Eco-indicator 99. Process “SF-UF-RO” had fewer impacts in most categories than those of “SF-EDR”, except the categories of eutrophication substances (ammonia NH_3 and phosphate P) of Ecopoints 97 and non-carcinogens of Impact 2002+.

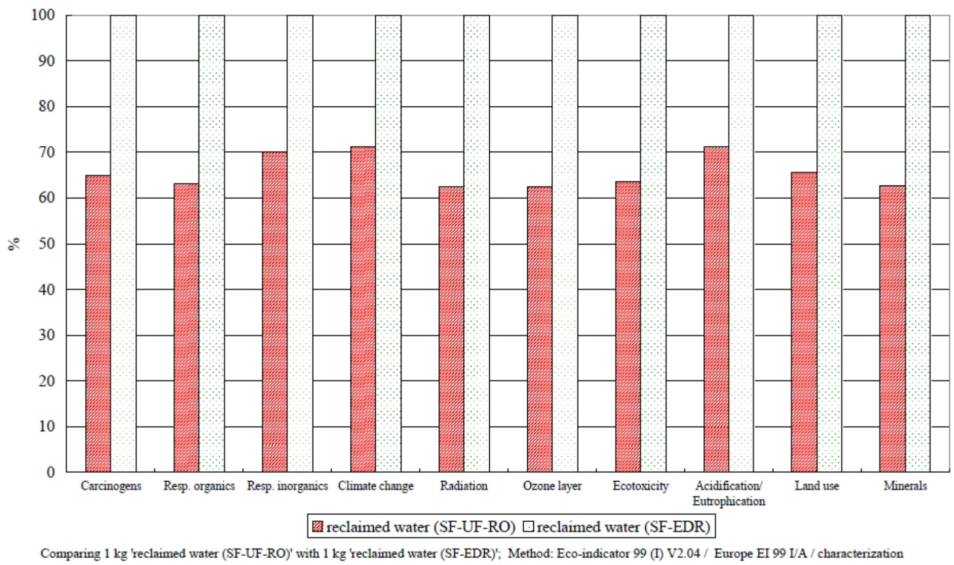

Fig. 3a. Percentage characterization chart of method eco-indicator 99

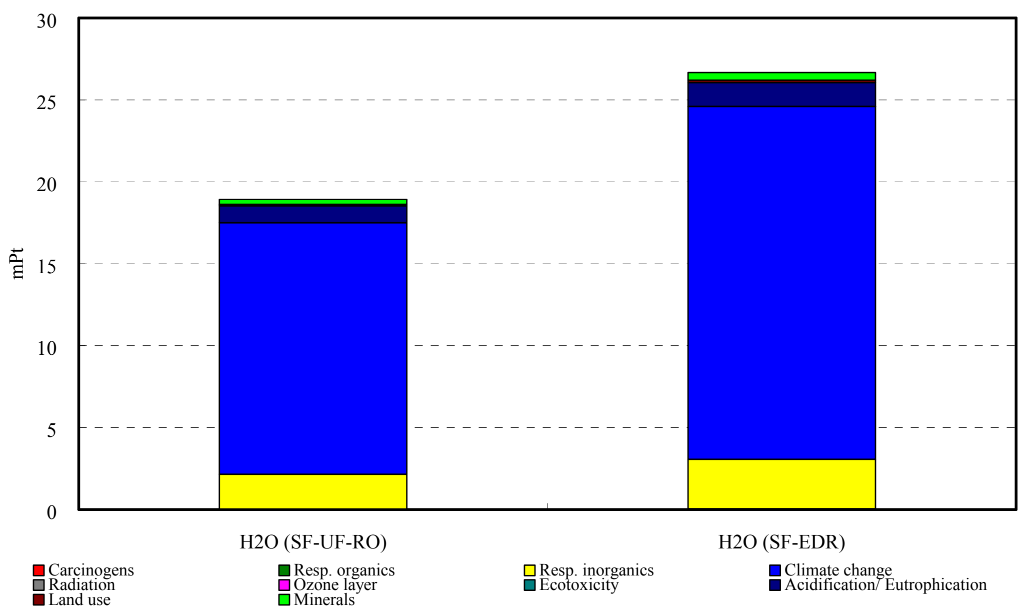

Fig. 3b. Overall scores of method eco-indicator 99

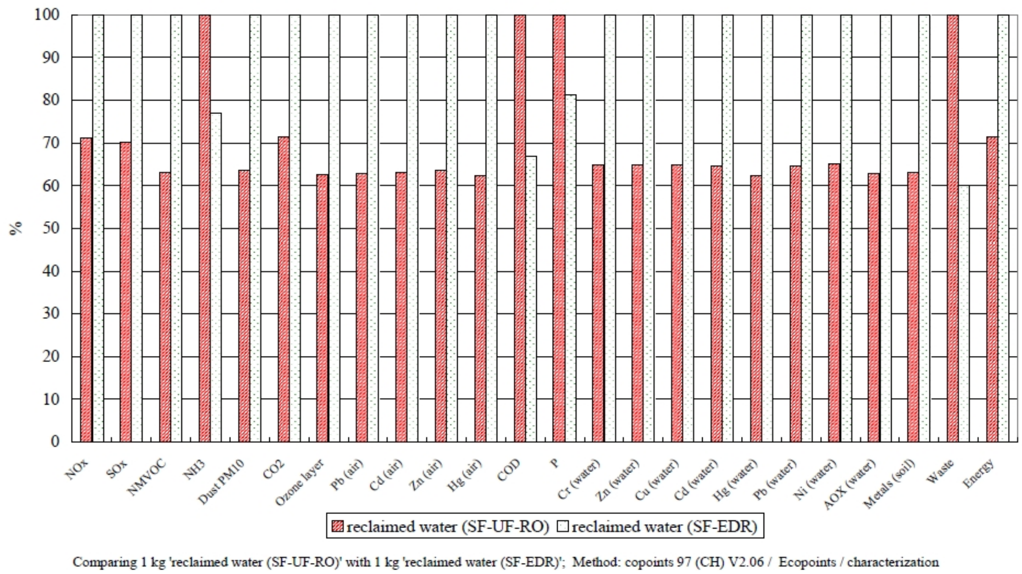

Fig. 4a. Percentage characterization chart of method ecopoints 97

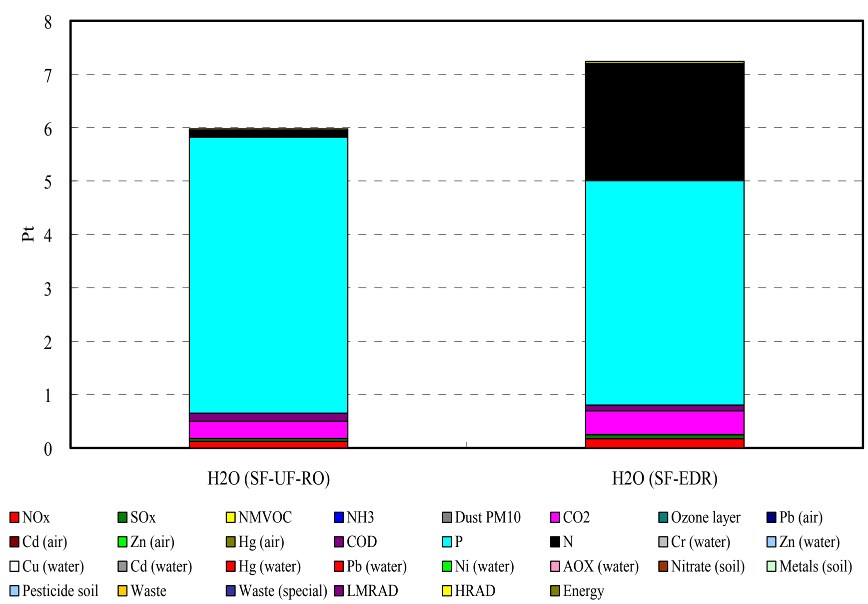

Fig. 4b. Overall Scores of Method Ecopoints 97

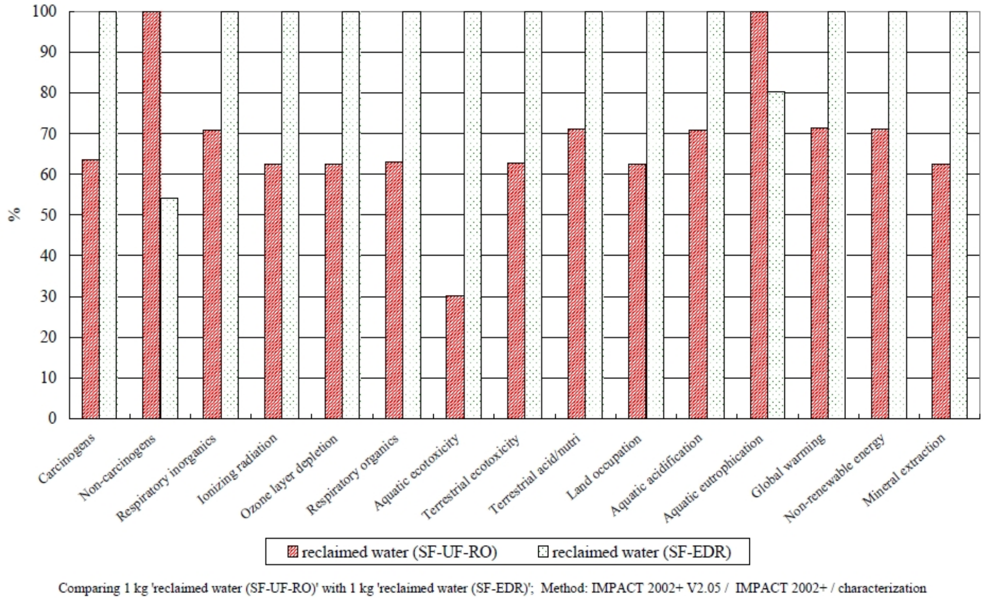

Fig. 5a. Percentage characterization chart of method impact 2002+

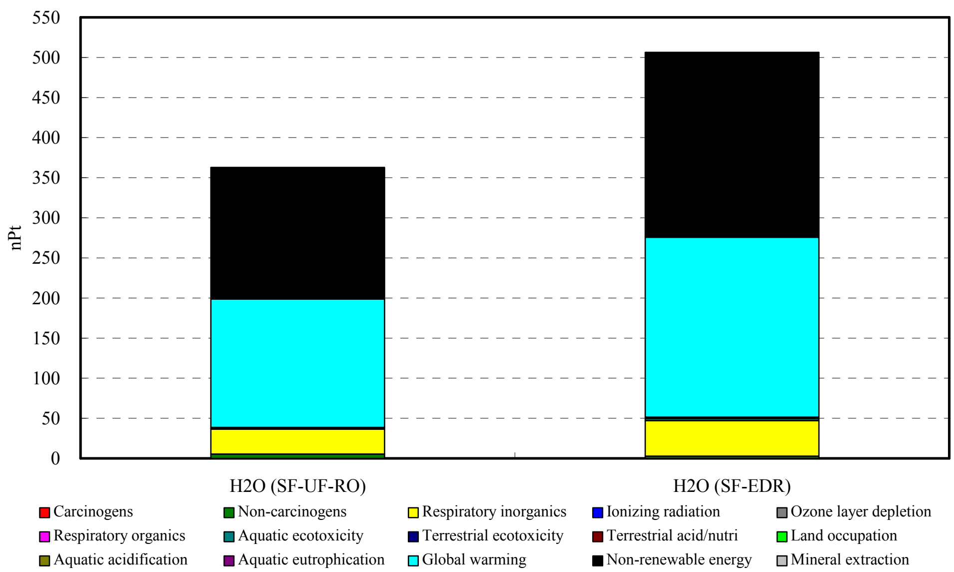

Fig. 5b. Overall scores of method impact 2002+

On the other hand, CML 2 baseline 2000 gave different results from the other three methods (Fig. 6). Process “SF-EDR” impacts less in the categories of human toxicity, fresh-water aquatic eco-toxicity and marine aquatic ecotoxicity than those of “SF-UF-RO”. It is related to more concentrated pollutants in the retentate from RO due to its higher rejection ratio to the substances in the influent.

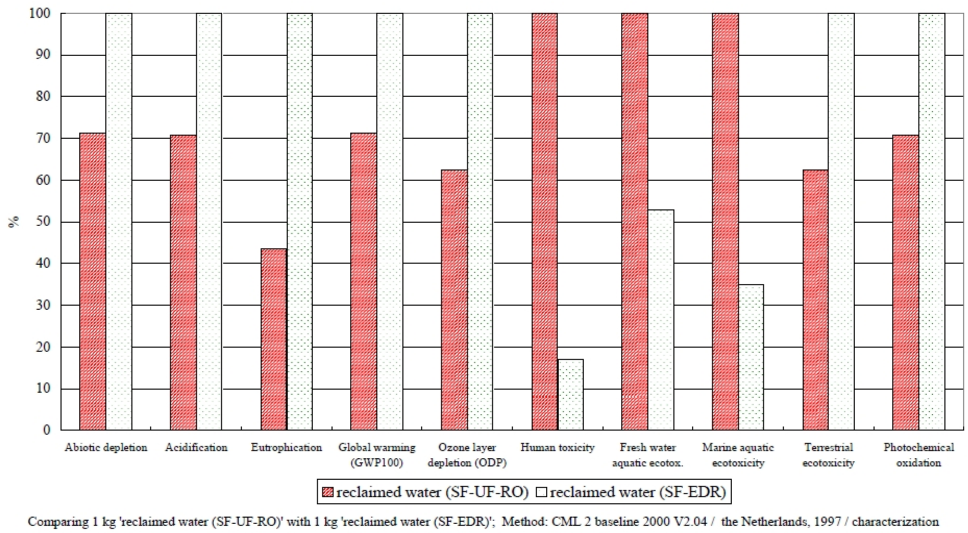

Fig. 6a. Percentage Characterization Chart of Method Impact CML 2 Baseline 2000

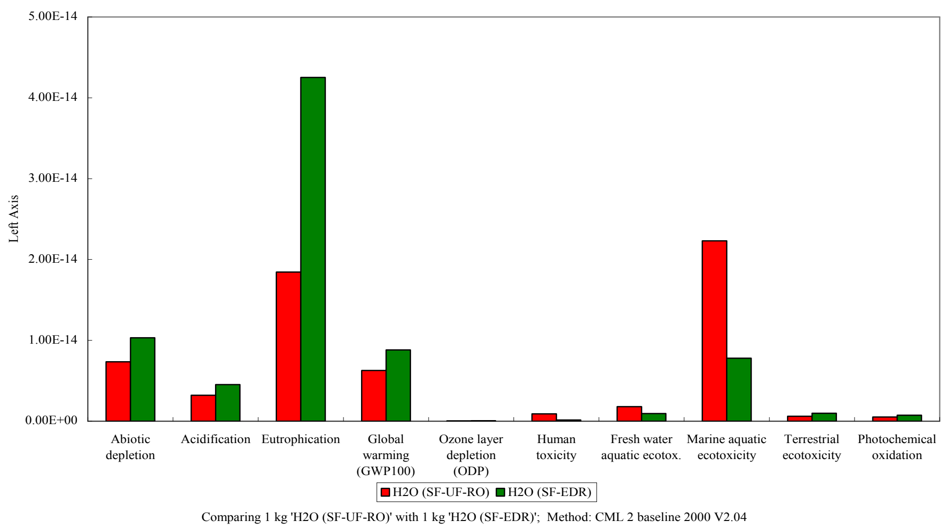

Fig. 6b. Normalization chart of method impact CML 2 baseline 2000

Accordingly, three of the four methods demonstrate that SF-EDR has more significant environmental impacts than SF-UF-RO (Table 3**).** The main reason is that the SF-EDR process consumes more electricity, and released more greenhouse gas than SF-UF-RO. The scores in greenhouse effects or climate change of SF-EDR are higher. On the other hands, the pretreatment SF provides less sufficient protection to EDR, and EDR requires chemical cleaning more frequently. It consumes more chemicals than SF-UF-RO and generally leads to higher scores in other fields (like respiratory inorganics, nitrogen emission and so on). Only the method "Impact CML2 baseline 2000" shows SF-UF-RO impacting more than SF-EDR due to the significant toxicity of the RO retentate. This may not be significant in the case of municipal wastewater reclamation as the composition is much simpler than the industrial wastewater. The ecological risk from toxicity issues of RO retentate may be controllable. It is concluded that the pressure-driven SF-UF-RO may be a more environmentally friendly process of effluent reclamation than SF-EDR, especially in the aspect of climate change mitigation.

Table 3. The Overall Score of Three Methods

Methods	Unit	The Overall Score of SF-UF-RO	The Overall Score of SF-EDR
Eco-indicator 99	Pt	2.505E-05	3.528E-05
Ecopoints 97	Pt	5.978E+00	7.239E+00
Impact 2002+	Pt	3.629E-07	5.064E-07

** Comparing 1 kg “reclaimed water (SF-UF-RO)” with 1 kg “reclaimed water (SF-EDR)”*
*** Method Impact CML2 baseline 2000 do not apply the single point score method to give an overall score.*

4. CONCLUSION

In the literature, the selection of the effluent reclamation process has been generally based on the production quality and the cost. To the authors’ best knowledge, this study is the first report considering not only the capital cost analysis but also environmental assessment of the two reclamation processes: SF-UF-RO and SF-EDR. We have noticed that the resulting water quality from both SF-EDR and SF-UF-RO are acceptable for supplying the general-purpose industrial use in Taiwan. As EDR requires less pre-treatment than RO and sand filter product with turbidity lower than 1.5 NTU is acceptable for EDR inlet, SF-EDR costs less than SF-UF-RO process in the production scale of 30,000 CMD. When evaluating the aspect of environmental impact assessment, we utilized the life cycle analysis concept with the software SimaPro 7.3. Applying the methods Eco-indicator 99, Ecopoints 97 and Impact 2002+ gave the conclusion that SF-UF-RO had fewer environmental impacts than SF-EDR. Although Impact CML 2 baseline 2000 gave the opposite results, the toxicity issues are expected to be less significant in this case of municipal wastewater reclamation. Based on the concerns of climate change mitigation, the process SF-UF-RO impacts the environment less as it emits fewer greenhouse gases and uses less non-renewable energy. SF-EDR may give more impacts to the environment due to more consumption on electricity and chemicals, although it may cost less financially. The results would be a relevant reference for the process selection for the scale-up construction in Taiwan, and it offers recommendations of process selection for climate change adaption in aid of environmental security.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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