Life Cycle Assessment for Tertiary Wastewater Treatment and Reuse versus Seawater Desalination

E Aleisa$^1$ and Asmaa Al-Mutiri$^2$

$^1$Industrial and Management Systems Engineering Department, Kuwait University, Safat 13060 Kuwait. e.aleisa@ku.edu.kw.
$^2$Department of General Services, Ministry of Electricity and Water, Kuwait

Abstract. Wastewater reuse is now indispensable for meeting the increasing water demand, particularly under conditions of alarming water scarcity, which is now already affecting every continent. The objective of this study is to apply life cycle assessment (LCA) to evaluate the environmental impact and missed opportunity of treating municipal wastewater to tertiary quality and compare it to conventional seawater desalination in the Gulf Corporation Council (GCC) countries, namely: Multistage flash distillation (MSF), multi-effect distillation (MED) and seawater reverse osmosis (SWRO). The study follows the ISO 14040/44 standards and uses a functional unit of 1 Mm$^3$ of tertiary treated effluent (TTE). The modeling concept adopts the cradle-to-gate consequential paradigm. The life cycle inventory is based on fielded data collection, reports, literature and Ecoinvent database processes. The scope includes: infrastructure, grid, materials, energy requirements, chemical additives and sludge disposal; for primary, secondary and tertiary treatment. The life cycle impact assessment is applied on both the characterized and normalized levels using the ReCiPe method. Compared to distillation, TTE exhibits an average reduction of 94% in fossil depletion. For climate change and particulate matter, an average reduction of 79% and 73% can be realized respectively. The large difference is due to energy consumption in desalination, despite that fact that the energy considered is only the allocated portion to distillation in the cogeneration total, using exergy specific power consumption.

1. Introduction

The Gulf Corporation Council (GCC) countries are of the most vulnerable regions to water stress and water scarcity [1]. The gap between water demand and availability is increasing, over the past decade. Water consumption has increased almost 12-folds, and the population has almost tripled during the same period. The demand for freshwater in the GCC is satisfied by seawater desalination followed by nonrenewable groundwater abstraction [2]. Approximately half of GCC oil production is consumed for and energy and water co-generation. The abundance of fossil fuels at relatively low extraction costs has allowed for more desalination [3]. With the global movement that urges sustainable energy and water production, oil prices are expected to fall within 2030; water and energy are pushed to decouple and decentralize; and use treated wastewater (TWW).

Utilizing TWW closes the water cycle by embracing the cradle-to-cradle philosophy of circular economy (CE) transition, aiming to reconcile sustainable development by giving water additional life cycles. CE and water decouple economic growth from natural resource use [4]. Within water context,
water recycling shifts wastewater from water category to one of the most untapped valuable solutions to contribute to elevating water scarcity. TWW contributes to food security; as over 20 million hectares of arable land worldwide are reported to be irrigated with TWW [5]. A study by Rezapour, et al. [6] indicates that TWW irrigation can not only be applied to combat water scarcity, but it can also improve soil nutrients level and increase productivity. Due to energy savings and contributing to satisfy demand, TWW reuse contributes to promoting Sustainable Development Goals (SDGs) 6: Clean water and 13: Climate action, SDG 11: sustainability, among others.

This study conducts a Life Cycle Assessment (LCA) to tertiary wastewater treatment and compares it to seawater desalination technologies in the GCC: multistage flash distillation (MSF), multi-effect distillation (MED) and seawater reverse osmosis (SWRO). The results are intended to assist in policymakers for a better utilization TWW. The study is applied to Kuwait but have a wider repercussion.

2. Country Context
Kuwait is a hyper arid desert climate located on the Arabian Gulf Peninsula, occupies a land area of 17,818 km². The population of Kuwait was approximately 4.3 million in 2020 [7]. Freshwater consumption data were collected from the ministry of electricity and water and renewable energy (MEWRE). Freshwater production has an average yearly increment rate of 3.8% (see Figure 1). The expected production for the next 15 years was forecasted using linear with $R^2 = 98\%$, where the amount of desalinated produced water ($P$) is $P = 4514.8$ (year) – $9 \times 10^6$ in million imperial gallons. Given this forecast, relying on recycling water is indispensable. Especially, with deteriorating environmental indicators and huge impact on the economy [3, 8].

![Figure 1. Total freshwater consumption in Kuwait from 2000 to 2020.](image)

Energy and water cogeneration is responsible for considerable GHG emissions [9]. The Kuwait environmental protection authority (KEPA) [10] database indicates that a staggering 82,556.572 Gg of CO$_2$ equivalent is attributed to energy water cogeneration, out of the total 86,336.448 Gg CO$_2$-equivalent emissions of the same year. Around 49% of Kuwait’s water demand is met by desalination, 29% by recycled wastewater and 22% by groundwater. The decision was made to exclude treated effluent from all amenity uses and to restrict it to agricultural use to safe crops even if its quality exceeded that required for potable use [11]. Currently, Kuwait has eleven desalination plants (DPs); three SWRO DPs, one operates using MED (cogeneration), while the remaining DPs operate using MSF (cogeneration).

As shown in Figure 2, there are seven wastewater treatment plants (WWTPs) in Kuwait: Alriqqa, Um Alhayman, Sulaibiya, Kabd, Wafra, Sabah Alhamed and Alkhiran (pilot plant). Wastewater generated
from activities of residential, governmental, commercial, and public areas is collected and then directed to the target treatment plant via dedicated sewer systems [12]. In contrast, stormwater is drained by stormwater network lines and then discharged without treatment to the sea.

![Figure 2. Kuwait wastewater treatment plants’ inflows and outflows. The Wafra and Khiran are smaller WWTPs with daily treated effluent of 749 and 232 cubic meters per day respectively [11].](image)

As shown in Figure 3, Kuwait municipal sewage network receives an inflow of 1075.73 Km³/d of wastewater and safely treats an average of 90% of household wastewater. The numbers vary from year to year according to floods if any and/or rejection of contaminated inflow due to illegal sewage connections (which hardly takes place nowadays). Approximately half of all wastewater is treated using reverse osmosis (RO) quality, the remainder to tertiary and advanced quality that uses ultraviolet (UV). RO permeate is utilized for irrigating edible crops while tertiary effluent is utilized for landscape and fodder irrigation in addition. Future use of RO permeate will be directed to air conditioning, cooling and oil excavation processes. The infrastructure is under early stages of construction. TWW sludge is not utilized.

![Figure 3. Wastewater treatment flows for Kuwait.](image)

3. Assessing wastewater treatment technologies using LCA
LCA has been applied since the 1990s to assess the environmental impact of different technologies, scenarios, and operation alternatives associated with wastewater and sludge management [13-22]. To date, more than 100 research papers have been published in this field. Detailed literature reviews comparing different LCA objectives, challenges, methodological choices and results related to wastewater treatment and sludge management can be found in Corominas et al. [23], Yoshida et al. [24],
Pradel et al. [25], Gallego-Schmid and Tarpani [26] among others. In addition, LCA has been used to analyze environmental impacts in the field of storm-water management [27]; to determine appropriate solutions in the field of the urban water cycle [28]; to control emitted greenhouse gases [29]; and to identify the environmental impacts of sea water desalination [30].

Table 1. The different LCA goal statements for selected wastewater LCA studies

| Literature                        | Intended Audience | Goal                                                                 | Country     |
|-----------------------------------|-------------------|----------------------------------------------------------------------|-------------|
| Ma, et al. [31]                   | Decision makers   | Examine effective methodologies to reduce freshwater consumption as well as wastewater discharge. | China       |
| Bai, et al. [32]                  | Stakeholders      | Evaluation of different wastewater treatment processes using multiple weighting methods and conjoint analysis. | China       |
| Liu, et al. [33]                  | Stakeholders      | To support the early stage and upgrade of a green biosorption reactor, i.e., an oxidation ditch treatment method; LCA was applied for this purpose. | China       |
| Zhang, et al. [30]                | -                 | To identify and eventually reduce the environmental impacts of microbial desalination cells used in WWTP and seawater desalination. | USA         |
| Tavakol-Davani, et al. [27]       | Stakeholders      | To evaluate of the environmental sustainability and benefits of rainwater harvesting systems used to control overflows in a combined sewer system. | USA         |
| Anastasopoulos, et al. [34]       | Stakeholders      | Presents a comparison using Nano Membrane toilets with different systems of lavatories. | South Africa |
| Petit-Boix, et al. [28]           | decision makers   | To determine critical variables and LCA stages of the urban water cycle. | Spain       |
| Li, et al. [35]                   | -                 | To investigate the critical issue of environmental impacts of organic micropollutants in advanced WWTPs for three different wastewater treatment technologies: ozonation, granular activated carbon adsorption and reverse osmosis. | China       |
| Awad, et al. [36]                 | Decision makers   | Address the economic and environmental benefits of adding a tertiary treatment/sludge treatment unit to primary and secondary treatment processes by using LCA. | Egypt       |
| Raghuvanshi, et al. [29]          | -                 | LCA was used in the assessment of the associated impacts from biodiesel production from microalgae feedstock cultivated in two different media: wastewater and fresh water. | India       |
| Guven, et al. [37]                | -                 | LCA is used to compare two options for upgrading a preliminary WWTP. The first uses a high-rate activated sludge system. The second option adds a food waste process. | Turkey      |
| Lopes, et al. [38]                | -                 | To evaluate the technical aspects and the environmental performance of a WWTP consisting of high-rate algal ponds as an alternative method for the activated sludge secondary treatment unit. | Spain       |
| Zhao, et al. [39]                 | decision makers   | To investigate the importance of incorporating a regional impact category using LCA in order to reflect the local impact of organic pollution. | China       |
| Pradel and Aissani [40]           | -                 | To investigate the environmental impacts related to phosphorus recovery from WWTPs. | -           |

LCA has also been used to address the environmental impacts as well as the benefits of supplementing, upgrading, and improving treatment processes [32, 36-38]. The obtained results indicated that LCA was powerful for optimizing the interaction among the operational parameters, thus facilitating access to the optimum decision [39-42]. A categorized literature review for LCA and wastewater treatment in accordance to LCA requirements by ISO 14040 [43] is provided in the next sections. The goal of an LCA states the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions to be disclosed to the public [44]. Table 1 shows the different goal statements for selected wastewater LCA studies.
3.1. The scope and functional units in wastewater LCA

The scope and systems boundaries indicate which aspects of the system are included to enable better comparative analysis and interpretation. The scope in wastewater LCA encompasses different boundaries, including the wastewater treatment, additional water purification, electricity production, the sewer system network, and materials production processes. In most wastewater LCA studies, the system boundaries have excluded end-of-life WWTP demolition due to the lower impact of this stage over other phases of the LCA. A comparison among different wastewater treatment scopes in LCA is shown in Table 2. The functional unit (FU) applied in WWTPs is quantified by the specific volume of wastewater generated or treated as a result of human activities on a daily basis (m³/day) [32, 36, 37]. It is used as a benchmark in the assessment of sewer systems from the generation point to the targeted treatment units [27, 28].

Table 2. The different FUs and scopes for selected wastewater LCA studies

| Literature          | FU                                                                 | Scope/System boundary                                                                 |
|---------------------|--------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Ma, et al. [31]     | 1 kWh of electricity With a reference flow of 3.2 × 10⁻³ m³/kWh   | Coal power supply plant: Coal mining, washing, transportation, and power generation technology |
| Bai, et al. [32]    | 0.1 m³                                                            | The operational stages of the constructed wetland                                       |
| Liu, et al. [33]    | 1 m³                                                              | WWTP: green biosorption reactor/oxidation ditch                                        |
| Zhang, et al. [30]  | 0.001 m³                                                          | Cradle to grave of microbial desalination cells                                         |
| Tavakol-Davani, et al. [27] | 1 m³                               | Rainwater harvesting system to control combined sewer overflows                        |
| Anastasopoulou, et al. [34] | 10-adult-occupant household                                   | From cradle to grave: nano membrane and conventional pour flush lavatories            |
| Petit-Boix, et al. [28] | 1 m³                                         | Raw material procurement, pipe production, transport to the construction site, pipe installation and trench preparation, and operation and maintenance |
| Li, et al. [35]     | 1 m³                                                              | Ozone-Sand filter, granular activated carbon-sand filter, microfiltration-reverse osmosis, and disinfection |
| Awad, et al. [36]   | 1 m³                                                              | Primary, secondary and tertiary treatment stages and anaerobic digestion of sludge     |
| Raghuvanshi, et al. [29] | 1 MJ of energy produced from biodiesel from fresh water and wastewater | Cradle-to-grave: The biodiesel production phases of cultivation, flocculation, centrifugation, extraction, and transesterification. |
| Guven, et al. [37]  | 1 m³ of influent wastewater And 2.88 kg of food waste            | Cradle-to-grave wastewater treatment, sludge treatment, and food waste treatment       |
| Lopes, et al. [38]  | 1 m³                                                              | Cradle-to-gate: From the stage of untreated wastewater input to sludge treatment.      |
| Zhao, et al. [39]   | 10,000 m³                                                         | WWTP                                                                                  |
| Pradel and Aissani [40] | 1 kg                                                    | WWTP                                                                                  |

3.2. Life Cycle Inventories and Databases Used for Wastewater LCA

The life cycle inventory (LCI) lists the comprehensive collection of the required data associated with the input and output of materials, energy, and emissions of the system boundary under consideration, including foreground and background data and elementary flows for the scenarios under consideration [45, 46]. The vast majority of wastewater LCA studies have used Ecoinvent [27-30, 36, 38, 40]. The USEtox and Ecoinvent databases were used in Li, et al. [35] and Zhao, et al. [39], respectively. Ma, et al. [31] created new LCI processes based on a coal-based power generation plant located in China. Liu, et al. [33] used a Chinese LCI Database. For wastewater LCA, the LCI database is often integrated within commercially available software such as SimaPro [28, 34, 38] or GaBi [27, 30]. Other software programs include Umberto NXT [29], e-Balance, open LCA and others.
3.3. Life Cycle Impact Assessment for Wastewater LCA

Life cycle impact assessment (LCIA) is the result of having elementary flows translated into environmental impact scores using an LCIA method. Table 3 shows some of the LCIA methods and impact categories discussed in wastewater LCA in selected studies.

Table 3. LCIA methods and categories used in selected wastewater LCA studies

| Literature | LCIA method | Impact categories |
|------------|-------------|-------------------|
| Ma, et al. [31] | USEtox™ | Carcinogens, noncarcinogens, freshwater ecotoxicity, aquatic eutrophication, and water scarcity. |
| Bai, et al. [32] | CML-AI | Acidification, eutrophication, human toxicity, photochemical oxidation, global warming, and abiotic depletion of fossil fuels. |
| Liu, et al. [33] | CML2002 | Fossil depletion potential, acidification potential, eutrophication potential, global warming potential, and the impacts of three emitted gases (CO₂, NOx, and SO₂). |
| Tavakol-Davani, et al. [27] | TRACI based on US impact data | Global warming potential, ecotoxicity in water, eutrophication potential, and ozone depletion potential |
| Anastasopoulou, et al. [34] | ReCiPe | Damage to human Health, damage to resources, and damage to ecosystems. |
| Li, et al. [35] | USEtox | Ecotoxicity, human health related to carcinogenic or noncarcinogenic pharmaceutical compounds, global warming, ozone depletion, acidification, eutrophication, smog air, and fossil fuel depletion. |
| Awad, et al. [36] | CML 2000 | Acidification potential, global warming potential, eutrophication potential, photochemical oxidation, depletion of abiotic resources, ozone layer depletion potential, terrestrial ecotoxicity potential, and freshwater aquatic ecotoxicity. |
| Guven, et al. [37] | ReCiPe | Climate change, terrestrial acidification, freshwater acidification, Marine eutrophication, human toxicity, freshwater contaminate, Marine ecotoxicity, and fossil fuel depletion. |
| Lopes, et al. [38] | CML-AI | Abiotic depletion of fossil fuels, global warming, ozone layer depletion, photochemical oxidant formation, acidification, and eutrophication. |
| Zhao, et al. [39] | CML-AI | Eutrophication, acidification, freshwater aquatic ecotoxicity, human toxicity, ozone depletion, photochemical oxidation, global warming, abiotic depletion of fossil fuels, and abiotic depletion of elements. |

4. Materials and Methods

The goal is to evaluate the environmental burden of TTE on two levels. The first to analyse the TTW system adhering to the four stages outlined by ISO 14040 [47]. At this level, analysis is conducted using open-loop consequential modelling. On a second level, the scope is expanded to compare TTE to distilled water from MSF, MED, and SWRO. In cogeneration systems, water is considered a co-product of an electricity-water cogeneration combined cycle, hence, only the distillation burden is considered using system allocation paradigm. The FU used is 1 Mm³ of TTE to the specifications found in Table 4.

Table 4. Specifications of TTE used in FU [48]

| Parameter      | Unit | Raw wastewater | Tertiary Treatment |
|----------------|------|----------------|--------------------|
| pH             | ---- | 6.5-8          | 6.5-7.5            |
| Conductivity   | µs/cm| 1200-3000      | 1100-2200          |
| T.S.S          | mg/l | 100-500        | < 10               |
| V.S.S          | mg/l | 70-350         | < 7.0              |
| C.O.D          | mg/l | 250-750        | < 40               |
| BOD₅           | mg/l | 100-400        | < 10               |
| Grease & Oil   | mg/l | 10-50          | NIL                |
IOP Conf. Series: Earth and Environmental Science 1026 (2022) 012001

4.1. System Scope and Boundary

The system boundaries are cradle-to-gate, so all processes, materials, energy requirements and chemical additives through operation are calculated through field visits, report or the literature. Water delivery and disposal are excluded. Electricity generation is modelled to partially supply requisite power to major WWTPs in the GCC. The phases included in the system boundary are provided in the following sections. The system boundary is shown in Figure 4.

Primary treatment is the physical/mechanical process that removes suspended and floating particles from wastewater entering the WWTP [49]. Primary treatment includes screening to screen grit and other suspended solids. Wastewater primary treatment removes 50-60% of the total solids and 20-30% of the BOD [50]. Four bar screens are used to remove large objects and grit from the incoming wastewater. The wastewater then passes through grit chambers to separate inorganic particles/fine materials, oil is removed from the wastewater using scrapers, then the wastewater undergoes an odour control process.

Secondary treatment uses biological processes to digest and dissolve organic pollutants to produce settleable solids [51]. In this stage, microorganisms consume organic matter and then convert it to water, energy and CO₂. The process is followed by aeration basins or settling tanks to clarify the influent by removing approximately 85% of its suspended solids and BOD [50, 52]. The biological treatment stage uses a vertical loop reactor (VLR), which is operated on the basis of partial ventilation and depends on a lack of oxygen [53]. The wastewater is then moved by gravity to secondary wastewater treatment, which consists of aeration chambers and primary clarifiers. The system includes four aeration tanks. Each aeration tank has two treatment systems: a VLR and return activated sludge (RAS) line. At the VLR, an average denitrification rate of approximately 80% is achieved without the need for internal recycling of sewage water. The oxygen supplying the VLR is supplied by six outside blowers into the aeration tank. The air is blown through diffusers at the upper end perforated with holes to form bubbles on the surface of the aeration tank. The suspended solids are reduced to no more than 15 mg/l using a peripheral feeding process using a hydraulic distribution system and sludge removal pipes at the bottom of the VLR [53]. The liquid from the aeration tanks passes to the clarifier and remains there for eight hours. The type of clarifier used is a “rim flow clarifier”, which has a depth of six meters with an internal diameter of 45 m to accommodate maximum flow with a capacity of 270 K m³/d. The flow inlet is at the centre, while the outlet is along the periphery for the centre feed clarifier. A concentric baffle spreads and distributes the discharge evenly in the radial direction. The resultant active sludge is continuously recycled to the aeration tank, where it mixes with incoming wastewater to feed bacteria and maintain the required food to microorganism (F/M) ratio. The surplus activated sludge (SAS) goes to sludge treatment [22].

| T.D.S.        | mg/l | 700-1800 | 800-1500 |
|----------------|------|----------|----------|
| Chloride       | mg/l | 200-400  | 200-400  |
| Ammonia        | mg/l | 15-50    | 1-5      |
| Nitrite        | mg/l | 0.04-0.7 | 0.1-1.5  |
| Total Count    | Colony/100 ml | 2.40E+09 | 1E+03    |
| T. Coli        | Colony/100 ml | 3.20E+08 | 400      |
| F. Coli        | Colony/100 ml | 4.10E+07 | 0–10     |
| Salmonella     | Colony/100 ml | 4.50E+06 | NIL      |
| Streptococci   | Colony/100 ml | 1.40E+07 | NIL      |
Tertiary treatment eliminates over 95% of all impurities from sewage. Tertiary treatment upgrades conventional secondary treatment by removing additional pollutants, residual suspended solids, phosphorus and nitrogen from secondary TWW [50]. The effluent discharge is distributed using a special chamber for purification using twenty-four rotating disc filters with a 100 m² effective filtration area per unit. The disc filters have a size of 10 microns (3.93x10⁻⁴ inches). The effluent is disinfected using an UV system. A four-channel UV system is used. The chlorination step is used for disinfection, colour removal and odour control. The effluent is treated at a concentration to achieve between 0.5 and 1.0 mg/l residual chlorine.

Excess sludge is thickened to reduce its volume. The system under study includes three operating units. A polymer preparation unit (PPU) is used for additional thickening and flocculation [53]. Eight aerobic digesters use gravity belts that carry sludge for dewatering to form a sludge cake. This sludge cake is landfilled [22].

**Figure 4.** System boundary for the LCA wastewater treatment.

### 4.2. Life Cycle Inventory

The LCI is built in accordance with the system boundaries described earlier using processes from Ecoinvent version 3.0. The chemical additives used are found in Table 5.

| Chemicals                      | Formula | Amount (g/m³) | Process [54]                  |
|--------------------------------|---------|---------------|-------------------------------|
| Sodium Hydroxide (50%)        | NaOH    | 1.096         | Sodium hydroxide 50% solution state |
| Sodium Hypochloride (12.5%)   | NaOCl   | 2.740         | Sodium hypochlorite 15% solution state |
| Activated carbon              | C       | 3.044x10⁻²    | Carbon black                  |
| Cationic polymer              | —       | 1.461         | Cationic resin                |
| Chlorine liquid               | Cl      | 3.288         | Chlorine Liquid               |
A new process was created for the UV disinfection system based on Lee, et al. [55]. The disinfection system with a flow rate of 100 K m$^3$/day is based on a 20-year lifetime. The electrical energy required for tertiary treatment is 0.39452 kWh/m$^3$. The electricity production process adopts the high voltage from Ecoinvent based on data found in Al-Shayji and Aleisa [56] and Aleisa and Heijungs [3] using an energy mix of heavy fuel oil, diesel, crude oil and natural gas (NG).

The landfilling for sludge and grit disposal facility is designed for biogenic waste from the Ecoinvent database version 3.0. It has a design capacity of 1.8 million m$^3$ volume with a 30-year lifetime. It is equipped with a leachate and landfill gas collection system [22]. The energy for the cogeneration alternatives are based on energy allocation to the distillers using exergy analyses of combined cycle arrangements and performance ratios obtained from Wakil Shahzad, et al. [57], Shahzad, et al. [58], Gude [59] and Ihm, et al. [60]. The types and amounts of chemical additives per cubic meter of desalinated water were obtained from local desalination plants [61] and from Al-Shayji and Aleisa [56].

4.3. Life Cycle Impact Assessment

The LCIA phase is conducted according to ReCiPe 2016 (H) V1.03 on the midpoint [62, 63] to determine the adverse effects on the environmental impact categories: climate change (CH) expressed in kg CO$_2$-eq to air, fossil fuel depletion (FD) in kg oil-eq, metal depletion (MD) in kg Cu-eq, human toxicity (HT) in kg 1,4-DCB-eq to urban air, and particulate matter formation (PM) in kg PM2.5-eq to air; these categories are considered the most critical in irrigation applications, which are the end use of TTE. The results are discussed in terms of both their characterized and normalized values, as are the process contributions and inventory substances with the most environmental impact.

5. Results

The LCIA phase was performed according to ReCiPe 2016 (H) V1.03 to determine the adverse effects on the environmental impact categories. The analyses are conducted on two levels: First to identify hotspots within tertiary wastewater treatment, the second compares TTE to desalination.

5.1. LCIA of Tertiary Effluent

The characterized results shown in Figure 5 are the relative environmental impact for each process with respect to midpoint impact categories. Infrastructure has the most significant impact on HT and MD. Generated electricity impacts CH, and PM.

![Figure 5](image_url). Results for the production of TTE using ReCiPe Midpoint (H) V1.10
Normalization enables the comparison among scenarios on the basis of the average human consumption and footprint within each category. Values are measured with a composite single score index (pt) and calculated using the ReCiPe (H) method. As shown in Figure 6, in normalized values, the categories that are most affected include: MD, FD and CH. Substances high in manganese, iron and nickel affect the MD category, while high oil and NG substances also affect the FD category. The normalized elementary flows or inventory results represent the significant number of substances that contribute to the impact categories. Using a cut-off of 1%, the five substances with the greatest impact are fossil depletion, carbon dioxide, dinitrogen monoxide fossil, fossil methane and biogenic methane.

![Figure 6. Normalized results for the production of TTE using ReCiPe Midpoint (H) V1.10](image)

5.2. LCIA of Tertiary Effluent compared to sweater distillation

Figure 7 shows the normalized environmental impact of TTE to that of distilled water from MSF, MED and SWRO. Compared to distillation, TTE exhibits an average reduction of 94% in FD. For CH and PM, an average reduction of 79% and 73% can be realized respectively. The large difference is due to energy consumption in distillation, despite that the energy considered is only the allocated to distillation boilers as opposed to that is used for cogeneration, using exergy specific power consumption (SPC) [60]. Regulations exclude all amenity uses or edible crops’ irrigation for TTE even if TWW properties exceeds standards [12]. Nonetheless, this policy has led to lost opportunities in the effective utilization of TTE. Research shows that TTE is a better option than distilled water for crop irrigation, including irrigation of vegetables and fruits consumed raw. This is because TTE contains essential salts and nutrients that are necessary for plant growth. This saves a proportion of the cost of organic and inorganic fertilizers and chemical compounds that are typically added to maximize crop yield. [64]. Finally, research has also linked excessive fertilizer imports to concerns related to food security [65], which is threatened by depletion of the Earth's resources, pollution, and climatic changes [66].
Figure 7. Normalized results comparing TTE with MSF desalination production using ReCiPe Midpoint (H) V1.10 The y-axis in million normalized points

6. Conclusions
This study conducts a Life Cycle Assessment (LCA) to tertiary wastewater treatment and compares it to seawater desalination technologies in the GCC: MSF, multi-effect distillation MED and SWRO. For the LCA comparison to desalination from cogeneration systems, the energy is based on energy allocation to the distillers using exergy analyses of combined cycle arrangements and performance ratios. The types and amounts of chemical additives per cubic meter of desalinated water were obtained from local desalination plants. The FU used is 1 Mm$^3$ of TTE meeting the specifications for agricultural use. The LCIA phase was conducted according to ReCiPe 2016 (H) V1.03 on the midpoint with respect to CH, FD, MD, HT, and PM.

The LCIA for comparing TTE to desalination, indicates an average reduction of 94% in FD. For CH and PM, an average reduction of 79% and 73% can be realized respectively. The large difference is due to energy consumption in distillation, despite that the energy considered is only the allocated to distillation boilers as opposed to that is used for cogeneration, using exergy specific power consumption. Although wastewater treatment in the GCC is commendable, the effluent reuse requires additional awareness, supporting legislation, and better applied strategies. Policies to promote TWW reuse remains by far one of the most important factors in addressing water scarcity issues in the GCC. It is a solution to mend the broken water cycle and support water sustainability, which is arguable the biggest challenge facing the GCC in the upcoming decade.

Acknowledgments
This research software was supported partially by Kuwait University. We thank engineer from Engineer Eisa Alrishidi and Engineer Huda Alengawi for providing data and description of the tertiary treatment process that greatly assisted of this paper.

References
[1] UN Water. "Water Scarcity." unwater.org. https://www.unwater.org/water-facts/scarcity/ (accessed 2020).
[2] E. Aleisa and W. Al-Zubari, "Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity," *Environmental Monitoring and Assessment*, vol. 189, no. 11, p. 553, 2017/10/12 2017, doi: 10.1007/s10661-017-6269-8.

[3] E. Aleisa and R. Heijungs, "Leveraging life cycle assessment and simplex lattice design in optimizing fossil fuel blends for sustainable desalination," *Int. J. Life Cycle Assess.*, vol. 25, no. 4, pp. 744-759, 2020/04/01 2020, doi: 10.1007/s11367-020-01738-4.

[4] Ellen MacArthur Foundation. "What is a circular economy?" [accessed Jan 8, 2020].

[5] J. Mateo-Sagasta, K. Medlicott, M. Qadir, L. R.-S. a. P. Drechsel, and J. Liebe, "Safe Use of Wastewater in Agriculture," *Food and Agriculture Organization (FAO)* of the United Nations And United Nations Water, Bon, August 2016. [Online]. Available: https://collections.unu.edu/eserv/UNU:2661/proceedings-no_11_WEB.pdf

[6] S. Rezapour, A. Nouri, H. M. Jalil, S. A. Hawkins, and S. B. Lukas, "Influence of Treated Wastewater Irrigation on Soil Nutritional-Chemical Attributes Using Soil Quality Index," *Sustainability*, vol. 13, no. 4, p. 1952, 2021.

[7] World Bank, "Kuwait," World Bank Group, Washington, DC, 2021. [Online]. Available: https://data.worldbank.org/

[8] E. Aleisa and K. Al-Shayji, "Ecological–economic modeling to optimize a desalination policy: Case study of an arid rentier state," *Desalination*, vol. 430, pp. 64-73, 15 March 2018, doi: doi.org/10.1016/j.desal.2017.12.049.

[9] KISR, "Kuwait Energy Outlook: Sustaining Prosperity Through Strategic Energy Management," Kuwait Institute for Scientific Research, The Supreme Council for Planning and Development, UNDP, 2019. [Online]. Available: https://www.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/KEO_report_English.pdf

[10] KEPA, "First biennial update report of the State of Kuwait for the UNFCCC," Kuwait Environment Public Authority (KEPA), Kuwait, September 2019, vol. 1. [Online]. Available: https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/391865_Kuwait-BUR1-1-State%20of%20Kuwait%20-%20BUR.pdf

[11] MPW, "Reports from The sanitary engineering sector in Kuwait.." Ministry of public Work, Sanitery Engineering Sector, Kuwait, 2021.

[12] E. Aleisa and K. Alshayji, "Analysis on Reclamation and Reuse of Wastewater in Kuwait," *Journal of Engineering Research*, vol. 7, no. 1, Mar 2019. [Online]. Available: <Go to ISI>://WOS:000466986200006.

[13] A.-M. Tillman, M. Svingby, and H. Lundström, "Life cycle assessment of municipal waste water systems," *Int. J. Life Cycle Assess.*, vol. 3, no. 3, pp. 145-157, 1998/05/01 1998, doi: 10.1007/BF02978823.

[14] S. Heimersson, M. Svanström, and T. Ekwall, "Opportunities of consequential and attributional modelling in life cycle assessment of wastewater and sludge management," *J. Clean. Prod.*, vol. 222, pp. 242-251, 2019/06/10/ 2019, doi: https://doi.org/10.1016/j.jclepro.2019.02.248.

[15] A. P. Machado, L. Urban, A. G. Brito, P. Janknecht, J. J. Salas, and R. Nogueira, "Life cycle assessment of wastewater treatment options for small and decentralized communities," (in eng), *Water science and technology : a journal of the International Association on Water Pollution Research*, vol. 56, no. 3, pp. 15-22, 2007.

[16] N. Makisha, "Waste Water and Biogas – Ecology and Economy," *Procedia Engineering*, vol. 165, no. Supplement C, pp. 1092-1097, 2016/01/01/ 2016, doi: https://doi.org/10.1016/j.proeng.2016.11.824.

[17] S. Raghuvanshi, V. Bhakar, C. Sowmya, and K. S. Sangwan, "Waste Water Treatment Plant Life Cycle Assessment: Treatment Procedure to Reuse of Water," *Procedia CIRP*, vol. 61, no. Supplement C, pp. 761-766, 2017/01/01/ 2017, doi: https://doi.org/10.1016/j.procir.2016.11.170.

[18] N. Buyukkamaci, "Life Cycle Assessment Applications in Wastewater Treatment " *Journal of Pollution Effects & Control*, vol. 1, no. 2, p. 2, 2013, doi: 10.4172/2375-4397.1000104.
[19] G. McNamara, L. Fitzsimons, M. Horrigan, and T. Phelan, "Life Cycle Assessment of Wastewater Treatment Plants in Ireland," of Sustainable Development of Energy, Water and Environment Systems, vol. 4, no. 3, pp. 216-233, September 2016, doi: 10.13044/j.sdewes.2016.04.0018.

[20] Pradip P. Kalbar, Subhankar Karmakar, and S. R. Asolekar, "Assessment of wastewater treatment technologies: life cycle approach," Water and Environment Journal, vol. 27, no. 2, pp. 261-268, 2 December 2012 2013, doi: 10.1111/wej.12006

[21] H. F. Larsen,"LCA of Wastewater Treatment," in Life Cycle Assessment: Theory and Practice, M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen Eds. Cham: Springer International Publishing, 2018, pp. 861-886.

[22] E. Aleisa, A. Alsulaili, and Y. Almuzaini, "Recirculating treated sewage sludge for agricultural use: Life cycle assessment for a circular economy," Waste Management, vol. 135, pp. 79-89, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.wasman.2021.08.035.

[23] L. Corominas et al., "Life cycle assessment applied to wastewater treatment: State of the art," Water Res., vol. 47, no. 15, pp. 5480-5492, 2013/10/01/ 2013, doi: https://doi.org/10.1016/j.watres.2013.06.049.

[24] A. Gallego-Schmid and R. R. Z. Tarpani, "Life cycle assessment of wastewater treatment in developing countries: A review," Waste Res., vol. 153, pp. 63-79, 2019/04/15/ 2019, doi: https://doi.org/10.1016/j.watres.2019.01.010.

[25] H. Yoshida, T. H. Christensen, and C. Scheutz, "Life cycle assessment of sewage sludge management: a review," (in eng), Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA, vol. 31, no. 11, pp. 1083-1081, Nov 2013, doi: 10.1177/0734242x13504446.

[26] M. Pradel, L. Aissani, J. Villot, J.-C. Baudez, and V. Laforest, "From waste to added value product: towards a paradigm shift in life cycle assessment applied to wastewater sludge – a review," J. Clean. Prod., vol. 131, pp. 60-75, 2016/09/10/ 2016, doi: https://doi.org/10.1016/j.jclepro.2016.05.076.

[27] E. Aleisa, A. Alsulaili, and Y. Almuzaini, "Recirculating treated sewage sludge for agricultural use: Life cycle assessment for a circular economy," Waste Management, vol. 135, pp. 79-89, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.wasman.2021.08.035.

[28] L. Corominas et al., "Life cycle assessment applied to wastewater treatment: State of the art," Water Res., vol. 47, no. 15, pp. 5480-5492, 2013/10/01/ 2013, doi: https://doi.org/10.1016/j.watres.2013.06.049.

[29] A. Petit-Boix, C. Arnal, D. Marin, A. Josa, X. Gabarrell, and J. Rieradevall, "Addressing the Life Cycle of Sewers in Contrasting Cities through an Eco-Efficiency Approach," Journal of industrial ecology, vol. 22, no. 5, pp. 1092-1104, 2018.

[30] S. Raghuwanshi, V. Bhakar, R. Chava, and K. Sangwan, "Comparative Study Using Life Cycle Approach for the Biodiesel Production from Microalgae Grown in Wastewater and Fresh Water," Procedia CIRP, vol. 69, no. 1, pp. 568-572, 2018.

[31] J. Zhang et al., "Life cycle assessment of a microbial desalination cell for sustainable wastewater treatment and saline water desalination," J. Clean. Prod., vol. 200, pp. 900-910, 2018.

[32] X. Ma, D. Yang, X. Shen, Y. Zhai, R. Zhang, and J. Hong, "How much water is required for coal power generation: an analysis of gray and blue water footprints," Science of The Total Environment, vol. 636, pp. 547-557, 2018.

[33] S. Bai, X. Zhao, D. Wang, X. Zhang, and N. Ren, "Engaging multiple weighting approaches and Conjoint Analysis to extend results acceptance of life cycle assessment in biological wastewater treatment technologies," Bioresource technology, vol. 265, pp. 349-356, 2018.

[34] R. Liu, Y. Zhao, Y. Yang, and O. W. Awe, "Diagnosis and evaluation of an early-stage green bio-sorption reactor by life cycle assessment," Journal of Cleaner Production, vol. 200, pp. 100-109, 2018.

[35] A. Anastasopoulou et al., "Conceptual environmental impact assessment of a novel self-sustained sanitation system incorporating a quantitative microbial risk assessment approach," Science of the Total Environment, vol. 639, pp. 657-672, 2018.
[35] Y. Li et al., "Life cycle assessment of advanced wastewater treatment processes: Involving 126 pharmaceuticals and personal care products in life cycle inventory," Journal of environmental management, vol. 238, pp. 442-450, 2019.

[36] H. Awad, M. G. Alalm, and H. K. El-Etriby, "Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries," Science of The Total Environment, vol. 660, pp. 57-68, 2019.

[37] H. Guven, O. Eriksson, Z. Wang, and I. Ozturk, "Life cycle assessment of upgrading options of a preliminary wastewater treatment plant including food waste addition," Water Res., vol. 145, pp. 518-530, 2018/11/15/ 2018, doi: https://doi.org/10.1016/j.watres.2018.08.061.

[38] A. C. Lopes, A. Valente, D. Iribarren, and C. González-Fernández, "Energy balance and life cycle assessment of a microalgal-based wastewater treatment plant: A focus on alternative biogas uses," Bioresource technology, vol. 270, pp. 138-146, 2018.

[39] X. Zhao, J. Yang, and F. Ma, "Set organic pollution as an impact category to achieve more comprehensive evaluation of life cycle assessment in wastewater-related issues," Environmental Science and Pollution Research, vol. 25, no. 6, pp. 5960-5968, 2018.

[40] M. Pradel and L. Aissani, "Environmental impacts of phosphorus recovery from a “product” Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers," Science of The Total Environment, vol. 656, pp. 55-69, 2019/03/15/ 2019, doi: https://doi.org/10.1016/j.scitotenv.2018.11.356.

[41] A. Gallego-Schmid and R. R. Z. Tarpani, "Life cycle assessment of wastewater treatment in developing countries: A review," Water research, 2019.

[42] A. H. Sabeen, Z. Z. Noor, N. Ngadi, S. Almuraisy, and A. B. Raheem, "Quantification of environmental impacts of domestic wastewater treatment using life cycle assessment: a review," J. Clean. Prod., vol. 190, pp. 221-233, 2018.

[43] Environmental Management Life Cycle Assessment Principle, ISO 14040, Geneva, Switzerland, 2006. [Online]. Available: https://books.google.com.kw/books?id=P-0aMwAACAAJ

[44] M. A. Curran, Goal and scope definition in life cycle assessment. Springer, 2016.

[45] M. Z. Hauschild, "Introduction to LCA Methodology," in Life Cycle Assessment: Springer, 2018, pp. 59-66.

[46] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Life Cycle Assessment: Theory and Practice. Springer, 2017.

[47] Environmental Management—Life Cycle Assessment—Requirements and Guidelines, ISO 14044, Geneva, 2006. [Online]. Available: https://www.iso.org/standard/38498.html

[48] MPW, "Reports from The sanitary engineering sector in Kuwait.," Ministry of public Work Kuwait, 2018.

[49] E. J. Wahlberg, R. B. Stallings, and A. R. Appleton, "Primary Clarifier Design Concepts and Considerations," Proceedings of the Water Environment Federation, vol. 2005, no. 11, pp. 4417-4430, 2005.

[50] M. Hamoda, "Advances in wastewater treatment technology for water reuse," Journal of Engineering Research, vol. 1, no. 1, pp. 1-27, 2013.

[51] S. Al-Shammar and A. Shahalam, "Effluent from an advanced wastewater treatment plant—an alternate source of non-potable water for Kuwait," Desalination, vol. 196, no. 1-3, pp. 215-220, 2006.

[52] A. Hsu et al., "Environmental Performance Index: Full Report and Analysis," Yale Center for Environmental Law & Policy, Yale University Center for International Earth Science Information Network, Columbia University World Economic Forum, Geneva, Switzerland The Samuel Family Foundation, Toronto, Canada, New Haven, CT, 2014. [Online]. Available: http://www.ciesin.org/documents/2014_epi_report.pdf

[53] MPW, "Kabd WWTP," Depatment of operation and maintenance of plants (North Zone), Kuwait, 2019.

[54] Ecoinvent. Electricity production, oil ROW
[55] K.-M. Lee, S. Yu, Y.-H. Choi, and M. Lee, "Environmental assessment of sewage effluent disinfection system: electron beam, ultraviolet, and ozone using life cycle assessment," *Int. J. Life Cycle Assess.*, vol. 17, no. 5, pp. 565-579, 2012/06/01 2012, doi: 10.1007/s11367-012-0388-9.

[56] K. Al-Shayji and E. Aleisa, "Characterizing the fossil fuel impacts in water desalination plants in Kuwait: A Life Cycle Assessment approach," *Energy*, vol. 158, pp. 681-692, 2018, doi: https://doi.org/10.1016/j.energy.2018.06.077.

[57] M. Wakil Shahzad, M. Burhan, H. Soo Son, S. Jin Oh, and K. Choon Ng, "Desalination processes evaluation at common platform: A universal performance ratio (UPR) method," *Applied Thermal Engineering*, vol. 134, pp. 62-67, 2018/04/01/ 2018, doi: https://doi.org/10.1016/j.applthermaleng.2018.01.098.

[58] M. W. Shahzad, M. Burhan, D. Ybyraiymkul, and K. C. Ng, "Desalination Processes’ Efficiency and Future Roadmap," *Entropy*, vol. 21, no. 1, p. 84, 2019. [Online]. Available: https://www.mdpi.com/1099-4300/21/1/84.

[59] V. G. Gude, "Exergy Evaluation of Desalination Processes," *ChemEngineering*, vol. 2, no. 2, p. 28, 2018. [Online]. Available: https://www.mdpi.com/2305-7084/2/2/28.

[60] S. Ihm, O. Y. Al-Najdi, O. A. Hamed, G. Jun, and H. Chung, "Energy cost comparison between MSF, MED and SWRO: Case studies for dual purpose plants," *Desalination*, vol. 397, pp. 116-125, 2016/11/01/ 2016, doi: https://doi.org/10.1016/j.desal.2016.06.029.

[61] MEW, "Statistical Year Book 2020 (Water)," Kuwait, 2020. [Online]. Available: https://www.mew.gov.kw/media/ovad3xpl/2019_المياه.pdf.

[62] M. A. J. Huijbregts et al., "ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization," Bilthoven, Netherlands, RIVM Report 2016-0104, 2016. [Online]. Available: https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf.

[63] M. A. Huijbregts et al., "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," (in English), *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138-147, Feb 2017 2017-02-07 2017, doi: http://dx.doi.org/10.1007/s11367-016-1246-y.

[64] A. R. Townsend et al., "Human health effects of a changing global nitrogen cycle," *Frontiers in Ecology and the Environment*, vol. 1, no. 5, pp. 240-246, 2003, doi: 10.1890/1540-9295(2003)001[0240:hheoac]2.0.co;2.

[65] S. Babu and A. Gulati, *Economic reforms and food security: the impact of trade and technology in south Asia*. CRC Press, 2005.

[66] E. M. Eid et al., "A sustainable food security approach: Controlled land application of sewage sludge recirculates nutrients to agricultural soils and enhances crop productivity," *Food and Energy Security*, vol. n/a, no. n/a, p. e197, 2020, doi: 10.1002/fes3.197.