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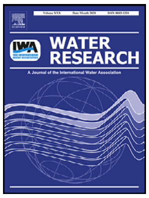

# Life-cycle cost analysis of a hybrid algae-based biological desalination – low pressure reverse osmosis system

Li Gao[a], Gang Liu[b,*], Arash Zamyadi[c,d,e], Qilin Wang[f], Ming Li[g,*]

[a] Institute for Sustainable Industries and Liveable Cities, Victoria University, PO Box 14428, Melbourne, Victoria 8001, Australia
[b] College of Management and Economics, Tianjin University, Tianjin 300072, China
[c] Water Research Australia (WaterRA), Adelaide/Melbourne, South Australia/Victoria, 5001, Australia
[d] Water Research Centre, School of Civil and Environment Engineering, University of New South Wales (UNSW), Sydney, New South Wales 2052, Australia
[e] Infrastructure Engineering, Faculty of Engineering, University of Melbourne, Melbourne, Victoria 3010, Australia
[f] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia
[g] College of Natural Resources and Environment, Northwest A&F University, Yangling, 712100, China

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## ABSTRACT

To fully understand the economic viability and implementation strategy of the emerging algae-based desalination technology, this study investigates the economic aspects of algae-based desalination system by comparing the life-cycle costs of three different scenarios: (1) a multi-stage microalgae based desalination system; (2) a hybrid desalination system based on the combination of microalgae and low pressure reverse osmosis (LPRO) system; and (3) a seawater reverse osmosis (SWRO) desalination system. It is identified that the capital expenditure (CAPEX) and operational expenditure (OPEX) of scenario 1 are significantly higher than those of scenarios 2 and 3, when algal biomass reuse is not taken into consideration. If the revenues obtained from the algal biomass reuse are taken into account, the OPEX of scenario 1 will decrease significantly, and scenarios 2 and 3 will have the highest and lowest OPEX, respectively. However, due to the high CAPEX of scenario 1, the total expenditure (TOTEX) of scenario 1 is still 27% and 33% higher than those of scenarios 2 and 3, respectively. A sensitivity study is undertaken to understand the effects of six key parameters on water total cost for different scenarios. It is suggested that the electricity unit price plays the most important role in determining the water total cost for different scenarios. An uncertainty analysis is also conducted to investigate the effects and limitations of the key assumptions made in this study. It is suggested that the assumption of total dissolved solids (TDS) removal efficiency of microalgae results in a high uncertainty of life-cycle cost analysis (LCCA). Additionally, it is estimated that 1.58 megaton and 0.30 megaton $CO_2$ can be captured by the algae-based desalination process for scenarios 1 and 2, respectively, over 20 years service period, which could result in approximately AU $18 million and AU $3 million indirect financial benefits for scenarios 1 and 2, respectively. When algal biomass reuse, $CO_2$ bio-fixation and land availability are all taken into account, scenario 2 with hybrid desalination system is considered as the most economical and environmentally friendly option.

## 1. Introduction

Desalination plays an increasingly important role in meeting the high purity water demand in the coastal areas (Humplik et al., 2011). The total volume of produced desalinated water increased from approximately 25 million $m^3$/d in 2000 to around 95 million $m^3$/d in 2019, and this trend is expected to continue in the future due to the rapid population growth, the higher water demand and effects of climate change (Ahmed et al., 2019; Jones et al., 2019; Shahzad et al., 2019). Although various technologies (Multistage Flash (MSF) (Borsani and Rebagliati, 2005; Fiorini and Sciubba, 2005), Multi-effect Distillation (MED) (Ophir and Lokiec, 2005; Sharaf et al., 2011), electrodialysis (Al-Amshawee et al., 2020; Lee et al., 2002), and membrane distillation (Gao et al., 2019a; b; Warsinger et al., 2015)) have been used for desalination purpose, Reserve Osmosis (RO) currently dominates the desalination market, supplying 69% of the total produced desalinated water with approximately 65.5 million $m^3$/d (Jones et al., 2019).

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* Corresponding authors.
*E-mail address:* lileaf@nwsuaf.edu.cn (M. Li).

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RO is considered as the state-of-art technique for desalination, but it is an energy intensive process with 3–5 kWh/m$^3$ energy consumption. Although the renewable energy sources have been investigated to drive the RO systems (e.g., solar-driven, wind-driven), they have not been utilized to drive the large desalination plants (Mito et al., 2019). Consequently, the large scale desalination plants are still powered by the conventional energy sources, and the high energy consumption will result in a high greenhouse gas emission (Berenguel-Felices et al., 2020; Jia et al., 2019; Qasim et al., 2019). Additionally, a large amount of brine is produced as the noxious by-product from the RO desalination plant, which could lead to significant environmental and ecological issues (Morillo et al., 2014). Thus, a more environmentally friendly and sustainable desalination technology is highly desired. The utilization of microalgae for desalination started to attract attentions. The salt removal by microalgae is based on biosorption (adsorption) and bioaccumulation (absorption), which is a natural and energy-passive process (Wei et al., 2020). The microalgae also capture $CO_2$ during the photosynthetic process for growth, resulting in a lower greenhouse gas emission. Furthermore, the harvested algal biomass can be used as the raw materials for various high-value products, including biodiesel generation, food additives manufacturing, and biogas production (Acién Fernández et al., 2018; Passos et al., 2016; Salama et al., 2017).

As an energy-efficient process, algae-based salt removal shows high potential in desalination application, however, this emerging technology has limitations. Microalgae are vulnerable to the high saline condition, only limited microalgae species can survive in high salinity environments with reduced growth (Shetty et al., 2019). Algae-based desalination could be used for brackish water treatment rather than seawater desalination. Brackish water with lower salinity could benefit the growth of algae. Meanwhile, more algae species could be selected for the brackish water desalination. Furthermore, seawater is only available in the coastal areas, but brackish water is more widely available, leading to more opportunities for algae-based desalination system. Previous studies have also demonstrated that the intracellular sodium concentration of the salt-stressed microalgae is always lower than the sodium concentration in the microalgae culture medium, this is due to the active sodium export mechanism as a part of the physiological and metabolic responses of microalgae to reduce the toxic effect of high sodium concentration (Hagemann, 2011). Wei et al. (2020) have used the microalgae *Scenedesmus obliquus* to investigate the desalination mechanisms. They found both adsorption and absorption contributed to the salt removal, however, the adsorption process played a more important role and required less reaction time compared to absorption. The desalination efficiency increased when the culture medium salinity increased from 2.8 g/L to 8.8 g/L, and the maximum desalination efficiency achieved by that study was 20%. Sahle-Demessie et al. (2019) have examined desalination potential of *Scenedesmus* sp. and *Chlorella vulgaris*. They found that the salt removal increased steadily along the reaction time until day 40 reaching 32% removal efficiency, and the maximum removal efficiency of 36% was achieved at day 85. Other studies (Gan et al., 2016; Moayedi et al., 2019; Yao et al., 2013) have identified the similar phenomenon that the maximum desalination efficiency achieved by algae was in the range of 16% - 33%. To overcome this barrier of limited salt removal capacity of microalgae, multi-stage process is suggested (Sahle-Demessie et al., 2019). When the maximum salt removal is achieved after reacting with the microalgae at the first stage, the effluent flows into the next stage and reacts with the fresh ‘un-saturated’ microalgae again. With multi-stage desalination process, a higher salt removal efficiency can be achieved. Nagy et al. (2017) used a pilot installation to investigate the desalination performance of *Scenedesmus*. The pilot plant consisted of three parallel treatment trains and each train had three consecutive algae basins (3 stages). The saline water flowed through each basin to remove the salts. The retention time in each basin varied between 7 - 9 days. The total dissolved solids (TDS) removal efficiencies were 52%, 78% and 93% after first, second and third stages, respectively. El Sergany et al. (2019) used the similar pilot installation to investigate the optimum algae dose for algae-based desalination system. They found that with 300 mL/path algae dosage, 38%, 60% and 66% of TDS removal could be achieved after first, second and third stages, respectively. The retention time of each stage was 7 days.

It is obvious that a complete salt removal cannot be achieved even with the multi-stage algae-based desalination system, and its desalination efficiency is lower compared to RO process. However, the ‘fit-for-purpose’ desalinated water could be produced directly from the algae-based desalination system. Certain amount of the salts can be removed from each stage of the algae-based desalination system. The salty water after 3 – 4 stages of treatment may still have high salt concentration, which could not be used for drinking purpose, but it could be potentially utilized for other applications with higher salt tolerance, such as car washing, landscaping, and gardening.

Another alternative approach is to utilize algae-based desalination as the pre-treatment for RO process. The seawater can be firstly treated by the microalgae to reduce its salinity level, afterwards, it can be further treated by RO. Generally, the low pressure RO (LPRO) system has a lower operating pressure and energy consumption but a higher recovery rate compared to the seawater RO system (SWRO), leading to a lower capital expenditure (CAPEX) and operational expenditure (OPEX) (Al-Karaghouli and Kazmerski, 2012).

Various previous studies (Arashiro et al., 2018; Garfí et al., 2017; Linares et al., 2016; Pazouki et al., 2020) have investigated the life-cycle costs for algae-based wastewater treatment systems and SWRO systems, however, to the best of the authors’ knowledge, no life-cycle cost analysis (LCCA) has been undertaken for algae-based desalination system. A better understanding of the life-cycle cost of algae-based desalination system can help us to determine the system’s economic viability and implementation strategy.

This study investigates the economic aspects of algae-based desalination system by comparing three different scenarios: (1) a multi-stage microalgae based desalination system; (2) a hybrid desalination system based on the combination of microalgae and RO system; and (3) a RO desalination system. This LCCA is undertaken based on a total expenditure (TOTEX) approach, which takes a holistic view to manage the life-cycle cost of the water infrastructure. Our analysis also takes resource recovery (algal biomass reuse) and possible integration with wastewater treatment into consideration. The sensitivity analysis and uncertainty analysis are also carried out. In addition to the economic aspects, the environmental impacts of different scenarios are discussed.

Although this LCCA will guide researchers and technology early adopters to explore the new research direction and undertake option analysis, it is worthwhile mentioning that RO and algae-based desalination systems have different Technology Readiness Levels (TRLs). RO based desalination technology is fully commercialized with standard operating and maintenance procedures. Its supply chain is mature at industrial scale, from the membrane manufacture to pre-/post-treatment installation. On the contrary, algae-based desalination is at proof of concept phase. The majority of the investigations are based on laboratory experimental study with artificial operating conditions (nutrients, carbon and light), further technology assessment is still required before the full scale implementation.

## 2. Methodology

### 2.1. Scenarios

Three different scenarios are assessed in this study, which include a multi-stage algae-based desalination system, a hybrid desalination system based on the combination of algae-based desalination and LPRO system and a SWRO desalination system. Based on this comparison, a better insight of the financial viability and implementation strategies for algae-based desalination system can be obtained.

Scenario 1: a multi-stage microalgae based desalination system. A medium size plant is assumed for this study with the total production capacity of 5000 $m^3$/d. The feed water is considered to be seawater with the typical TDS level at approximately 40,000 mg/L (Abdel-Aal et al., 2015; Nadi et al., 2014). The most widely used high rate algae pond (HRAP) configuration is selected here due to its lower CAPEX and OPEX. The halophilic algae *Dunaliella* sp. is considered as the suitable algae species. It has been widely used in algae-based desalination process (Moayedi et al., 2019; Shirazi et al., 2018), furthermore, *Dunaliella* sp. has a great potential in biomass reuse. Cho et al. (2015) have suggested that *Dunaliella* sp. can survive and accumulate high lipids and triacylglycerides under high salinity condition, which make it particularly suitable to generate biomass for biofuel production. Ahmed et al. (2017) have investigated the bioenergy application of *Dunaliella* sp. cultured with different salt concentrations. They have suggested that all the physicochemical parameters of *Dunaliella* sp. increased with increasing salinity, and the total lipids of 22.28% could be achieved. Based on the results from previous studies, it is assumed that the TDS removal efficiency is 40% for each stage. Totally 8 stages (8 different algae ponds) are required to reduce the TDS (40,000 mg/L) to the level acceptable for drinking purpose (600 mg/L) (WHO, 1996), and each stage has 7 days reaction time (hydraulic retention time (HRT)). The initial algae concentration (dosage) is 2 g/L (dry weight) for each stage (Wei et al., 2020). The algae growth rate (dry weight based) is conservatively assumed at 15%/d. The harvested algae are then used for biodiesel production and anaerobic digestion (electricity generation).

Scenario 2: a hybrid desalination system based on the combination of microalgae and LPRO system. The seawater (production capacity of 5000 $m^3$/d and TDS: 40,000 mg/L) is firstly pre-treated by a 1 stage microalgae-based desalination system (HRAP). With the 40% TDS removal efficiency, the effluent from the HRAP has a TDS level of 24,000 mg/L. The pre-treated seawater is further treated by LPRO system. As per scenario 1, the HRT of HRAP is 7 days, the initial algae concentration (dosage) is 2 g/L, and algae growth rate is 15%/d. The harvested algae are also used for biodiesel production and anaerobic digestion. For the LPRO system, it has a recovery rate of 55%, the osmotic pressure is 16.5 bars, and the TDS of the RO permeate is 200 mg/L (Kim and Hong, 2018; Valladares Linares et al., 2014).

Scenario 3: a SWRO desalination system. The seawater (production capacity: 5000 $m^3$/d and TDS: 40,000 mg/L) is treated by high pressure RO system. The TDS of the RO permeate is 200 mg/L. The osmotic pressure and recover rate are considered to be 27.6 bars and 45%, respectively (Kim and Hong, 2018; Valladares Linares et al., 2014).

It is worthwhile mentioning that the TDS of the RO permeate (200 mg/L, scenarios 2 and 3) is lower compared to that of produced water from eighth stage of algae-based desalination system (600 mg/L, scenario 1). However, as per World Health Organisation (WHO) Guidelines for Drinking-water Quality, the TDS of the produced water from all scenarios are acceptable for drinking purpose. The different TDS values clearly demonstrate the unique characteristics of different desalination processes. Membrane based desalination system can produce a better water quality with a lower TDS. However, 'fit-for-purpose' water could be produced from different stages of algae-based desalination system (scenario 1). Furthermore, algae-based desalination process could be used as the pre-treatment for membrane based desalination system (scenario 2).

The schematic diagrams of different scenarios can be found in Fig. 1.

### 2.2. LCCA

In this study, the LCCA is undertaken for 3 different scenarios based on a TOTEX approach, which combines both OPEX and CAPEX presented in net present value (NPV). The service life of the desalination plant is considered to be 20 years (Pazouki et al., 2020).

The OPEX includes 7 main categories for algae-based desalination system, including energy, labour, chemicals, carbon, nutrients, algal biomass reuse, and maintenance and others. For membrane system, the OPEX includes 5 main categories, including energy, labour, chemicals, membrane & cartridge filter replacement, and maintenance and others.

To calculate the NPV for year n, the following equation is used (Pazouki et al., 2020):

$$NPV_n = \frac{C_n}{(1+i)^n} \tag{1}$$

Here, $NPV_n$ is the NPV for year n; $C_n$ is the projected net cash flow at year n (TOTEX at year n); i is the discount rate, which is generally within the range of 6 −12%. Based on the similar LCCA study on desalination processes (Pazouki et al., 2020), the discount rate of 7% is selected for this study; and n is the year of service for the desalination plant (from year 1 to year 20).

$C_n$ can be calculated by the following equation:

$$C_n = OPEX_n + CAPEX_n \tag{2}$$

Here, $OPEX_n$ and $CAPEX_n$ are the operational expenditure and capital expenditure at year n, respectively.

Because of the projected 20 years service life, inflation has to be taken into consideration and the $OPEX_n$ can be calculated as follows (Pazouki et al., 2020):

$$OPEX_n = OPEX_1 \times (1+f_a)^n \tag{3}$$

Here, $OPEX_1$ are operational expenditure at year 1; and $f_a$ is the annual inflation factor, 2% is used here as the inflation factor based on the consumer price index data from Australian Bureau of Statistics (2010 – 2019).

To calculate the annual $CAPEX_n$, the total capital investment is amortized over the service life of the desalination plant (20 years), and the following equation is used, taking equipment's depreciation into consideration:

$$CAPEX_n = CAPEX_0 \times \frac{i \times (1+i)^T}{(1+i)^T - 1} \tag{4}$$

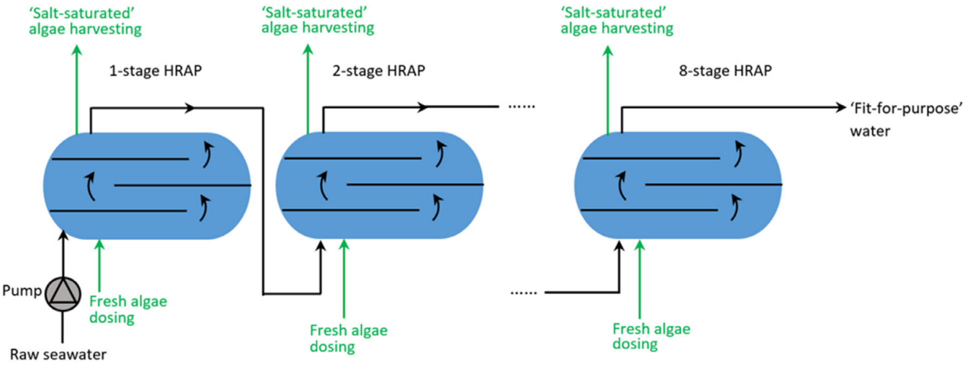
Here, $CAPEX_0$ is the capital investment made at year 0; T is the service life of the desalination plant (20 years).

Based on the above calculation, the cost for producing 1 $m^3$ desalinated water (water total cost) can be obtained based on the daily production rate of 5000 $m^3$/d and 20 years asset service life.

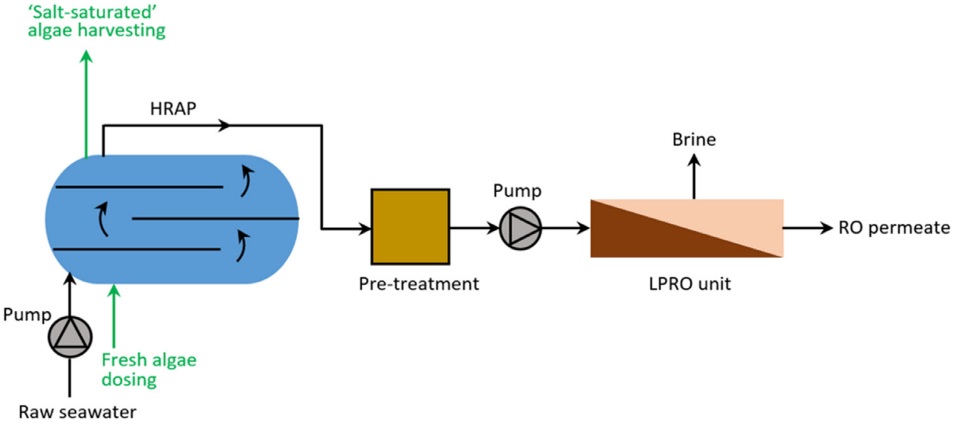
### 2.3. System assumptions

For the multi-stage microalgae based desalination system, the following assumptions have been made Table 1. For the hybrid desalination system based on the combination of microalgae and LPRO system, the following assumptions have been made Table 2.

a) Scenario 1: multi-stage microalgae based desalination system



b) Scenario 2: hybrid desalination system based on the combination of microalgae and LPRO system



c) Scenario 3: SWRO desalination system

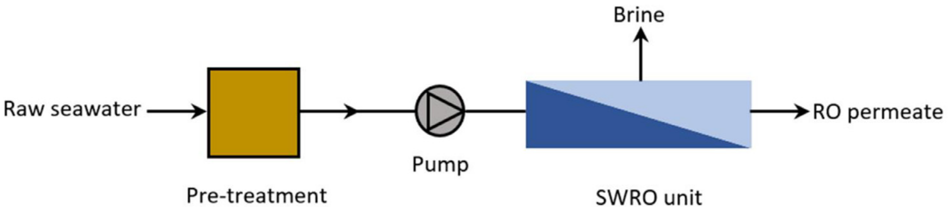


**Fig. 1.** Schematic diagrams of different scenarios.

For the SWRO desalination system, the following assumptions have been made Table 3.

### 2.4. Data collection

The reliable data plays an important role in undertaking LCCA study. Two main groups of data are used in this study: RO and HRAP processes. For the RO process, the operational data and cost information have been widely published. In order to check the validity of the conservative assumptions based on literatures, Winflows (Membrane System Design Software version 3.3.3, SUEZ) is used to simulate the design and operation of RO systems in scenarios 2 and 3. The obtained OPEX and CAPEX information is used to verify our estimated values and the differences are within approximately 20%.

Previous algae-based desalination studies are mainly laboratory-based, there is no full-scale HRAP system for desalination purpose, which creates difficulties in obtaining reliable

**Table 1**
Key assumptions for multi-stage microalgae based desalination system.

| | | |
|---|---|---|
| Algae species | *Dunaliella* sp. | |
| Lipid content | 21% (% dry algae weight) | Gan et al. (2016). |
| Water loss due to evaporation | 1080 mm/year | Based on Melbourne annual evaporation rate 1200 mm/year and 10% evaporation reduction due to the coverage of algae. |
| Water loss due to algae harvesting | 1% of total influent | Based on algae moisture content 80% after de-watering and the extracted water from de-watering process returns to algae pond. |
| The influent flowrate | 8622 $m^3$/d | Based on 41% water loss due to the evaporation and 1% loss due to the algae harvesting. |
| Algae pond depth | 0.4 m | |
| Land unit price | AU $18,000/hectare (ha) | Land unit price based on rural land price in 2020 at Wonthaggi where Victorian Desalination Plant is located. |
| Land area | 98.30 ha | |
| Land cost | AU $1,769,400 | |
| Algae dosing rate | 2 g/L (dry algae) | |
| Fresh algae dosing amount | 112.35 ton/d | |
| Algae productivity | 117.97 ton/d | Based on the growth rate of 15%/d. |
| Average relative CAPEX (land cost exclusive) | AU $322,417/ha | Value estimated based on previous studies (Batten et al., 2013; Davis et al., 2016; Griffin et al., 2013; Lundquist et al., 2010). |
| Average relative OPEX | AU $37,768/ha.y | Value estimated based on previously studies (Batten et al., 2013; Davis et al., 2016; Doshi et al., 2017; Griffin et al., 2013; Lundquist et al., 2010; Richardson et al., 2014). |
| Electricity unit price | AU $0.292/kWh | Based on Australian average electricity unit price (industry) in the first quarter of 2020. |
| $CO_2$ unit price | AU $11.5/ton | Parry et al. (2015). |
| Flocculant unit price | AU $77/ton harvested algal biomass | Hoffman et al. (2017). |
| Volatile solids (VS) percentage | 90% (% algae dry weight) | Yuan et al. (2015). |
| Theoretical $CH_4$ yield | 0.66 L $CH_4$/g VS | Yuan et al. (2015). |
| Digestability (VS degradation) | 52% | Yuan et al. (2015). |
| Actual $CH_4$ yield | 0.34 L $CH_4$/g VS | Yuan et al. (2015). |
| Biodiesel unit price | AU $1.192/L | Based on Australian market diesel price in September 2020, although biodiesel price is usually higher than petro-diesel. |
| Conversion efficiency of algae oil to biodiesel | 90% | Preiss and Kowalski (2010). |
| Algal oil percentage | 16.33% (% dry weight of harvested algal biomass) | Yuan et al. (2015). |
| Solid digestates percentage | 32% (% dry weight of harvested algal biomass) | Yuan et al. (2015). |
| Solid digestates unit price | AU $60.28/ton (calculated based on USD) | Yuan et al. (2015). |

data for algae-based desalination system cost estimation. To resolve the data limitation issue, different approaches are applied. Firstly, HRAP system has been widely studied for wastewater treatment, its operational data and cost information have been extensively reported (Arashiro et al., 2018; Kohlheb et al., 2020; Richardson et al., 2012; Rogers et al., 2014). The CAPEX and OPEX of HRAP based wastewater treatment system should be similar to those of HRAP based desalination system, although additional nutrients and carbon are required for algae-based desalination system. Furthermore, although a very limited studies have investigated the performance of algae-based desalination, the effects of salinity on algae have been widely examined (Abubakar, 2016; Mohy El-Din, 2015; Shetty et al., 2019), the algae growth and nutrient/carbon requirements under high saline condition have been well understood. This information helps to calculate the chemical usage and algal biomass productivity.

The OPEX and CAPEX information obtained from previous studies is firstly reviewed. Because different studies have different operating conditions, such as process configuration, plant capacity, influent water quality, and time of the study. Only the studies with similar operating conditions are used to calculate the OPEX and CAPEX. Extrapolation and interpolation are also applied to identify more accurate data. Based on the above approach, the reliable cost range can be built. To further ensure the accurate cost estimation, the highest and lowest values from the cost range are excluded when the average OPEX and CAPEX are calculated. It is worthwhile mentioning that the selected studies not only provide OPEX information but also include the detailed breakdown of OPEX. This information facilitates the calculation of different items of OPEX (e.g., algal biomass reuse cost, energy cost, chemical cost, etc.).

## 3. Results and discussion

### 3.1. CAPEX, OPEX and TOTEX comparison

Fig. 2 shows the CAPEX, OPEX and TOTEX analyzed for 3 different scenarios. The OPEX and CAPEX of different system components (algae system and membrane system) for different scenarios are summarized in Tables 4 and 5. Further detailed calculation can be found in Tables S1 – S5 in Appendix A. It is worthwhile mentioning that the revenues obtained from algal biomass reuse for scenarios 1 and 2 are not taken into account for the calculated values shown in Fig. 2. The effect of algal biomass reuse will be discussed in Section 3.2.

Scenario 1 and scenario 3 have only algae component and membrane component, respectively, but scenario 2 has both algae and membrane components, since it utilizes algae-based desalination as the pre-treatment for RO process. Fig. 2 clearly shows that both CAPEX and OPEX of scenario 1 are the highest among 3 scenarios. The CAPEX of scenario 1 is 83.22% and 81.63% higher than those of scenario 2 and scenario 3, respectively. The SWRO system of scenario 3 is replaced by LPRO system in scenario 2, therefore, the CAPEX of membrane system for scenario 2 is significantly lower than that of membrane system for scenario 3 (Table 4). However, due to the additional CAPEX for algae-based desalination pretreatment, the CAPEX of scenario 2 is very similar to that of scenario 3 (difference is less than 1%).

For the OPEX, scenario 1 is 34.71% and 59.98% higher than scenarios 2 and 3, respectively (Table 5). A further breakdown of OPEX for scenarios 1 and 3 is shown in Fig. 3. It is worthwhile mentioning that a breakdown of OPEX for scenario 2 is not shown here, since the OPEX breakdown of algae component for scenario 2 is

**Table 2**
Key assumptions for the hybrid desalination system based on the combination of microalgae and LPRO system.

| **Algae system** | | |
|---|---|---|
| Algae species | *Dunaliella* sp. | |
| Lipid content | 21% (% dry algae weight) | Gan et al. (2016). |
| Water loss due to evaporation | 1080 mm/year | Based on Melbourne annual evaporation rate 1200 mm/year and 10% evaporation reduction due to the coverage of algae. |
| Water loss due to algae harvesting | 1% of total influent | Based on algae moisture content 80% after de-watering and the extracted water from de-watering process returns to algae pond. |
| The influent flowrate | 9684 $m^3/d$ | Based on 5.18% water loss due to the evaporation and 1% loss due to the algae harvesting. |
| Algae pond depth | 0.4 m | |
| Land unit price | AU $18,000/ha | Land unit price based on rural land price in 2020 at Wonthaggi where Victorian Desalination Plant is located. |
| Land area | 16.95 ha | |
| Land cost | AU $305,055 | |
| Algae dosing rate | 2 g/L (dry algae) | |
| Fresh algae dosing amount | 19.37 ton/d | |
| Algae productivity | 20.34 ton/d | Based on the growth rate of 15%/d. |
| Average relative CAPEX (land cost exclusive) | AU $322,417/ha | Value estimated based on previous studies (Batten et al., 2013; Davis et al., 2016; Griffin et al., 2013; Lundquist et al., 2010). |
| Average relative OPEX | AU $37,768/ha.y | Value estimated based on previously studies (Batten et al., 2013; Davis et al., 2016; Doshi et al., 2017; Griffin et al., 2013; Lundquist et al., 2010; Richardson et al., 2014). |
| Electricity unit price | AU $0.292/kWh | Based on Australian average electricity unit price (industry) in the first quarter of 2020. |
| $CO_2$ unit price | AU $11.5/ton | Parry et al. (2015). |
| Flocculant unit price | AU $77/ton harvested algal biomass | Hoffman et al. (2017). |
| Volatile solids (VS) percentage | 90% (% algae dry weight) | Yuan et al. (2015). |
| Theoretical $CH_4$ yield | 0.66 L $CH_4$/g VS | Yuan et al. (2015). |
| Digestability (VS degradation) | 52% | Yuan et al. (2015). |
| Actual $CH_4$ yield | 0.34 L $CH_4$/g VS | Yuan et al. (2015). |
| Biodiesel unit price | AU $1.192/L | Based on Australian market diesel price in September 2020, although biodiesel price is usually higher than petro-diesel. |
| Conversion efficiency of algae oil to biodiesel | 90% | Preiss and Kowalski (2010). |
| Algal oil percentage | 16.33% (% dry weight of harvested algal biomass) | Yuan et al. (2015) |
| Solid digestates percentage | 32% (% dry weight of harvested algal biomass) | Yuan et al. (2015) |
| Solid digestates unit price | AU $60.28/ton (calculated based on USD) | Yuan et al. (2015) |
| LPRO system | | |
| Water recovery | 55% | |
| The influent flowrate | 9091 $m^3/d$ | Based on 55% water recovery. |
| Land unit price | AU $18,000/ha | Land unit price based on rural land price in 2020 at Wonthaggi where Victorian Desalination Plant is located. |
| Land area | 0.72 ha | EU (2013) |
| Land cost | AU $12,960 | |
| Average relative CAPEX (land cost exclusive) | AU $1373/$m^3$.d (calculated based on USD) | Linares et al. (2016) |
| Average relative OPEX | AU $1.24/$m^3$ | Value estimated based on previously studies (Bhojwani et al., 2019; Linares et al., 2016; Pazouki et al., 2020; Sarai Atab et al., 2016). |
| Electricity unit price | AU $0.292/kWh | Based on Australian average electricity unit price (industry) in the first quarter of 2020. |

**Table 3**
Key assumptions for SWRO desalination system.

| | | |
|---|---|---|
| Water recovery | 45% | |
| The influent flowrate | 11,110 $m^3/d$ | Based on 45% water recovery. |
| Land unit price | AU $18,000/ha | Land unit price based on rural land price in 2020 at Wonthaggi where Victorian Desalination Plant is located. |
| Land area | 0.83 ha | EU (2013) |
| Land cost | AU $ 14,940 | |
| Average relative CAPEX (land cost exclusive) | AU $1657/$m^3$.d (calculated based on USD) | Linares et al. (2016). |
| Average relative OPEX | AU $1.36/$m^3$ | Value estimated based on previously studies (Bhojwani et al., 2019; Linares et al., 2016; Pazouki et al., 2020; Sarai Atab et al., 2016). |
| Electricity unit price | AU $0.292/kWh | Based on Australian average electricity unit price (industry) in the first quarter of 2020. |

the same as scenario 1, and the OPEX breakdown of LPRO component is similar to that of scenario 3 (Tables S3 – S4). The amortization cost of CAPEX is also not shown in Fig. 3, because the percentage of CAPEX NPV varies over time.

Fig. 3 shows that the maintenance and chemicals are the two major items of OPEX for scenario 1 (algae-based desalination system), the energy cost only represents 10% of the OPEX. On the contrary, the energy cost for scenario 3 (membrane-based desalination) represents nearly half of the OPEX (44%), which is significantly higher than that of algae-based desalination system. This demonstrates that algae-based desalination system is an energy ef-

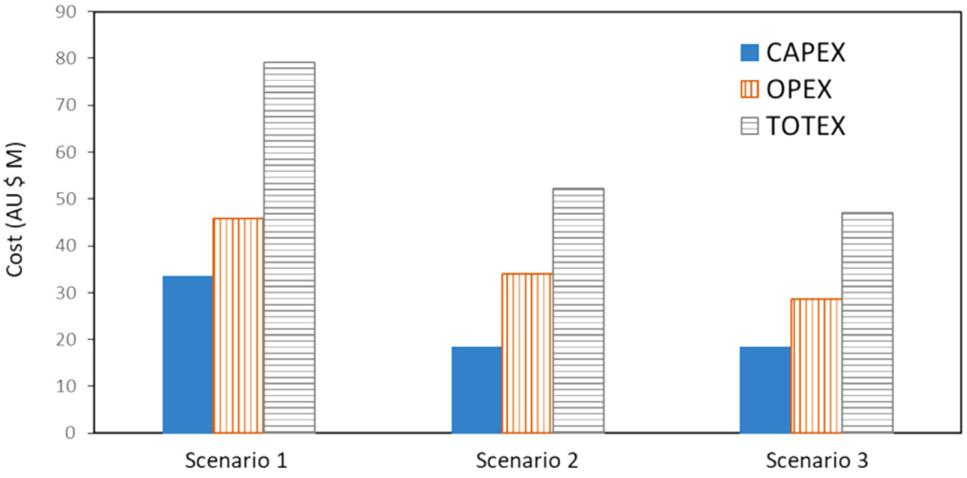


**Fig. 2.** CAPEX, OPEX and TOTEX analyzed for scenarios 1, 2 and 3.

**Table 4**
Summary of CAPEX for Scenarios 1, 2 and 3.

| | | Scenario 1 Multi-stage algae system | Scenario 2 Hybrid desalination system | Scenario 3 SWRO system |
|---|---|---|---|---|
| Algae system CAPEX (land cost exclusive) | AU $ | 31,693,591 | 5,464,164 | – |
| Algae system land cost | AU $ | 1,769,400 | 3,05,055 | – |
| Membrane system CAPEX (land cost exclusive) | AU $ | – | 12,481,943 | 18,409,270 |
| Membrane system land cost | AU $ | – | 12,960 | 14,940 |
| **Sub-CAPEX (algae system CAPEX + membrane system CAPEX)** | **AU $** | 31,693,591 | 17,946,107 | 18,409,270 |
| **Sub-land cost (algae system land cost + membrane system land cost)** | **AU $** | 1,769,400 | 318,015 | 14,940 |
| **Total CAPEX (Sub-CAPEX + Sub-land cost)** | **AU $** | **33,462,991** | **18,264,122** | **18,424,210** |

**Table 5**
Summary of OPEX for scenarios 1, 2 and 3

| | | Scenario 1 Multi-stage algae system | Scenario 2 Hybrid desalination system | Scenario 3 SWRO system |
|---|---|---|---|---|
| Algae system OPEX | AU $/y | 3,712,594 | 640,168 | – |
| Membrane system OPEX | AU $/y | – | 2,115,905 | 2,320,670 |
| Algae system OPEX over 20 years* | AU $ | 45,739,378 | 7,886,908 | **–** |
| Membrane system OPEX over 20 years* | AU $ | **–** | 26,068,075 | 28,590,792 |
| **Total OPEX over 20 years (algae system + membrane system)** | **AU $** | **45,739,378** | **33,954,983** | **28,590,792** |

*The calculation of OPEX over 20 years service period is based on NPV, taking discount rate (7%) and inflation factor (2%) into consideration. The revenue obtained from algal biomass reuse is not included here.

ficient process, but membrane-based desalination system is very energy intensive.

### 3.2. Algal biomass resource recovery

One of the key benefits for algae-based desalination process is that the algal biomass can be reused for producing high value products, leading to the lower TOTEX and water total cost. It is assumed that the halophilic algae *Dunaliella* sp. is used for the algae-based desalination process. With the optimal cultivation conditions (temperature, nutrients, sunlight, carbon, pH, etc.), a conservative value of 15%/d for algae productivity is used in this study. With this productivity, the algal biomass produced from HRAP is enough for the daily algae consumption for algae-based desalination process, additional algal biomass can also be produced for manufacturing other high value products.

High salinity cultivation is one of the strategies to induce lipid production, which results in a higher lipid accumulation in the algal biomass (Aratboni et al., 2019). Therefore, it is assumed that the algal biomass harvested from the algae-based desalination process is firstly used for biodiesel production, glycerine is also produced as the co-product from biodiesel production process. The lipid-extracted algal biomass residual is then used in the anaerobic digestion process to produce biogas (electricity). The final solid digestates could be further utilized as the raw materials for bio-fertilizer and other chemical products due to the high nutrient (e.g., nitrogen, phosphorus, and potassium) and salt contents. In this study, the algae-based desalination plant includes biodiesel production and anaerobic digestion facilities, but it does not include the treatment facility for the digestates. It is assumed that the final digestates will be sold to others, who can recover the nutrient and salt contents efficiently. The mass balance of the algal biomass resource recovery process is based on the values obtained from Yuan et al.'s study (Yuan et al., 2015).

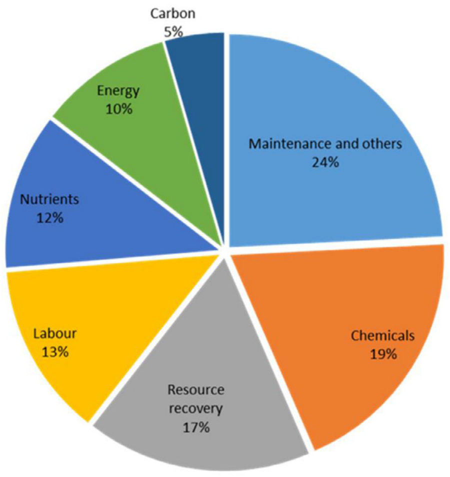
It should be mentioned here that the salts removed from the seawater will be finally concentrated into the digestates for algae-based desalination system. If the nutrient and salt contents are not recovered and the final digestate is considered as the pure

**Table 6**
Revenues obtained from algal biomass reuse for scenarios 1 and 2.

| | | Scenario 1 Multi-stage algae system | Scenario 2 Hybrid desalination system |
|---|---|---|---|
| Revenue from biodiesel production | AU $/y | 467,926 | 80,668 |
| Revenue from anaerobic digestion | AU $/y | 850,174 | 146,566 |
| Revenue from solid digestates | AU $/y | 39,551 | 6818 |
| Revenue from biodiesel production over 20 years* | AU $ | 5,764,882 | 993,836 |
| Revenue from anaerobic digestion over 20 years* | AU $ | 10,474,188 | 1,805,696 |
| Revenue from solid digestates over 20 years* | AU $ | 487,273 | 84,003 |
| **Total revenue over 20 years** | **AU $** | **16,726,343** | **2,883,535** |

*The calculation of revenue over 20 years service period is based on NPV, taking discount rate (7%) and inflation factor (2%) into consideration.

a) breakdown of OPEX for scenario 1 (algae-based desalination system)



b) breakdown of OPEX for scenario 3 (membrane-based desalination system)

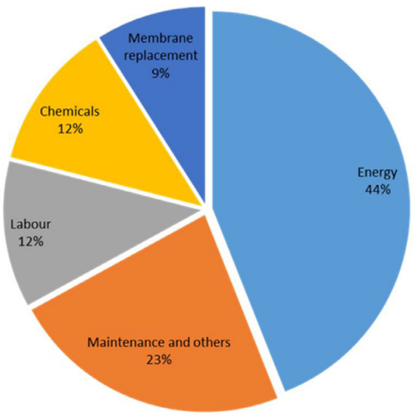


**Fig. 3.** Breakdown of OPEX for scenarios 1 and 3.

waste, different waste disposal/treatment methods have to be applied, such as landfill or incineration. This will result in the negative impacts on the environment. As a result, further reuse of digestates is strongly encouraged to eliminate the negative environmental impacts of algae-based desalination system.

Table 6 shows the summary of the revenues obtained from algal biomass reuse for scenarios 1 and 2. It can be seen clearly that the revenues obtained from scenario 1 is significantly higher than that of scenario 2, since there is only 1 HRAP and a lower amount of harvested algal biomass for scenario 2. Further details of the revenue calculation can be found from Tables S6 – S7.

The effects of algal biomass reuse on TOTEX and water total cost can be found in Fig. 4. It can be seen that the TOTEX reduces from AU $79.20 million to AU $62.48 million (26.77% reduction) and the water total cost reduces from AU $2.17/m$^3$ to AU $1.71/m$^3$ (26.77% reduction) for scenario 1. For scenario 2, TOTEX reduces from AU $52.22 million to AU $49.34 million (5.84% reduction) and the water total cost reduces from AU $1.53/m$^3$ to AU $1.45/m$^3$ (5.84% reduction). Algal biomass reuse has no effect on scenario 3 as it is purely based on membrane desalination process.

With the revenues obtained from algal biomass reuse, the water total cost of scenario 1 is 18.31% higher than that of scenario 2, and the water total cost of scenario 2 is only 4.94% higher than that of scenario 3. Because a conservative algae productivity value (15%/d) is used in this study, the conservative revenues are calculated for scenarios 1 and 2. The TOTEX and water total cost for scenario 2 could be at the same level or even lower compared to scenario 3, which indicates that scenario 2 could be the cheapest scenario, when algal biomass reuse is taken into consideration.

### 3.3. Sensitivity analysis

To understand the effects of six key parameters (evaporation rate, flocculant unit price, biodiesel unit price, land unit price, electricity unit price and membrane unit price) on water total cost, a sensitivity study is undertaken.

Fig. 5a shows the effects of different parameters on water total cost for scenario 1. It can be seen that the change of membrane unit price does not have any impact on the water total cost, because scenario 1 is the algae-based desalination process without any membrane component. Change of electricity unit price has the most significant impact on the water total cost. However, when electricity unit price is higher, the water total cost will be reduced. The total electricity cost will increase as a function of electricity unit price, however, the harvested algal biomass is used for anaerobic digestion, leading to the electricity generation. The produced electricity is not only enough to supply for the algae-based desalination process but also generates additional revenues. Because algae-based desalination system is an energy efficient process and consumes relatively less electricity. Consequently, the higher electricity unit price actually leads to a higher revenue, resulting in a reduced water total cost. As the algae-based desalination process, scenario 1 requires a very large land area (98.30 ha). However, due to the relatively cheap land unit price, the change of land unit price has a relatively less impact on the water total cost. Evaporation rate has two major impacts on the algae-based desalination process. Firstly, a higher evaporation rate results in a larger pond

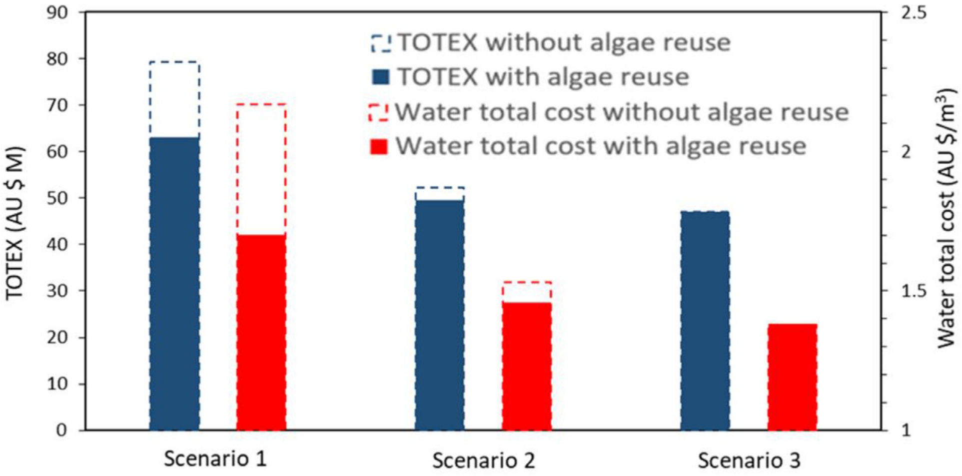


**Fig. 4.** Effects of algal biomass reuse on TOTEX and water total cost.

area, leading to a higher land cost. Secondly, a higher evaporation rate indicates a higher volume of influent. With the same algae dosing rate (2 g/L), more algal biomass can be harvested to generate revenue. Because of the relatively cheap land unit price, the revenue generated by the algal biomass reuse is more significant, which results in a net benefit. As a result, a higher evaporation rate actually leads to a reduced water total cost.

Scenario 2 is a hybrid desalination system based on the combination of microalgae and LPRO system. The effects of different parameters on the water total cost is shown in Fig. 5b. It can be seen that the changes of the evaporation rate, flocculant unit price, biodiesel unit price and land unit price have less impacts on the water total cost. Because these four parameters are related to algae-based desalination process, which is a relatively smaller component compared to LPRO process. The electricity unit price and membrane unit price have the major impacts on the water total cost. However, for scenario 2, a higher electricity unit price will lead to a higher water total cost. Because membrane process is very energy-intensive, 41% of the OPEX for LPRO system is used for energy. At the same time, the energy generated from the harvested algal biomass is not enough to compensate the energy used by the LPRO process.

Similar to scenario 2, electricity unit price has the most significant impact on the water total cost for scenario 3 (Fig. 5c), and a higher electricity unit price leads a higher water total cost.

Based on the above discussion, it can be suggested that the electricity unit price plays the most important role in determining the water total cost for all scenarios. Fig. 6 shows the relative effect of electricity unit price on water total cost for different scenarios. It can be seen clearly that a higher electricity unit price leads to a reduced water total cost for scenario 1; on the contrary, a higher electricity unit price results in a higher water total cost for scenarios 2 and 3. The effect of electricity unit price on scenario 3 is more significant compared to scenarios 1 and 2, because SWRO is a more energy intensive process compared to algae-based desalination process (scenario 1) and hybrid desalination system (scenario 2).

### 3.4. Uncertainty analysis

It is generally accepted that the LCCA is highly dependent on the local conditions (e.g., land price, energy price, and chemical price), the conservative and representative values and standard LCCA method are applied in this study to calculate the OPEX and CAPEX, which make it easier to re-evaluate the cost based on the conditions from other areas. Furthermore, the scenarios of this LCCA are based on different implementation strategies of algae-based desalination system (e.g., replacement of RO (scenario 1), pre-treatment for RO (scenario 2)). The general understanding in the economic viability and implementation strategies could guide future research in this area, resulting in a wider application of algae-based desalination system.

To further understand the effects and limitations of the key assumptions made in this study, an uncertainty analysis is conducted. Compared to the matured RO desalination technology, there is only limited laboratory-based experimental data for algae-based desalination system, and the assumptions made could have high uncertainties. Therefore, three key parameters from algae-based desalination system (TDS removal efficiency, lipid content of microalgae, and unit price of solid digestates) are selected for the uncertainty analysis.

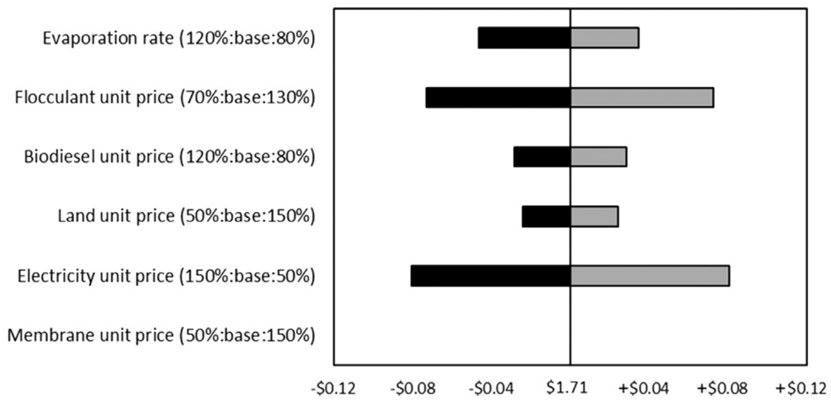
Table 7 shows the assumptions and uncertainties for these three parameters. For the TDS removal efficiency by microalgae, it is assumed 40% as the mean TDS removal efficiency with 25% uncertainty. For the lipid content of microalgae, it is assumed 21% as the mean lipid content with 50% uncertainty. For the solid digestates, it is assumed that it could be sold at AU $60.28/ton, with the maximum unit price at AU $72.34/ton (20% higher). However, if the solid digestates cannot be sold due to the high salt content, it will result in a waste disposal fee. Based on the current Australian landfill cost (Serpo and Read, 2019), it is assumed that the landfill cost is AU $ 64.20/ton.

Fig. 7 shows that the effects of uncertainties on scenario 1 are more significant compared to scenario 2. This is due to the fact that the scale of algae-based desalination system of scenario 1 is much bigger than that of scenario 2, and there is only 1 stage of algae-based desalination process as the pre-treatment for RO system for scenario 2. Consequently, it can be suggested that the LCCA for scenario 2 is relatively accurate.

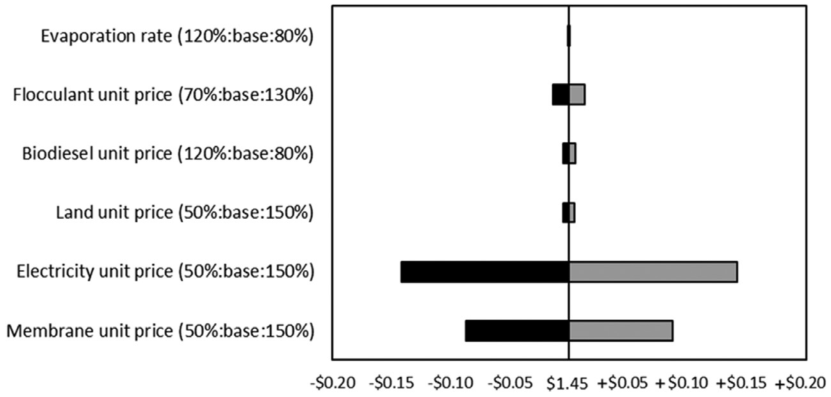
It can also be seen clearly that the uncertainty of TDS removal efficiency has a great effect on the water total cost. When the TDS removal efficiency of microalgae is higher (50%), only 6 stages are required for algae-based desalination system. On the contrary, when TDS removal efficiency is 30%, 12 stages are required, which results in a higher water total cost. The uncertainties of lipid content and unit price of solid digestates both have low effects on water total cost (less than 5%). This is mainly due to their low effects on the revenues obtained from algal biomass reuse.

Based on the above results, it can be suggested that the assumption of TDS removal efficiency of microalgae results in a high uncertainty of LCCA. Further study should focus on the salt removal mechanisms and efficiency of microalgae, which could lead to a more reliable result of TDS removal efficiency of microalgae.

a) Effects of different parameters on water total cost for scenario 1



b) Effects of different parameters on water total cost for scenario 2



c) Effects of different parameters on water total cost for scenario 3

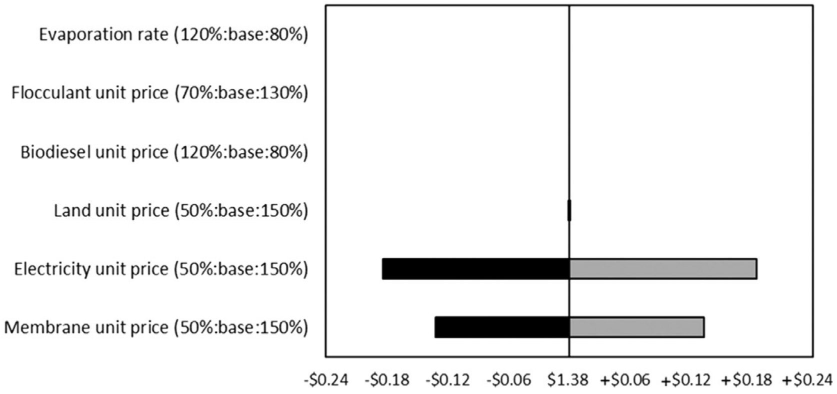


**Fig. 5.** Effects of different parameters on water total cost for different scenarios.

### *3.5. Approaches to improve economic viability of algae-based desalination system*

#### *3.5.1. Integration of algae-based desalination and wastewater treatment plant*

Algae require carbon and nutrients to grow. Marine algae usually take up carbon and nutrients at a Redfield ratio ($C:N:P = 106:16:1$) (Tett et al., 1985). The naturally oligotrophic seawater may not contain enough carbon and nutrients to support the optimal growth of algae, leading to an inferior desalination performance. Previous algae-based desalination studies (Gan et al., 2016; Sahle-Demessie et al., 2019; Wei et al., 2020) also show that nutrients have been artificially added to support the algae growth/survive and desalination.

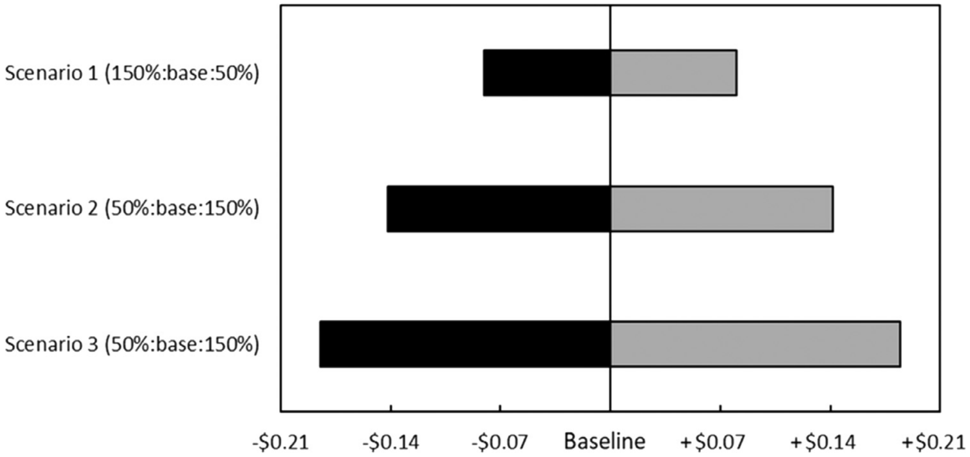


**Fig. 6.** Effect of electricity unit price on water total cost for different scenarios.

**Table 7**
Assumptions and their uncertainties for three parameters.

| Parameter | Assumptions and uncertainties | | |
|---|---|---|---|
| | Low | Assumption | High |
| TDS removal efficiency | 30% | 40% | 50% |
| Lipid content | 11% | 21% | 32% |
| Unit price of solid digestates | AU $ −64.20/ton (landfill cost) | AU $60.28/ton | AU $72.34/ton |

The effects of uncertainties on water total cost for scenarios 1 and 2 can be found in Fig. 7.

For scenarios 1 and 2, the nutrients cost and carbon cost represent 11.79% and 4.48% (see Table S3) of the total OPEX, respectively. As a result, the total cost of nutrients and carbon for scenario 1 over 20 years service period is AU $7.4 million, the total cost of nutrients and carbon for scenario 2 over 20 years service period is AU $1.3 million.

Wastewater contains abundant carbon and nutrients, which can be used to offset the costs of carbon and nutrients for algae-based desalination process. However, domestic wastewater generally contains carbon and nutrients at the ratio of 100:5:1 (C:N:P) (Permatasari et al., 2018), which indicates the difficulty in direct use of raw wastewater as the carbon and nutrients sources. Furthermore, wastewater may contain various contaminants which could have inhibitory effects on algae growth. For example, the toxic heavy metal and nanoparticles could hinder the algae growth (Hwang et al., 2016). The light intensity can also be reduced considerably due to the high turbidity of the raw wastewater, this will further inhibit the growth of photosynthetic algae. Based on the above consideration, it is suggested that raw wastewater should be pre-treated to improve its suitability as the carbon and nutrients source for algae-based desalination system. In addition to the wastewater quality, other factors should be taken into account during the design, such as volume and distance of the wastewater source.

### 3.5.2. Utilization of dead algae instead of living algal biomass

Previous algae-based desalination studies have demonstrated that a significantly long reaction time is required (7 – 85 days) to complete the salt removal process (Gan et al., 2016; Sahle-Demessie et al., 2019; Sergany et al., 2014; Yao et al., 2013). Wei et al. (2020) have suggested that 2/3 of the salt removal was completed by the first 30 mins, and it was mainly due to the non-metabolic biosorption process. It required more than 2 weeks to complete another 1/3 of the salt removal, and this phenomenon was attributed to the slow metabolic-dependent bioaccumulation process.

Because of the long salt removal process, the footprints for scenarios 1 and 2 are very large (98.30 ha and 16.95 ha, respectively), which result in both high CAPEX and OPEX. The dead algae could be used instead of the living algal biomass, the reaction time could be significantly decreased, and subsequently, the CAPEX and OPEX could potentially be reduced. In addition, various researchers have suggested that the dead algae cells may display a better metal binding capacity, because they are not subject to the metal toxicity limitations (González et al., 2011; Mehta and Gaur, 2005). Dead algal biomass also does not require carbon, light and nutrients to grow, which could further reduce the OPEX.

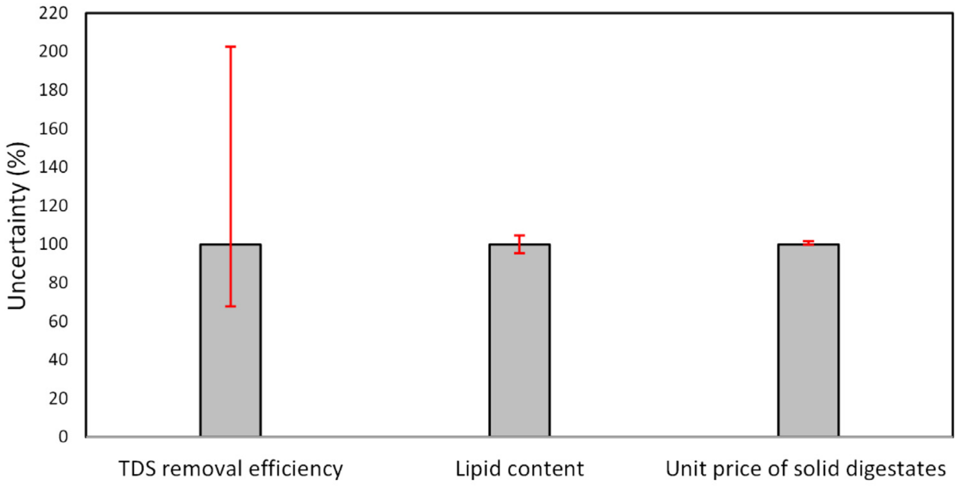
It is obvious that dead algal biomass has some limitations. First of all, the metabolic-dependent bioaccumulation capability is completely lost. The dead algae cells usually have smaller cell size and lower mechanical strength compared to living algal biomass, resulting in difficulties in biomass harvesting and recovery. Furthermore, the beneficial reuse of algal biomass will be restricted with the dead algal biomass. Based on the above considerations, it is suggested that further technical assessment should be undertaken to compare the long term desalination performance and the relevant cost implications between dead and living algal biomass.

### 3.5.3. Engineering approaches to develop optimal algae strains

Biosorption and bioaccumulation capacities of algal biomass could be enhanced by various engineering approaches. One of the approaches is ‘starvation’ strategy, which has been widely utilized in algae-based wastewater treatment processes (Solovchenko et al., 2016; Zhang et al., 2008). The amount of nutrient addition should be regulated, so it is just sufficient for algae’s optimal growth with enough energy to against the salt stress. When the algae cells are depleted of energy, they cannot actively export $Na^+$ from algal cells, and more salts will be accumulated within the algae cells accordingly (Minas et al., 2014).

Genetic engineering has been widely used to enhance the salt tolerance of algae cells (Amezaga et al., 2014; Shetty et al., 2019), but the ability to grow in high salinity environments does not necessarily result in a better salt removal performance. It is suggested

a) Effects of uncertainties of design parameters on water total cost for scenario 1



b) Effects of uncertainties of design parameters on water total cost for scenario 2

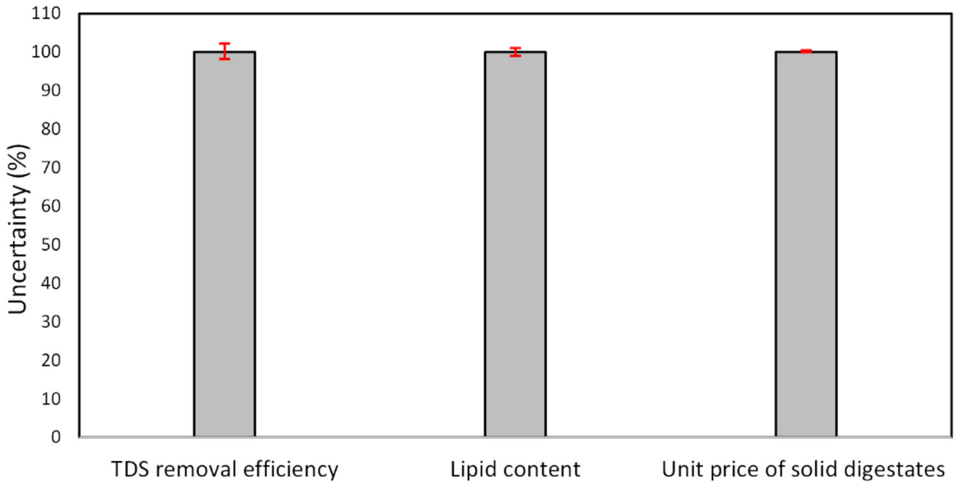


**Fig. 7.** Effects of uncertainties on water total cost for scenarios 1 and 2.

that different genetic approaches should be investigated in the future to enhance the salt bioaccumulation ability of algae cells, which could potentially improve the economic viability of algae-based desalination system.

### 3.6. Environmental considerations

The LPRO and SWRO processes have low recovery rates of 55% and 45%, respectively, which indicate that large volumes of brine will be produced from the membrane-based desalination process. The brine could cause acute and chronic toxicity, and alterations to the ecosystem of the receiving environment (Roberts et al., 2010), which restrict the implementation of RO process in environmentally sensitive areas. On the contrary, the optimal algae growth and desalination performance are highly dependent on the local environmental conditions. It is expected that the algae strains can grow optimally in the temperature range between 20 – 40 °C, which allows the utilization of the selected strains under ambient conditions in a large geographical area (Minas et al., 2014).

As the photosynthetic organisms, algae have the ability to fixate the atmospheric $CO_2$, which contributes to reduce the global warming impact. This is considered as one of the great environmental benefits for algae-based desalination process. However, the $CO_2$ in the atmosphere usually cannot provide enough carbon for algae growth, because the diffusion of $CO_2$ from the atmosphere into water is slower than the carbon utilization by algae. Additional carbon has to be added. It is assumed that $CO_2$ from other sources could be utilized to support the optimal algae growth. The $CO_2$ could be sourced from the by-product or waste product from various industries (e.g., natural gas industry, power plant) or even from internal algal biomass reuse process (e.g., digestion process) (Anguselvi et al., 2019; Fallowfield et al., 2016). The relevant costs for $CO_2$ utilization have been taken into consideration during the CAPEX and OPEX calculations (see Tables S1 and S3). Because algae can utilize $CO_2$ as their main carbon source for metabolic process, algae-based desalination process will have a lower carbon footprint compared to the energy intensive membrane-based desalination process.

The carbon fixation rate by algae can be calculated by the following equation (Adamczyk et al., 2016):

$$R_c = C_c \times P_{algae} \times \frac{M_{co_2}}{M_{carbon}} \tag{5}$$

Here, $R_c$ is the annual $CO_2$ fixation rate (ton/y); $C_c$ is the average carbon content (% dry weight of algal biomass), which is approximately 50% for *Dunaliella* sp. (Mortezaeikia et al., 2016); $P_{algae}$ is the annual productivity of algae (ton/y); and $M_{co_2}$ and $M_{carbon}$ are the molecular weights for $CO_2$ and carbon, respectively.

Based on Eq. (5), it can be estimated that 1.58 megaton and 0.30 megaton $CO_2$ can be captured by the algae-based desalination process for scenarios 1 and 2, respectively, over 20 years service period. $CO_2$ price varies in different countries and if a conservative value of AU $11.5/ton $CO_2$ is used (Parry et al., 2015), approximately AU $18 million and AU $3 million indirect financial benefits can be obtained for scenarios 1 and 2, respectively. It is worthwhile mentioning that this indirect financial benefits are calculated based on the assumption that carbon credits can be generated from algae-based desalination system. The generated carbon credits could be subsequently traded in the global carbon market. If these indirect financial benefits are taken into consideration during the TOTEX calculation, scenario 1 and scenario 3 will have the lowest and highest TOTEX, respectively, although the difference between scenarios 1 and 3 is only 5%.

Because of the potential issue of land availability, scenario 2 with hybrid desalination system based on the combination of microalgae and LPRO is considered as the most economical and environmentally friendly option, when algal biomass reuse and $CO_2$ bio-fixation are taken into account. Current design of scenario 2 only includes 1 stage of HRAP, which limits the benefits of algal biomass reuse and $CO_2$ bio-fixation, the scale of algae-based desalination pre-treatment could be expanded to further reduce the TOTEX and water total cost.

It should also be mentioned that this study focuses on life-cycle costs for different scenarios. A full Life Cycle Assessment (LCA) should also be undertaken to further evaluate the environmental impacts associated with different scenarios, which could identify the key environmental benefits and bottlenecks for algae-based desalination system.

## 4. Conclusions

This study analyzes the economic aspects of algae-based desalination system by comparing the life-cycle costs of three different scenarios: (1) a multi-stage microalgae based desalination system; (2) a hybrid desalination system based on the combination of microalgae and LPRO system; and (3) a SWRO desalination system. It is identified that the CAPEX and OPEX of scenario 1 are significantly higher than those of scenarios 2 and 3, when algal biomass reuse is not taken into consideration. The CAPEX of scenario 2 is similar to that of scenario 3, however, its OPEX is 16% higher than that of scenario 3.

If algal biomass reuse is taken into consideration, the OPEX of scenario 1 will decrease significantly due to the revenue obtained from harvested algal biomass reuse. Scenarios 2 and 3 will have the highest and lowest OPEX, respectively. However, due to the high CAPEX of scenario 1, the TOTEX of scenario 1 is still 27% and 33% higher than those of scenarios 2 and 3, respectively.

A sensitivity study is undertaken to understand the effects of six key parameters on water total cost for different scenarios. It is identified that the electricity unit price plays the most important role in determining the water total cost for all scenarios. For scenario 1, a higher electricity unit price leads to a reduced water total cost. Because scenario 1, as algae-based desalination process, has the lowest energy demand, at the same time, a large amount of algal biomass can be harvested to generate electricity, which is not only enough to supply for the algae-based desalination process but also generates additional revenues. On the contrary, for scenarios 2 and 3, a higher electricity unit price results in a higher water total cost. To further understand the effects and limitations of the key assumptions made in this study, an uncertainty analysis is also conducted. It is suggested that the assumption of TDS removal efficiency of microalgae results in a high uncertainty of LCCA. Further study should focus on the salt removal mechanisms and efficiency of microalgae, which could lead to a more reliable result of TDS removal efficiency of microalgae.

As the membrane-based desalination process, scenarios 2 and 3 produce large amounts of brine, which could have negative environmental impacts on the receiving environment. In addition, algae have the ability to fixate the atmospheric $CO_2$, which contributes to reduce the global warming impact. It is estimated that 1.58 megaton and 0.30 megaton $CO_2$ can be captured by the algae-based desalination process for scenarios 1 and 2, respectively, over 20 years service period, which could result in approximately AU $18 million and AU $3million indirect financial benefits for scenarios 1 and 2, respectively.

Based on the above considerations, it is suggested that the scenario 2 with hybrid desalination system based on the combination of microalgae and LPRO is considered as the most economical and environmentally friendly approach, when algal biomass reuse, $CO_2$ bio-fixation and land availability are all taken into account. This will help us to design the future algae-based desalination system.

## Declaration of Competing Interest

All the authors (Li Gao, Gang Liu, Arash Zamyadi, Qilin Wang, Ming Li) agreed to submit our original research paper titled "Life-cycle cost analysis of a hybrid algae-based biological desalination – low pressure reverse osmosis system" for consideration of publication in Water Research.

This manuscript is not under consideration by any other journal. The authors declare no conflict of competing interest.

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## Supplementary materials

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