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Feasibility of Nutrient Removal and Recovery from Abattoir Wastewater Using Microalgae

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Abstract: The wastewater produced from the meat-processing industry is a rich source of nutrients which can be recovered using microalgae. This study assesses the potential of microalgae cultivation on abattoir wastewater based on its nutrient removal capacity from wastewater, biomass production and greenhouse gas (GHG) emission savings potential. Designing the treatment ponds at the recycling rate of almost 80% of treated water results in high-quality water containing less than 1 mg/L nitrogen and 12 mg/L phosphorus. At the same time, the process can produce valuable algal biomass (≈2 kg/m^3 of abattoir wastewater) which can be further dewatered to make the process either economically self-sufficient or profit-making depending upon the use of algal biomass. It can finally avoid GHG emissions from 3.46 kg CO_2-eq to 6.11 kg CO_2-eq per m^3 of wastewater treated depending upon the credit of the product displaced by the algal biomass.

Keywords: waste-to-profit; wastewater treatment; anaerobic digestor effluent; nutrient recovery

Citation: Chaudry, S.; Alavianghavanini, A.; Darvehei, P.; Moheimani, N.R.; Bahri, P.A. Feasibility of Nutrient Removal and Recovery from Abattoir Wastewater Using Microalgae. *Energies* **2024**, *17*, 308. https://doi.org/10.3390/en17020308

Academic Editor: Frede Blaabjerg

Received: 13 December 2023
Revised: 4 January 2024
Accepted: 5 January 2024
Published: 8 January 2024

1. Introduction

Meat-processing facilities are the largest consumer of freshwater in the food and beverages industry and produce a large volume of wastewater through processing of animals, meat processing, and cleaning [1,2]. Water consumption in abattoirs can range between 3–5 m^3 per tonne of hot standard carcass weight (HSCW) in small domestic facilities, and 10–11 m^3 per tonne of carcass weight in large integrated export facilities [3]. The wastewater from the animal-processing industry can be a potential source of energy and nutrient recovery if suitable technologies are employed for wastewater treatment [4,5]. Anaerobic digestion (AD) is the most common method used for the removal of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of wastewater and can be a source of energy recovery if methane is captured. The collected organic waste streams from a red-meat-processing facility are rich in organic material and nutrients are normally introduced to an AD lagoon to convert the carbon content to biogas with a possible volumetric ratio of 63% methane and 37% carbon dioxide [6].

However, the effluent from anaerobic digestion is still rich in nutrients such as nitrogen and phosphorus which are normally discharged to the environment after some aeration process and dilution with water [7–9]. The average concentration of total nitrogen and phosphorus in red-meat-processing facilities can reach 427 mg/L and 50 mg/L, respectively [10]. Microalgae have been known to mitigate CO_2 as well as efficiently assimilate nutrients from AD wastewater [4,11–13]. Moreover, they produce various organic compounds such as proteins, carbohydrates, and lipids which can be used to produce animal-feed products [14,15]. Protein-rich algae provide a sustainable alternative to conventional protein sources (e.g., soy, whey, and fish proteins) not only for animal feed, but they can also replace conventional egg, dairy, and grain proteins in human food [16,17]. Furthermore, microalgae are also rich source of omega-3 fatty acids and essential amino acids such as lysine (the most limiting amino acid in plant-based feed) for the growth of animals and aquaculture [18,19]. Use of microalgae can reduce or eliminate the requirement for synthetic lysine in the animal and aquaculture feed production industries. There are concerns regarding the direct use of microalgae grown in wastewater for human consumption. However, their applicability as animal and fish feed is showing some promising results [9,15,20].

The greenhouse gas (GHG) emissions from Australian red-meat-processing facilities have been reduced to 69 million tonnes CO_2-eq per year (13 wt% of total carbon emission across Australia) which were improved by manure and red-meat-processing organic waste management policies using anaerobic digestion and composting. [21]. Natural gas consumption can be reduced by 25% using AD operations in red-meat-processing facilities [22]. The carbon footprint of the red-meat-processing industry using a microalgae production process could be reduced more, since 1.8 kg CO_2 is required to cultivate 1 kg microalgae [23]. Moreover, using microalgae for treating anaerobically digested effluent has demonstrated the capability to fix 34 and 26 wt% of total nitrogen and phosphorus, respectively, into the biomass in long-term cultivation [24].

As a result, integrating microalgae cultivation with agricultural wastewater treatment processes can effectively tackle the sustainability and environmental-related issues associated with current wastewater treatment methods, while at the same time it can provide added incentive for generating profit from waste [25]. Many microalgal species have been successfully grown on different types of wastewater such as municipal wastewater [26–28], industrial wastewater [29], and piggeries effluent [30–32] with wide variations in nutrient concentrations [33]. However, to the best of our knowledge, no study has been conducted to assess the potential of microalgae cultivation on the effluent of meat-processing industries. This study targeted to analyze the potential of microalgae cultivation on wastewater to serve two purposes: (1) treating the wastewater by assimilating nitrogen and phosphorus, and (2) converting the waste into products to make a revenue. The data from an existing wastewater process at a local medium-to-large meat-processing facility were collected, and the process and economic models were developed to estimate the potential of the nutrient recovery form the abattoir's wastewater.

2. Materials and Methods

To treat the wastewater with microalgae, some pre-treatment is required. This pre-treatment aims to make the wastewater suitable for microalgae cultivation by addressing issues such as turbidity, nutrient concentration, and chemical and biological oxygen demand. [15]. Anaerobically digested abattoir effluent (ADAE) is suitable for treating abattoir wastewater due to its higher concentration of nutrients and lower levels of BOD and COD. A local abattoir's routine monitoring data for 5 years were analyzed to confirm this hypothesis. The effluent from anaerobic digestion (1000 m^3/day) was rich in nitrogen (200–210 mg N-NH_3^+./L) and phosphorus (23–26 mg P-PO_4^{3-}/L), essential for the growth of microalgae [23]. Local *Scenedesmus* sp. and *Chlorella* sp. showed the capability of growing under outdoor conditions in Western Australia through paddle-driven raceway ponds and to reach the maximum productivity of 19.24 g/m^2/day at the pH level of 6.5 [23,24]. The nitrogen to phosphorus mass ratio of ADAE wastewater was very close to that of algal biomass (7.1:1) according to the Redfield ratio ($C_{106}H_{171}O_{42}N_{16}P\ S_{0.3}\ Mg_{0.05}$) [34], and due to slightly smaller N/P ratio of ADAE than Redfield ratio, nitrogen was identified as the limiting component for the growth of microalgae. However, it was still in the range of the optimum nitrogen to phosphorus ratio (5–30:1) for microalgae growth in wastewater [26].

The objective of microalgae cultivation was to maximize nutrient removal from the wastewater, enabling water recycling for non-potable use without additional treatment. Two main scenarios were analyzed: (1) a wastewater treatment focus, where algal biomass was considered a by-product, and (2) a biomass production focus. For the wastewater treatment focus, the algal biomass was considered as the by-product of the wastewater treatment process. After algae cultivation and harvesting (primary dewatering), no further treatment of biomass was considered onsite. The harvested algae culture (enriched with algal proteins) was assumed to be supplied as protein-rich cattle drinking water, replacing the conventional protein meal for the co-existing animal farm to generate the credit for the process. For the biomass production focus scenario, the algae biomass was considered as the main product of the process. After harvesting, further concentration and drying of the biomass was considered onsite. The treated wastewater was considered as the by-product of the biomass production process to generate the credit for the process. No wastewater treatment credit was assumed. SuperPro-V10 was used for the process and economic modelling. Excel spreadsheet models were developed to assist with the data generation for the models in SuperPro Designer® licensed to Murdoch University.

2.1. Process Description

For the wastewater treatment scenario, the system boundary includes cultivation of microalgae using ADAE as the nutrient media for harvesting of algal biomass. The biomass production scenario includes secondary dewatering and drying of biomass, too. The process flow diagrams for both scenarios of wastewater treatment (WWT) and biomass production (BP) are shown in Figure 1.

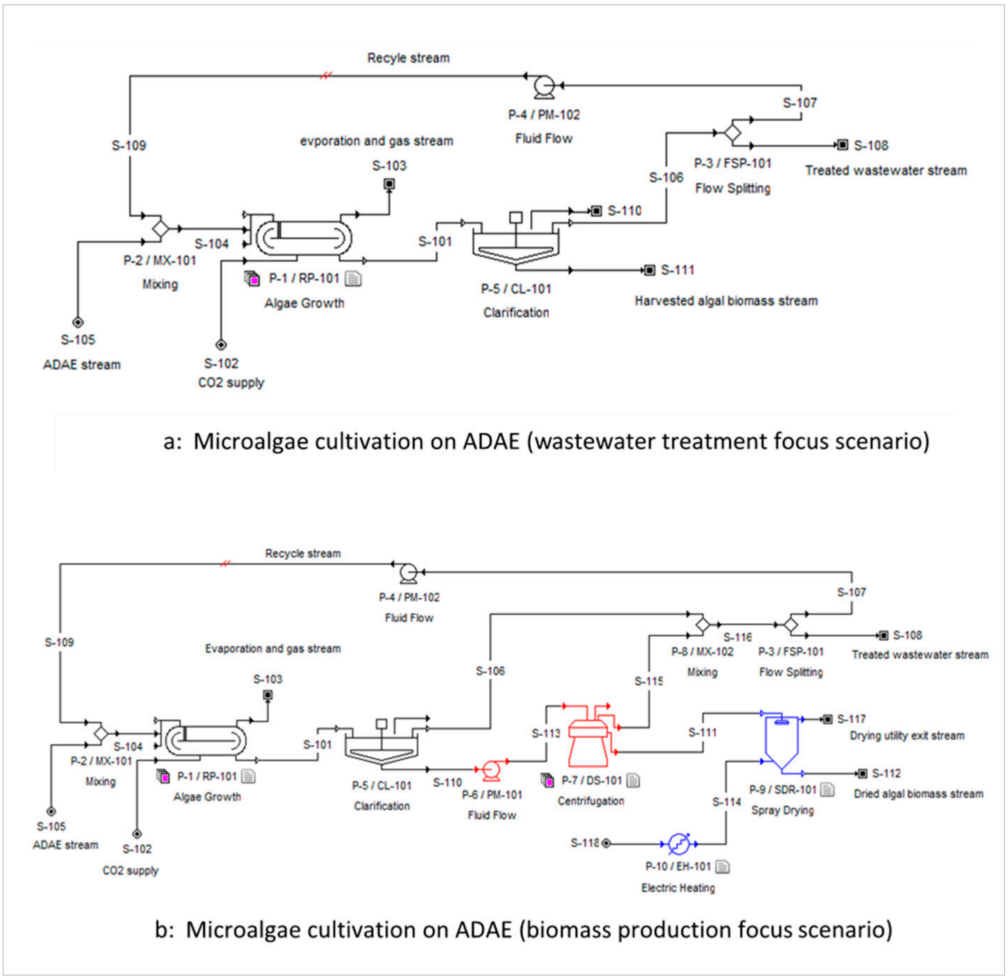

Figure 1. Process flowsheet for microalgae cultivation on anaerobically digested abattoir effluent (ADAE) for (**a**) the wastewater treatment (WWT) focus scenario, and (**b**) the biomass production (BP) focus scenario.

The ADAE flowrate was assumed to be 1000 m^3/day with total nitrogen and total phosphorus concentration of 220 mg/L and 28 mg/L, respectively (estimated from the local abattoir's data). For the cultivation of microalgae, various technologies are used. Paddle-wheel raceway ponds are considered most economical for algae cultivation [35]. Hydraulic retention time of 7.5 days and culture concentration of 0.5 g/L (equivalent to productivity of 20 g/m^2/day) were assumed for the operation paddle-wheel raceway ponds. The algae growth, disregarding S and Mg, was modelled as the stoichiometric reaction as shown in Equation (1) [36].

$$6\,NH_3 + 106\,CO_2 + 61\,H_2O + HPO_4^- \rightarrow C_{106}H_{171}O_{42}N_{16}P + 117.5\,O_2 \quad (1)$$

After cultivation in raceway ponds, the microalgae were harvested and dewatered in settling tanks to achieve a solid concentration of 15 g/L with detention time of 6 h in 3 m deep settling tanks [37]. For the biomass production focus scenario, further concentration was considered to be achieved via a secondary dewatering step with spiral plate technology (Evodos centrifuge) which is suitable for small-scale operations as in this case [38]. The concentration achieved via secondary dewatering was assumed to be 300 g/L (personal communication). Spray drying was considered as the final step for drying of biomass to achieve the water contents of the final product less than 5% in the biomass production focus scenario.

Nitrogen, usually, is the limiting nutrient for microalgae cultivation in wastewater and mainly present in the form of ammonia and hence is the most influencing parameter for microalgae cultivation on wastewater [39]. Effluent nitrogen is removed in raceway ponds by (1) biomass, and (2) ammonia stripping [40] which will be discussed in more detail.

The take-up of the nutrients by the algal biomass is determined by the nitrogen and phosphorus content of the algal biomass. Nutrient concentration in microalgae biomass varies significantly from 0.03 to 3% of dry mass for P and between 3–12% of dry mass for N. Studies have shown that algal species adjust their cellular N/P ratio with the external N/P ratio of culture media [11]. The microalgal species that can assimilate higher nitrogen contents are suitable candidates for nutrient recovery from the wastewater. As the N/P ratio of the ADAE was very close to the Redfield ratio, hence, it was assumed as the biomass composition of the microalgae in this study. The rate of uptake of nutrients depends upon the hydraulic retention time of the reactor which is dependent on the productivity of algal biomass and the maximum viable culture concentration in the ponds. The ammonia concentration of the influent stream also indirectly affects the rate of nitrogen uptake as high ammonia concentration (>300 mg/L) can inhibit the growth of microalgae increasing the required hydraulic retention time [26]. Further, the maximum nutrient removal from the wastewater in raceway ponds is dependent on the maximum viable culture concentration in the ponds. With microalgal biomass concentration of 0.5 g/L in a raceway pond and 6 wt% nitrogen contents of biomass (based on the Redfield ratio), only 31.5 mg of nitrogen is fixed in biomass per L of effluent culture stream. Considering 200 mg/L as the average nitrogen concentration of ADAE, only a fraction would be fixed in biomass in a single pass. If the nitrogen fixation in biomass is the main objective of the process, as in the case of wastewater treatment systems, either a microalgae cultivation system able to produce higher culture concentrations such as a closed photobioreactor, or multiple paddle-wheel-driven raceway ponds in series or multiple passes of the wastewater through the ponds by introducing a recycle stream would be required to enhance the removal efficiency on the expense of high capital cost. In this study, 80% of the effluent wastewater at the downstream of microalgae harvesting/dewatering was assumed to be recycled back to the raceway ponds. The effect of this recycle ratio on the quality of treated water, total mass of algae biomass produced, and ammonia volatilization in treating ponds will be further discussed.

Ammonia nitrogen in the wastewater exists in equilibrium between the molecular ammonia and ammonium ions as shown in Equation (2).

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \quad (2)$$

The distribution between molecular ammonia and ammonium ions is dependent upon the pH and the temperature. An increase in pH shifts the equilibrium towards the left causing the formation of gaseous ammonia [41]. An increase in pH of the culture through algal photosynthesis increases ammonia stripping and phosphate precipitation resulting in indirect nutrient removal [42]. Higher temperatures on summer days also increase the ammonia stripping from raceway ponds. Furthermore, the mass transfer rate of ammonia increases via CO_2 aeration similar to the conventional ammonia stripping process [41]. Garcia et al. (2000) observed that ammonia stripping has a higher efficiency of nitrogen removal (up to 47%) than fixing in algal biomass in high-rate algal ponds and is mainly dependent on the pH and the hydraulic retention time. However, they did not study the effect of controlling pH by CO_2 aeration in ponds [40]. The pH for the raceway pond could be regulated at 6.5 using CO_2 to reduce nitrogen evaporation, ultimately reaching a final value of 13.7 wt% from input total flows [23,24]. However, increasing the pH to 8.5 might result in 37 wt% nitrogen stripping, and at uncontrolled pH conditions almost 59 wt% of the nitrogen would be directly evaporated to the atmosphere which would lead to a decrease in efficiency of nitrogen assimilation and microalgae production [23].

2.2. Economic Evaluation

The capital and operating cost was estimated by the usual module costing technique. The cost factors associated with the new facility such as buildings and auxiliary facilities (site development, electrical facilities, etc.) are required for a new facility only and are not suitable for the expansion or modification in an existing facility [43]. As algae cultivation is considered to be integrated into the existing wastewater treatment facility of the abattoir, hence, the new facility cost factors were assumed to be zero in this study. For estimation of labor, 0.25 labor-hr/operation hr was assumed for each operation (cultivation, sedimentation, centrifugation, and spray drying). Due to the existing facility, no administration and supervisory labor, insurance, local taxes, and factory overheads were considered. The standard power supply was assumed to be available at $0.1/kWh for the operation and 10% line losses were assumed. Depreciation was calculated via a straight-line method for a period of 15 years. Twenty years and 300 days/year were assumed as the project life and the working days, respectively. No raw material cost was associated with the microalgae cultivation as the nutrients and water were supplied from the wastewater. CO_2 was assumed to be available onsite from the combustion of CH_4 produced by anaerobic digestion, and no extra CO_2 supply cost was assumed.

As mentioned earlier in the text, the microalgae grown on wastewater can be used as animal and fish feeds. For the wastewater treatment scenario, it was assumed that the algal biomass slurry produced can be used to replace the soybean meal (SBM) for the co-existing animal farm to generate credit for the process at $0.35/kg SBM (http://www.indexmundi.com/commodities/, accessed on 1 December 2022). For the biomass production focus scenario, it was assumed that treated wastewater can be recycled onsite to generate credit for the process (as class B recycle water at $0.84/m^3 of recycle water, https://urbanutilities.com.au/business/business-services/recycled-water, accessed on 1 December 2022).

2.3. Environmental Assessment

The direct GHG emissions of the meat-processing industry are around 432 kg $CO_{2\text{-eq}}$/t HSCW (onsite emissions and emissions associated with electricity) [44]. By using microalgae for wastewater treatment, the meat-processing industry can reduce its GHG emissions. The net GHG emissions were calculated as follows as shown in Equation (3) [45].

$$\text{Net emissions} = \text{total emissions} - \text{onsite } CO_2 \text{mitigation credit} - \text{displaced product credit} \quad (3)$$

The emissions of wastewater treatment using microalgae are mainly associated with electricity consumption, taken as 0.48 kg $CO_{2\text{-eq}}$/kWh of electricity (GREET). The credit of GHG emission savings arise from onsite CO_2 fixation by microalgae and displaced product credit by microalgae. The onsite CO_2 mitigation credit was calculated by stoichiometry defined in Equation (1). For the displaced product credit, the credits associated with the soybean meal for the wastewater treatment scenario and the fishmeal for the biomass production scenario were assumed to be 0.62 kg CO_2/kg SBM and 3.42 kg CO_2/kg fishmeal, respectively [46].

3. Results and Discussion

3.1. Nutrient Removal and Biomass Production

As mentioned earlier in the text, nutrient removal by microalgae and nutrient concentration in the treated wastewater for the fixed algal biomass composition depend upon the hydraulic retention time (HRT) of paddle-wheel-driven raceway ponds and the recycle ratio. For a fixed HRT (7.5 days), the nutrient concentration of the treated wastewater vs. recycle ratio for both scenarios is shown in Figure 2. The minimum nutrient concentration (TN < 1 mg/L) is achieved at 80% recycle ratio for the biomass production focus scenario and 82% for the wastewater treatment scenario with maximum biomass production (around 2 kg/m^3 wastewater) (see Figures 2 and 3). For further analysis, these recycle ratios were assumed for the base case designs of both scenarios to achieve the maximum removal of the limiting component (TN < 1 mg/L). This also brings the total phosphorus low enough (TP < 12 mg/L) to enable the recycling of the treated water for irrigation of gardens and green areas, and crops and pasture for fodder production or other onsite non-potable uses such as cleaning of yards, infrastructures, and trucks, washing of animals, animal drinking water, and fire control without any further treatment [47].

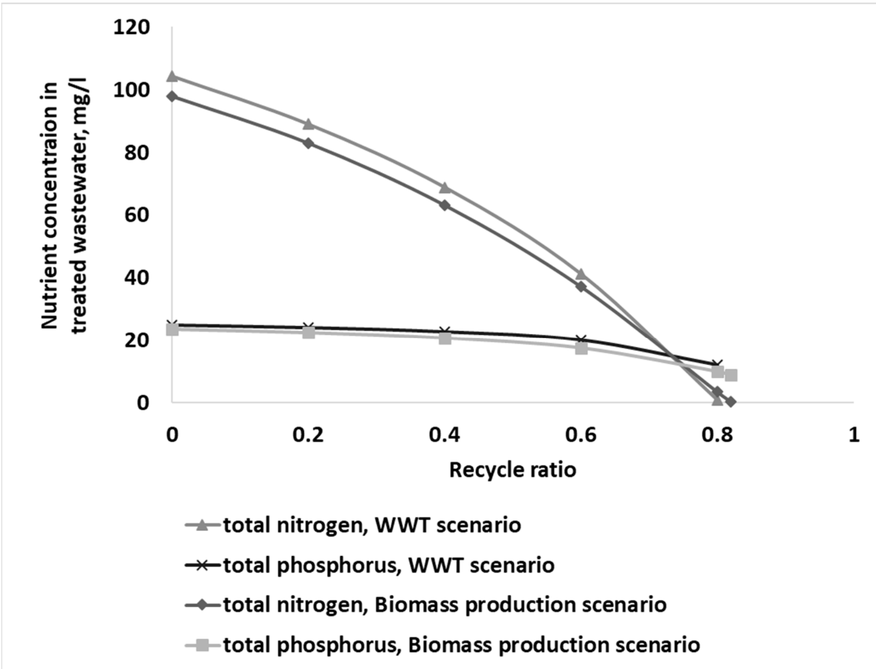

Figure 2. Nutrient concentration in wastewater treated with microalgae for base case concentration (0.5 g/L) and HRT (7.5 days). WWT: wastewater treatment.

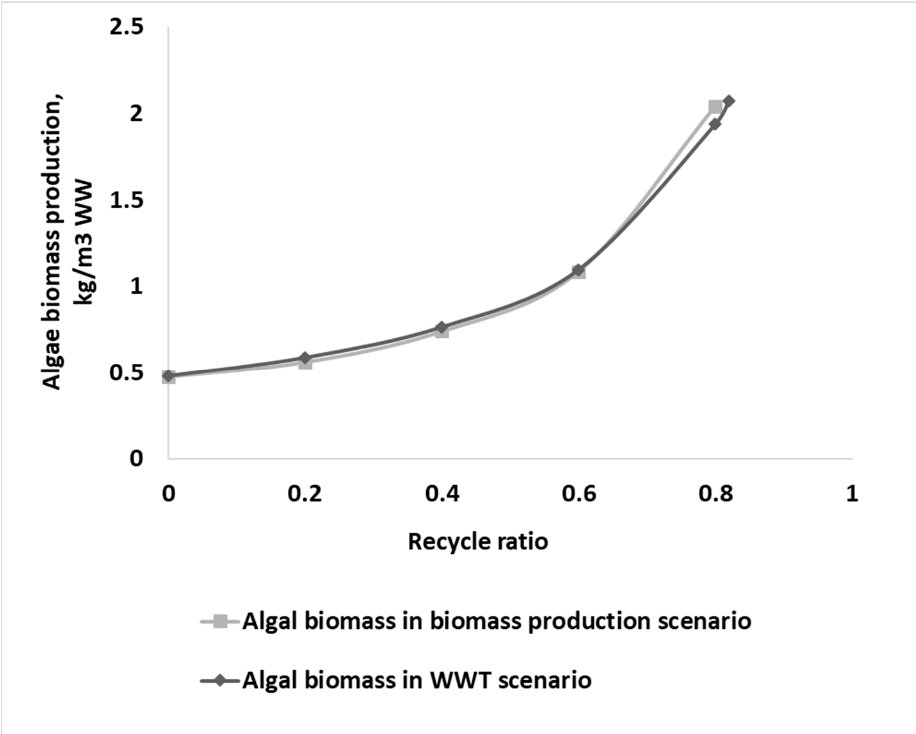

Figure 3. Algae biomass production vs. the recycle ratio considering two scenarios of wastewater treatment (WWT) and biomass production (BP). WW: wastewater.

3.2. Economics

The capital and operating cost and the by-product credits for the base cases of the both scenarios are given in Table 1.

Table 1. Base case economics for algae cultivation on ADAE 1000 m^3/day.

Parameter	Wastewater Treatment (WWT) Focus	Biomass Production (BP) Focus
Paddle-wheel-driven raceway pond area, hectare (ha) *	10	11
Capital cost, million $	1.58	4.64
Operating cost, million $/year	0.27	0.85
By product credit	-	-
Algae biomass credit (as soybean meal) for WWT focus scenario, million $/year	0.21	-
Recycle water credit (class B) for biomass production focus scenario, million $/year	-	0.22
Net operating cost after by-product credit, million $/year	0.06	0.63
Wastewater treatment cost, $/$m^3$ of treated wastewater	0.2	
Biomass production cost, $/kg of algal biomass	-	1.03

* Based on an average biomass productivity of 20 g/m^2/day.

For the WWT focus scenario, it was assumed that the algae culture is supplied as the cattle drinking water for onsite or nearby farms. An average daily drinking water consumption for beef cattle is 45 L/head/day and can go up to 60 L/head depending upon the climate [48]. Considering a daily average supplement intake by cattle at 3.5 mg/kg animal weight (250 kg/head weight), the average intake of algae supplement is 875 g of algae/day/head instead of using soybean meal or cottonseed meal as a protein supplement for animal feed [49]. Cattle can drink up to 58 L of harvested algae culture daily with a concentration of 15 g/L. The wastewater treatment scenario (base case) generated 143 m^3/day of algae culture, enough to fulfil the water and 70% of the protein requirement for about 3170 cattle. The credit considered for protein-rich drinking water was based on the dry weight of algae meal replacing the soybean meal, and no credit was assumed for animal drinking water. For the base case scenario, the cost of wastewater treatment is \$0.92/m^3 while the credit generated by the algal culture (replacing the soybean meal) is \$0.72/m^3 reducing the WWT cost to \$0.2/m^3 WW. Assuming the treated water can be used as class B recycle water (\$0.84/m^3 of recycle water, https://futurebeef.com.au/knowledge-centre/water-requirements/) generates further revenue for the treatment process. The total revenue generated by the treated WW and the algal biomass is \$1.34/m^3. This leads to a potential revenue generation of \$0.42/m^3 wastewater (before applying any discount rate), meaning nutrient removal by microalgae is not only economically self-sufficient but adds value by turning the wastewater treatment into a profit-making process. Comparing to the conventional nutrient removal process, the nitrogen removal cost by microalgae cultivation before any credit (\$4.2/kg N removed) is similar to the conventional nitrification and denitrification processes (between \$3.3–5.5/kg N removed [49]). Considering the credit of biomass, the nitrogen removal cost by microalgae cost reduces to \$ 0.92/kg N removed.

It should be noted that the value of algae can be different than that considered here depending upon the nutritional value of the microalgal specie and its digestibility. For example, Barone et al. have estimated the price of *Chlorella* meal as the replacement of fishmeal and soybean meal as \$2.65/kg and \$0.66/kg, respectively, based on the digestibility of proteins [48]. Furthermore, as mentioned earlier, algal biomass can not only replace the protein meal, but it can also reduce the requirement of addition of supplements in the feed. Therefore, the value of algal specie grown on ADAE should be estimated based on its nutritional value and digestibility to estimate the credit of algal biomass more precisely.

For the base case biomass production focus scenario, the cost of production of algal biomass is \$1.39/kg dry weight biomass, which reduces to \$1.03/kg dry weight biomass after adding the by-product credit of the recycled water (based on class B recycled water). The economics of the biomass production scenario depends upon the product and product quality and the potential market. It should be noted here that no wastewater treatment credit was considered in the biomass production focus scenario. However, wastewater treatment for nutrient removal from ADAE is inevitable, and credit can be claimed for replacing it with the biomass production process, further reducing the cost of biomass production. The cost breakdown results in the literature also indicate that the cost of raw materials (carbon source, nutrients, and fresh water) and the required wastewater treatment facility after raceway pond cultivation to remove the excess nutrients would be responsible for 36% of total microalgae production cost [49]. As a result, the advantages of using free-of-charge nutrients, water, and carbon dioxide could result in very low cost of microalgae production.

The breakdown of the operating costs of the two scenarios are shown in Figure 4. The cost of labor and depreciation are the major costs of both scenarios. The biomass production focus scenario has high cost associated with the electricity consumption of dewatering and drying of algal biomass. The drying cost can be reduced or avoided if solar drying or no drying are considered. Dried microalgae supplements are supplied to aquaculture after mixing with water (10% algae content). Both animal and aquaculture microalga feed supplied in the form of paste/slurry have better digestibility than dried algae powder [50]. Drying or freezing is only necessary for the extended shelf-life of biomass. In the case of co-existing aquaculture, the dewatered algae can be directly sent to it and extended shelf life is not required, which omits the freezing/drying step of the process. Shelf life can also be extended by the addition of feed-grade preservatives such as glycerine [50]. On the other hand, in case of extraction of other valuable products from algal biomass, the downstream process can be different and result in different economics. The section-wise production cost for the algal biomass scenario is given in Table 2. The cost associated with secondary dewatering and drying is almost two-third of the total cost. The energy requirements of both scenarios are also shown in Figure 5.

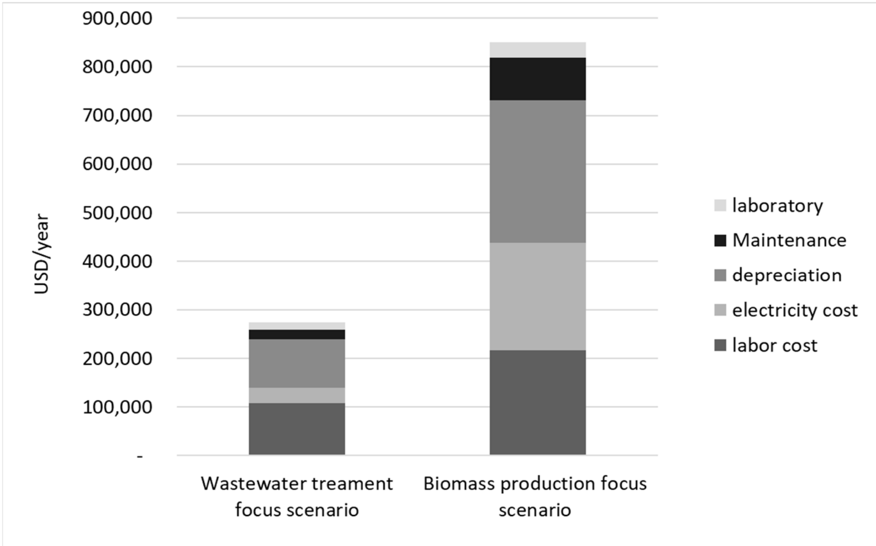

Figure 4. Breakdown of operating cost into major components in both scenarios.

Table 2. Section-wise cost of production for the biomass production focus scenario.

Section	Cultivation and Harvesting	Secondary Dewatering	Drying
Cost, $/kg biomass	0.46	0.48	0.45

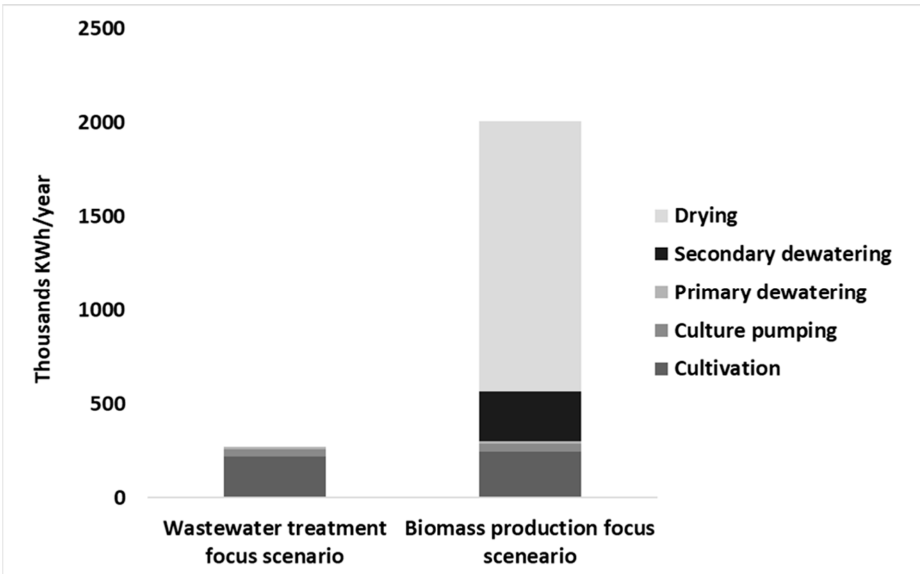

Figure 5. The energy requirement of the two scenarios.

The sensitivity analysis to observe the effect of different assumptions on the economics of both scenarios are presented in Figures 6 and 7. For sensitivity analysis, the recycle ratio was adjusted to achieve the maximum removal of the limiting component (TN < 1 mg/L) for both scenarios. The results of sensitivity analysis show that the wastewater flowrate is the most influencing parameter for both scenarios. This is the main reason why the production cost of 1 kg microalgae in this research reached 1.39 AU$ at the scale of 1000 m^3/day (11 ha raceway pond facility) in case of using agricultural effluent for cultivation. Techno-economic results from literature studies also indicate that at a smaller scale of production (5 ha raceway pond facilities) the production cost of 1 kg microalgae using agricultural wastewater could be as high as 2.6–3.6 € (4.3–6 AU $) [51]. If the biomass by-product has 50% higher value than considered in this study, which is likely as mentioned earlier, the process would be profitable even without the credit of recycle water. For the biomass production focus scenario, the capex of centrifuge, labor cost, and recycle water credit play a significant role in determining the economics.

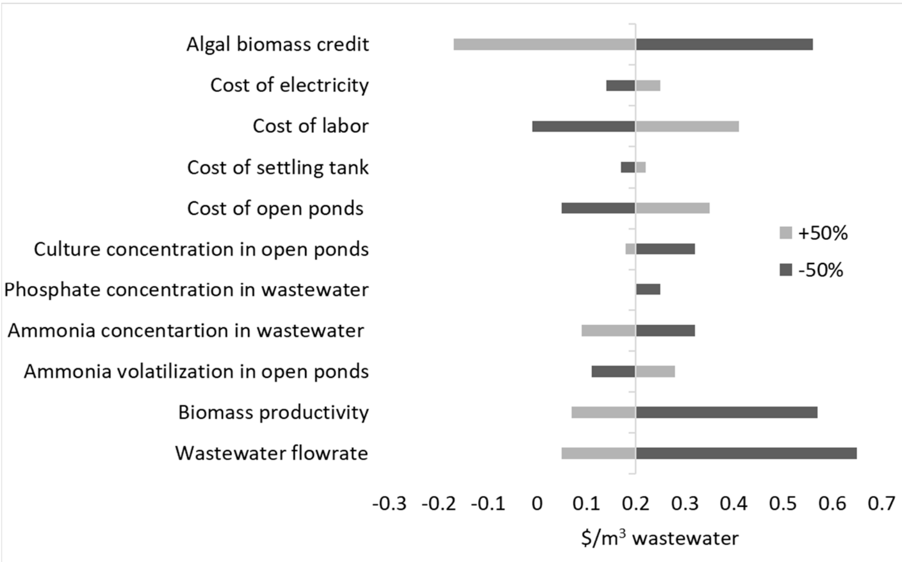

Figure 6. Sensitivity analysis of wastewater treatment cost for the wastewater treatment scenario without any credit for reuse of treated water.

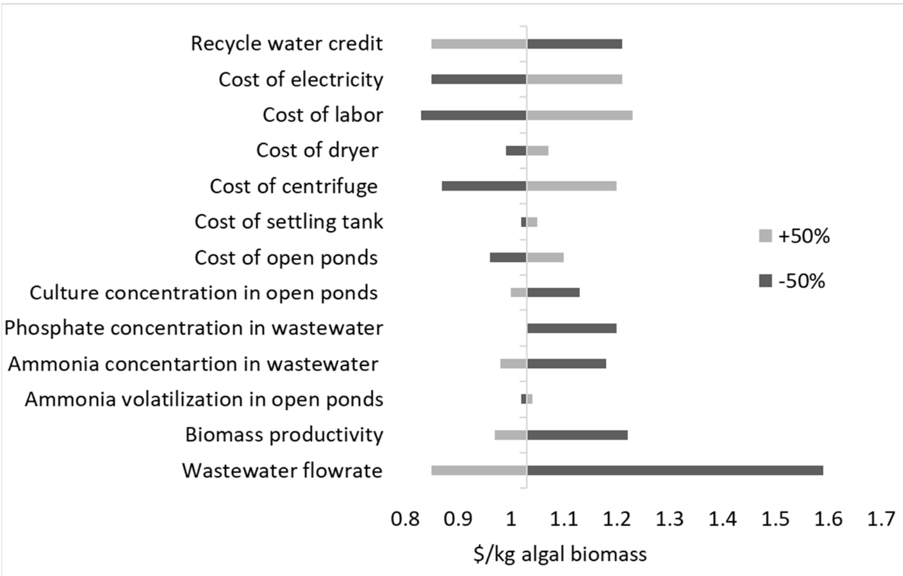

Figure 7. Sensitivity analysis of algal biomass production cost in the biomass production focus scenario.

3.3. Feasiblity Analysis

Net Present Value (NPV) as one of the key economic indicators was calculated for both scenarios using a discount rate of 14% considering the worst-case scenario which is twice as much as the maximum discount rate in the agricultural industry (7%) [52]. The biomass production scenario is the more costly option compared to wastewater treatment, in terms of both capital and operating costs. However, the biomass production scenario generates approximately five times as much revenue compared to wastewater treatment. Hence, using NPV allows a better comparison between the scenarios as it takes into account the revenue as well as the operating and capital costs. The estimated NPV for both scenarios were below zero (−$1.25 million and −$1.70 million for WWT and BP) which means neither of the scenarios can generate high profit. To reach a positive NPV, the produced biomass must achieve a minimum selling price of $2.26/kg. Alternatively, a better NPV can be achieved by optimizing other process conditions.

3.3.1. Impact of Ammonia Loss on Profitability

In both scenarios, it was assumed that 40% of the ammonia in the culture is lost to the atmosphere, which results in lower amounts of ammonia for the microalgal cells to absorb. But if the volatilization is controlled (for instance, by controlling pH level), it can increase the productivity and hence the economics of the plant. On the other hand, if the ammonia is not absorbed by the culture, it leads to higher ammonia in the treated water (i.e., lower quality of treated water). To ensure the quality of the treated water remains at an acceptable level, the recycling ratio can be manipulated to achieve a minimal amount of ammonia in the output. Figure 8 shows the relationship between volatilization and required recycle rate for both scenarios.

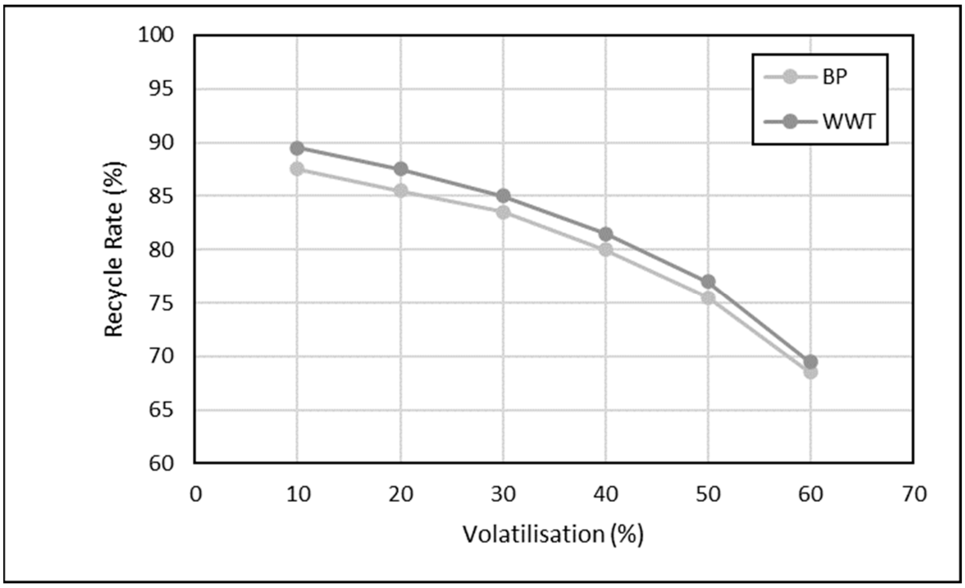

Figure 8. Required recycle rate for different volatilization rates considering two scenarios of wastewater treatment (WWT) and biomass production (BP).

Having a higher recycle rate means the equipment needs to be designed to handle higher volumes, which itself can increase the costs of the plant. Figure 9 shows how different volatilization values (under optimum recycle rate) would impact NPV.

Lowering the volatilization down to 20% significantly improves the economics of both scenarios. Any further decrease in volatilization results in a lower NPV due to the increased size of the equipment. Despite an improvement in NPV, none of the scenarios managed to reach a positive NPV.

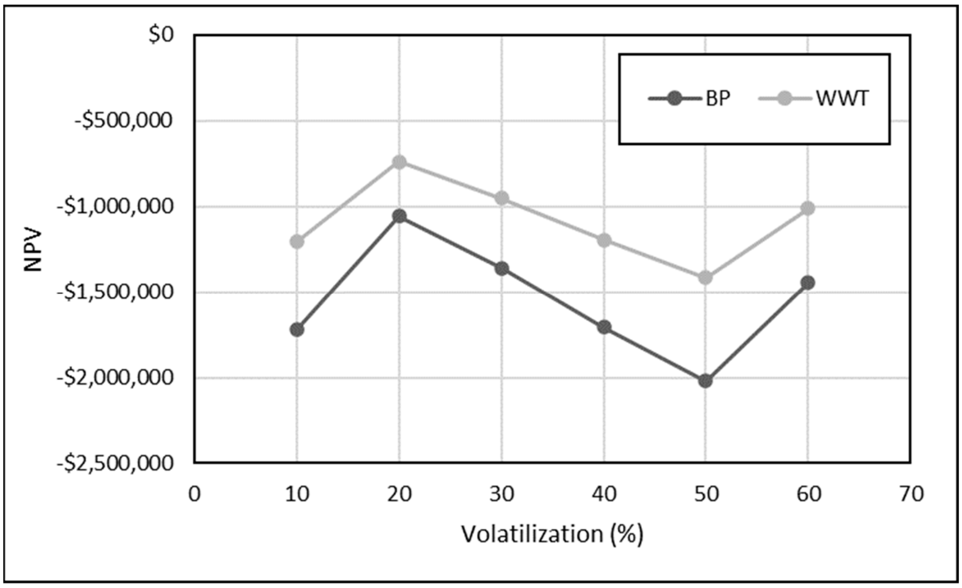

Figure 9. The relationship between volatilization and net present value (NPV) considering two scenarios of wastewater treatment (WWT) and biomass production (BP).

3.3.2. Impact of Wastewater Flowrate on Profitability

Another way to improve the economics of the plants is by optimizing the size of the plant, i.e., changing the flowrate of wastewater it is designed to process. For this purpose, the sizes of the equipment were re-evaluated for different ADAE flowrates from 500 m^3/day to 10,000 m^3/day. Figure 10 presents NPV for both scenarios against different ADAE flowrates.

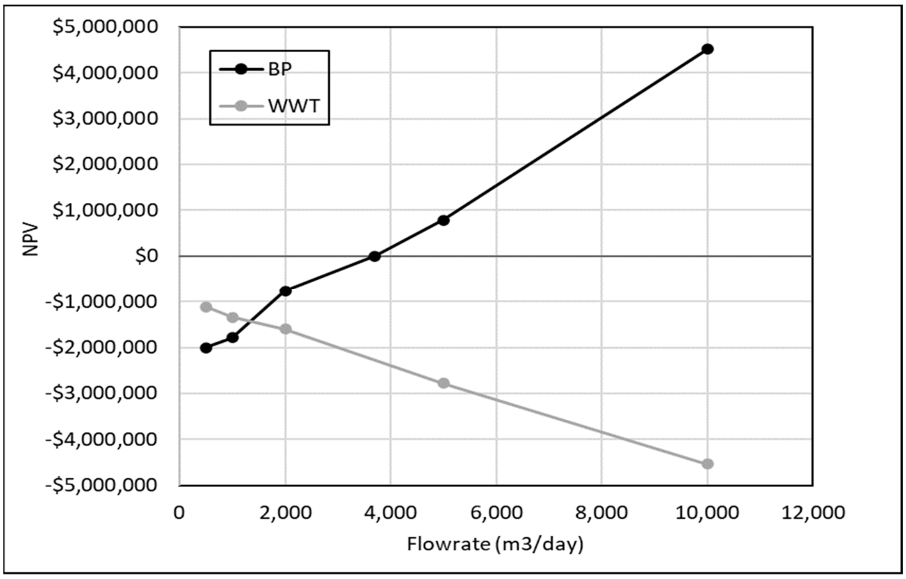

Figure 10. Impact of flowrate on net present value (NPV) considering two scenarios of wastewater treatment (WWT) and biomass production (BP).

In case of the WWT scenario, increasing the input flowrate had a negative effect on NPV to the point that at 10,000 m^3/day, NPV fell to −$4.5 million. On the other hand, the BP scenario significantly benefitted from higher flowrates. NPV consistently improved by increasing ADAE flowrate, and at flowrates above 3700 m^3/day it produced a positive NPV, showing its high profitability. While increasing the flowrate improved the NPV in the BP scenario, it must also be noted that higher flowrate also resulted in higher capital and operating costs. Changing the flowrate from 1000 to 10,000 m^3/day can increase the capital cost for this scenario from $4.3 million to just over $30 million.

3.4. GHG Emission

In the wastewater treatment focus scenario, microalgae assimilate more CO_2 than the indirect emissions associated with the electricity consumption and save (-ve GHG emissions) 2.18 kg CO_2-eq and 3.46 kg CO_2-eq per m^3 of wastewater with and without soybean meal replacement credit (see Figure 11). The biomass production focus scenario has higher indirect emissions associated with electricity consumption than it assimilates onsite by microalgae cultivation, resulting in positive GHG emissions of 0.87 kg CO_2-eq/m^3 wastewater before any credit. However, if dried algal biomass is considered to replace the fishmeal, the credit for fishmeal replacement is higher making it more environmentally friendly with savings of 6.11 kg CO_2-eq of emissions per m^3 of wastewater (see Figure 11). It is worth noting here that methane generated in anaerobic digestion onsite can be used to produce heat and power onsite avoiding emissions associated with purchased electricity. Furthermore, it should also be noted that no wastewater treatment credit was added in calculating GHG emissions. However, the conventional wastewater treatment process will also cause significant GHG emissions, such as related to aeration and sludge disposal [53], which are avoided in the case of algae cultivation and can be considered in GHG calculations. The GHG emission savings of a microalgae-based wastewater treatment process is in contrast to the conventional nutrient-removal processes which generate CO_2 emissions such as anaerobic/anoxic/oxic process and sequencing batch reactor process which generate 1.5 kg CO_2/m^3 wastewater and 0.44 kg CO_2/m^3 wastewater treated, respectively [54]. A complete lifecycle analysis should be performed for a microalgae-based abattoir wastewater treatment process considering climate change, eutrophication potential, and source depletion to identify the true environmental benefits/impacts associated. Furthermore, as microalgal biomass can produce various high-value products, a wastewater treatment process focusing on the production of high-value products should also be analyzed.

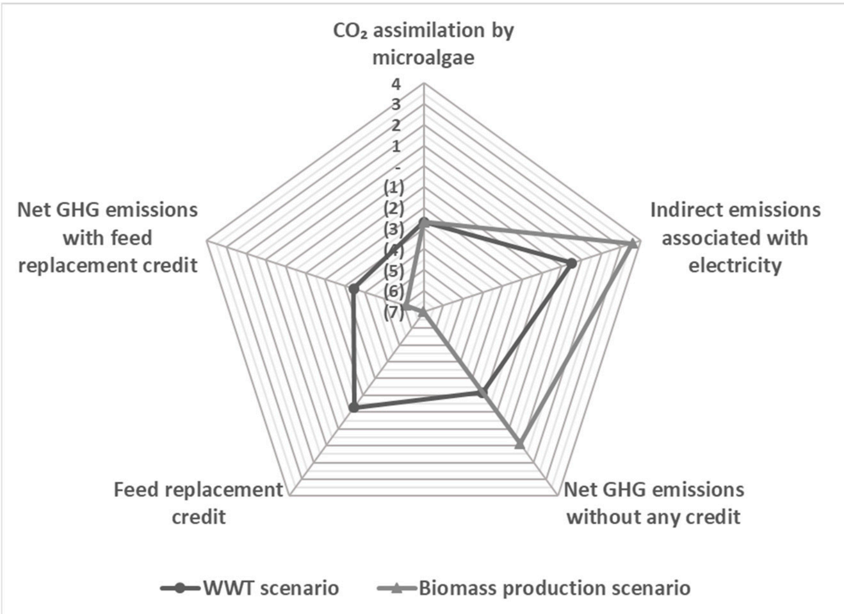

Figure 11. Greenhouse gas (GHG) emissions kg CO_2-eq/m^3 of wastewater treatment considering two scenarios of wastewater treatment (WWT) and biomass production (BP) (+values indicate the emissions and −values indicate the savings).

4. Conclusions

The treatment of wastewater for the removal of nutrients using microalgae is either profit generating (when class B recycle water is produced) or low cost and sustainable as it recovers the nutrients, unlike nutrient-removal technologies that change the form of the nitrogen to release it into the atmosphere. Treatment using microalgae mitigates GHG emissions, reduces the eutrophication potential and can claim environmental benefit credits. However, such algae cultivation is most suitable for larger meat-processing facilities as the wastewater flowrate has a significant impact on the cost of treatment/production. The value of the biomass generated plays an important role in determining the economics and the pathway selection. Moreover, algal species of high value suitable to be grown on wastewater should be identified and tested for their uses as agricultural products and animal feed, and their value/price should be estimated. A complete techno-economic and lifecycle analysis should be performed to identify the true potential of a microalgae-based wastewater treatment process.

Author Contributions: S.C.: Conceptualization, Methodology including process design modelling and techno-economic analysis; Validation, Writing—original draft; Writing—review and editing. A.A.: Investigation; Analysis and Discussion; Writing—review and editing. P.D.: Methodology, Validation; Analysis and Discussion; Writing—review and editing. N.R.M.: Conceptualization, Funding acquisition; Investigation; Methodology; Resources; Supervision; Writing—review and editing. P.A.B.: Conceptualization, Funding acquisition; Resources; Supervision; Methodology; Validation; Analysis and Discussion; Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: Wastes to Profits project was supported by Meat and Livestock Australia through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program and partners.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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