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The bioeconomy of microalgal heterotrophic bioreactors applied to agroindustrial wastewater treatment

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ABSTRACT

This paper presents a techno-economic analysis of microalgal heterotrophic bioreactors applied to the treatment of poultry and swine slaughterhouse wastewater. The process is based on a multifunctional bioreactor used to simultaneously convert organic matter (chemical oxygen demand [COD]), nitrogen (N–TKN) and phosphorus ($P–PO_4^{-3}$) into microalgal biomass. The experimental data, obtained from a bench-scale facility, were used to estimate the costs of an industrial scale (16,000 m^3/d). The results indicate removal efficiencies of 97.6%, 85.5% and 92.4% for COD, N–TKN and $P–PO_4^{-3}$, respectively, in parallel to a microalgal sludge productivity of 0.27 kg/m^3/d. The economic analysis demonstrated a cost of USD 2.66/m^3 of treated industrial wastewater, and as consequence of this process, the production cost of microalgal sludge was USD 0.03/kg of dehydrated biomass.

Keywords: Microalgae/cyanobacteria; Industrial effluent; Heterotrophic cultivation; Cost analysis

1. Introduction

Society has been demanding a sustainable industrial development outlined by environmental responsibility, renewable energy use and higher energy efficiency [1]. It is believed that there can be a transformation in the industrial sector with less impact on the environment, and therefore, industries have invested in process intensification, through the development of innovative apparatuses and techniques that offer drastic improvements in manufacturing and processing, substantially decreasing equipment volume, energy consumption, or waste formation, and ultimately leading to cheaper, safer, sustainable technologies [2]. One of the basic components of process intensification is the so-called multifunctional reactors, which are described as reactors combining at least one more function, usually a unit operation [3].

Currently, Brazil has high competence and competitiveness in the production and productivity of poultry and swine meat; it is the third largest producer and the largest exporter of poultry meat and the fourth largest producer and exporter of swine [4]. The industry of poultry and swine slaughterhouses generates a large volume of wastewater with a high pollutant load. It is estimated that this industrial process demands an average water volume of 10 m^3 per ton of final product, leading to a high volume of wastewater to be treated [5].

In the wastewater treatment facilities, although conventional methods can be used, the high energy consumption and the generation of secondary pollution limit the techno-economic feasibility of the main wastewater treatment systems, such as activated sludge, nitrification-denitrification, and phosphorus precipitation.

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In this sense, processes with high efficiency, cost effectiveness, and environmental friendliness should be developed to make the global production chain sustainable [6–9].

Heterotrophic microalgal bioreactors are a potential technology to be applied in industrial wastewater treatment facilities. One characteristic of heterotrophic microalgae metabolism is the simultaneous conversion of pollutants present in wastewater in a single step, thereby reducing capital and operational costs. In addition, substantial amounts of microalgae biomass with a high potential of exploitation as industrial feedstocks are formed, and they are inherent in the process of treatment [10,11].

Phormidium is a genus of single-cell blue green algae, belonging to the phylum cyanobacteria. It is filamentous, unbranched in shape and about 3–4 μm in diameter. Several species live in limiting environments such as thermal springs, desert soils, and polluted sites. These blue green algae show considerable potential for use as biocatalysts in environmental biotechnology processes because of their robustness and simple nutritional requirements [12,13].

The techno-economic studies of the microalgae-based processes have been shown to be economically infeasible scenarios [14–16]. This infeasibility is related mainly to the reduced scalability of the photosynthetic and the high operational costs of the heterotrophic processes. According to Wijffels et al. [17], the technological routes are immature and need to be fully developed, implying the need for a large effort in research and development (R&D). These authors reported that microalgal biotechnology will be competitive and commercially attractive by 2020.

In the analysis and cost estimate for designing a new process, almost all the decisions are impacted by the economic factors, and therefore, it is critical to study process economics. The major criteria to judge feasibility are preliminary design and economic potential estimation to be attained, and knowledge of the price of the final product is necessary for covering the costs involved. The feasibility of these processes has been determined based on the techno-economic analysis of the simultaneous process of wastewater treatment and biomass production, which is conducted based on a relationship of a benefit-cost ratio. Feasibility indicators such as economic equilibrium (EE), profitability, rentability, and period of return on investment are the main parameters in use [18].

In this regard, the aim of this study is to evaluate the techno-economic modeling of microalgal heterotrophic bioreactors when applied to wastewater treatment in poultry and swine slaughterhouses.

2. Material and methods

2.1. Microorganism and culture conditions

The microalgae used was *Phormidium* sp., originally isolated from the Cuatro Cienegas desert (26°59′N, 102°03′W, Mexico) [19]. Stock cultures were propagated and maintained in solidified agar-agar (20 g/L) containing synthetic BG11 medium [20]. The incubation conditions used were 25°C, light intensity of 1,000 lux, and a photoperiod of 12 h. To obtain the inoculums in liquid form, 1 mL of sterile synthetic medium was transferred to slants; the colonies were scraped and then homogenized with the aid of mixer tubes. The entire procedure was performed aseptically.

2.2. Wastewater

The poultry and swine slaughterhouse wastewater used in the experiments was obtained from an industry located in Santa Catarina, Brazil (27°14′02″S, 52°01′40″W). It was collected from the discharge point of an equalization tank over a period of 1 year, and analyzed for pH, chemical oxygen demand (COD), N–TKN, $P–PO_4^{-3}$, TS, SS, VS, and FS following the Standard Methods for the Examination of Water and Wastewater [21]. Table 1 shows the average composition of the wastewater, in a 1 year of sampling. The C/N ratio and N/P ratio were calculated through COD, N–TKN, and $P–PO_4^{-3}$.

2.3. Description of the process

The unit operations of the process were based on a patent application developed by Jacob-Lopes et al. [22]. The core of the process is one heterotrophic microalgal bioreactor that is used to simultaneously convert COD, N–TKN, and $P–PO_4^{-3}$ into microalgal biomass. A primary treatment composed by a fine screen, Parshall flume, rotary sieve, and equalization tank was used. After the biological treatment, the microalgal sludge was processed by a decanter, a belt filter, and a drum dryer. Fig. 1 shows the flow diagram of the process.

The bench-scale bioreactor was made of polyvinyl chloride and had an external diameter of 12.5 cm and a height of 16 cm, resulting in a height/diameter (h/D) ratio equal to 1.28 and a nominal working volume of 2.0 L. The dispersion system of the reactor consisted of a 1.5 cm diameter air diffused device located inside the bioreactor. In addition to the bioreactor, the bench-scale facility is fitted with all the necessary ancillaries to convert the pollutants of the agroindustrial wastewater into dried microalgal biomass.

The operational conditions of the continuous process were previously optimized in order to define a pH adjusted to 7.6, temperature of 20°C, volumetric airflow rate per volume unit of 1 VVM (volume of air per volume of wastewater per minute), absence of light, and a dilution rate of 0.6/d [23]. The loading rates of COD, N–TKN, and $P–PO_4^{-3}$ were 2,460.0 ± 524.4, 77.1 ± 7.2, and 1.7 ± 0.12 mg/L/d, respectively.

Table 1
Average composition of the wastewater

Parameter	Value
pH	5.9 ± 0.05
COD (mg/L)	4,100 ± 874
N–TKN (mg/L)	128.5 ±12.1
$P–PO_4^{-3}$ (mg/L)	2.84 ± 0.2
TS (mg/L)	3.8 ± 2.7
FS (mg/L)	0.9 ± 0.3
VS (mg/L)	2.9 ± 1.4
SS (mg/L)	1.9 ± 0.8
C/N	31.9
N/P	45.2

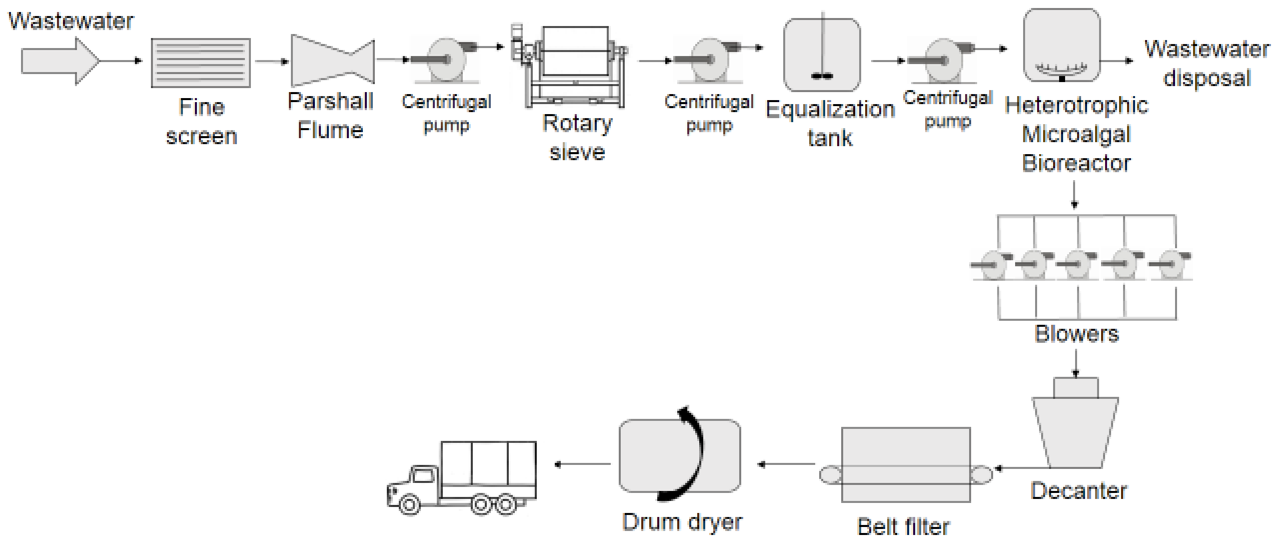

Fig. 1. Process flow diagram of the agroindustrial wastewater treatment.

The steady-state was considered to have been established after at least 3 volume charges, with a variation of cell dry weight less than 5%.

2.4. Sampling and analytical methods

Samples were collected at regular intervals of 24 h and characterized for COD, N–TKN, $P–PO_4^{-3}$, cell biomass, and dissolved oxygen concentration. The COD, N–TKN, and $P–PO_4^{-3}$ were determined according to the methodology previously defined in section 2.2. Cell biomass was gravimetrically evaluated by filtering the wastewater through a 0.45-µm membrane filter (Millex-FG®, Billerica, MA, USA), drying at 60°C until constant weight. The dissolved oxygen concentration in the wastewater was determined by a polarographic oxygen sensor (Mettler-Toledo, Zurich, Switzerland). The analysis was performed in triplicate, and data refer to the average of six repetitions.

2.5. Scale-up and sensitivity analysis of the wastewater treatment process

The theoretical scale-up of the process was performed using the criteria of constant oxygen transfer rate, through the constant volumetric mass transfer coefficient (KL_a) method [24]. The volumetric mass transfer coefficient (KL_a) was estimated by Eq. (1):

$$\ln\left(\frac{C^* - C}{C^* - C_0}\right) = -KL_a\left(t_1 - t_2\right) \tag{1}$$

where C^* is the oxygen concentration in saturation (mg/L); C is the oxygen concentration at time $t = t_i$ (mg/L); C_0 is the critical oxygen concentration (mg/L); KL_a is the volumetric mass transfer coefficient (min^{-1}); and t is the time (min).

The scale-up sought to keep the geometric similarity of the bench-scale bioreactor (Eq. (2)). The constant volumetric oxygen transfer coefficient (KL_a) was determined, and the new operating conditions were found that allegedly reproduce the same conditions on a bench-scale (Eq. (3)) [25]:

$$\frac{d_1}{H_1} = \frac{d_2}{H_2} \tag{2}$$

$$\frac{Q_2}{V_2} = \frac{Q_1}{V_1}\left(\frac{H_1}{H_2}\right)^{2/3} \tag{3}$$

where d_1 is the diameter of the bench-scale reactor (m); d_2 is the diameter of the full-scale reactor (m); H_1 is the height of the bench-scale reactor (m); and H_2 is the height of the full-scale reactor (m); Q_2 is the air flow rate of the full-scale reactor (m^3/min); Q_1 is the air flow rate of the bench-scale reactor (m^3/min); V_1 is the reactor volume at the bench-scale; and V_2 is the reactor volume at the full-scale.

The power density demand was directly obtained by the correlation between the volumetric airflow rate per volume unit used in the bioreactor and the capacity of blowers.

The estimation of the large-scale process was based on an industrial plant operating at a wastewater flow rate of 16,000 m^3/d, working 24 h/d, and 336 d/year.

2.6. Cost analysis methodology

To assess the wastewater treatment cost and the production cost of microalgal sludge in the described facility, the flowchart of the process had to be described in detail, including a list of equipment, its size, and the consumables of the process.

The used methodology to determine the total capital investment (TCI) is shown in Fig. 2 [25]. The TCI was based on estimation of the TCI, which is the sum of the fixed capital investment (FCI) and the working capital (WC). Manufacturing fixed-capital investment represents

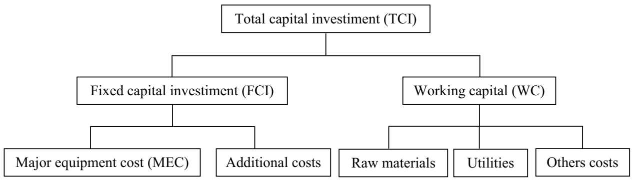

Fig. 2. Representation of the cost methodology.

the capital necessary for the installed process equipment with all auxiliaries that are needed for the complete process operation.

In keeping with standard bioprocess engineering practice, the fixed costs were estimated as factors of the major equipment costs (MEC). The total fixed capital was calculated after MEC determination, using appropriate factors (Lang factors), by multiplying the corresponding factor according to the nature of the item. The estimate cost for each piece of equipment was obtained from a website that estimates engineering the prices in free on board (FOB) in USD [26].

The WC estimated to the proposed industrial plant consisted of the total amount of money invested in raw materials and supplies, utilities, labor costs, and others (supervision, payroll charges, maintenance, operating supplies, general plant overheads, tax, and contingency). A percentage method was employed to calculate the different items. The amount of the raw materials was supplied per unit of product and determined from process material balances according to the direct quotations from market prices whereas the consumption of utilities was estimated from the power consumption of the process, which considered a value of 2% of the plant's capital for an overall utility cost [16,27].

The direct labor costs were calculated by estimating five workers, three shifts a day, working 8 h/d, and earning USD 8.50/h. This value was multiplied by two to include labor charges, totaling the costs.

2.7. Feasibility analysis of process

To determine the techno-economic feasibility of the process, an overall economic analysis was conducted based on a relationship of benefit/cost ratios, represented by feasibility indicators such as EE (EE = total fixed cost/index contribution margin), index contribution margin (ICM = total revenue – [total variable cost/total revenue]), profitability (P = net profit/total investment), rentability (R = net profit/total revenue), and period of return on investment (PRI = total investment/net profit) [18].

3. Results and discussion

3.1. Wastewater treatment and microalgal sludge production

The bioreactor performance parameters are shown in Table 2 and Fig. 3. A simultaneous conversion at high rates of organic matter (0.75 kg/m^3/d), total nitrogen (0.02 kg/m^3/d), and total phosphorus (0.001 kg/m^3/d) was evidenced, resulting in removal efficiencies of 97.6%, 85.5%, and 92.4% for COD, N–TKN, and P–PO_4^{-3}, respectively. In terms of microalgal growth, maximum specific growth rates of 0.6 d^{-1} and average microalgal sludge productivity of 0.27 kg/m^3/d were obtained. Moreover, this wastewater treatment process showed a biomass yield coefficient of 0.34 kg_{sludge}/kg_{COD} and a hydraulic detention time of 1.67 d. In terms of oxygen transfer, a volumetric mass transfer coefficient (KL_a) of 0.002 min^{-1} was evidenced in the bioreactor, in parallel to a power density demand of 9.7 W/m^3.

Table 2
Bioreactor performance parameters

Parameter	Value
$r_{S\,(COD)}$ (kg/m^3/d)	0.75 ± 0.01
$r_{S\,(N–TKN)}$ (kg/m^3/d)	0.02 ± 0.00
$r_{S\,(P–PO4-3)}$ (kg/m^3/d)	0.001 ± 0.00
$RE_{(COD)}$ (%)	97.6 ± 1.64
$RE_{(N–TKN)}$ (%)	85.5 ± 2.37
$RE_{(P–PO4-3)}$ (%)	92.4 ± 0.22
μ_{max} (d^{-1})	0.60 ± 0.00
P_X (kg/m^3/d)	0.27 ± 0.01
$Y_{X/COD}$ (kg_{sludge}/kg_{COD})	0.34 ± 0.00
HDT (d)	1.67 ± 0.00
KL_a (min^{-1})	0.002 ± 0.00

Note: $r_{S\,(COD)}$: COD consumption rate; $r_{S\,(N–TKN)}$: N–TKN consumption rate; $r_{S\,(P–PO4-3)}$: P–PO_4^{-3} consumption rate; $RE_{(COD)}$: COD removal efficiency; $RE_{(N–TKN)}$: N–TKN removal efficiency; $RE_{(P–PO4-3)}$: P–PO_4^{-3} removal efficiency; μ_{max}: maximum specific growth rate; P_X: average cellular productivity; $Y_{X/COD}$: biomass yield coefficient; HDT: hydraulic detention time; and KL_a: volumetric mass transfer coefficient.

The system performance complies with the main wastewater discharge standards [28] and could be an alternative to conventional wastewater treatment processes such as activated sludge, nitrification-denitrification, and chemical phosphorus precipitation, usually employed in the meat processing industry. Besides the wastewater treatment occurring in a single step, in a multifunctional reactor, the partial conversion of the pollutants in a microalgal biomass with a large potential of commercial exploitation is the differential of this technology.

Based on scale-up of the process (16.000 m^3/d), an air flow rate of 360 m^3/min was theoretically estimated. In these conditions, this process has the potential to generate 503,967.7 ton of microalgal biomass per year from the treatment of 5,376,000 m^3 of wastewater.

3.2. Determination of cost analysis

The cost estimate of wastewater treatment facility was determined using the basis description of the equipment in use, including its size and type (Table 3). The most costly equipment was the bioreactor, followed by the drum-dryer and then the belt filter used to dry the microalgae sludge. The total cost of the major equipment sums up to USD 25,968,800.00.

Table 4 shows the installation costs, including the deployment, instrumentation, piping, and other elements necessary that resulted in a total FCI of USD 70,894,824.00. Considering a lifetime of 10 years, the annual fixed capital per year, required to keep the facility in operation, was estimated at USD 8,112,393.40.

Within the WC, direct production costs such as raw materials, utilities, and labor were the main entries.

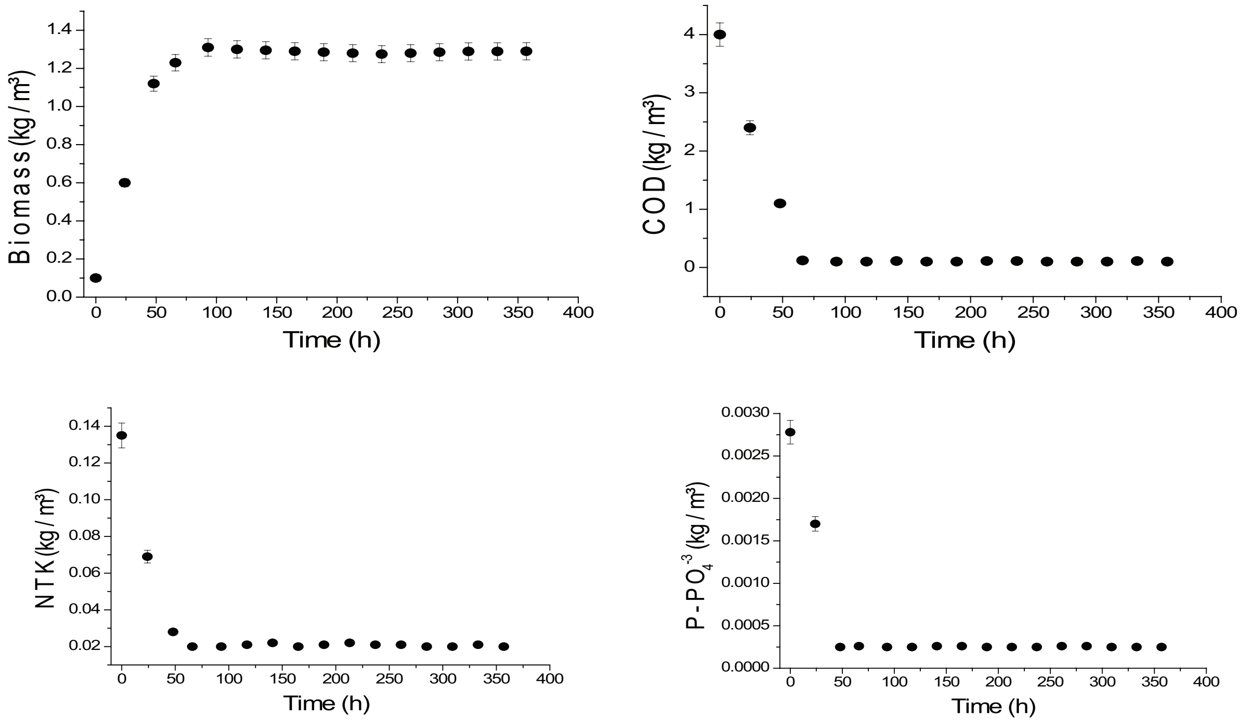

Fig. 3. Cellular concentration and substrate consumption dynamics in heterotrophic microalgal bioreactor.

Table 3
Major equipment costs used in the process

Item	Capacity	Cost (USD)	No. of units	Total cost (USD)
1. Fine screen	(0.70 m², carbon steel)	261,000.00	1	261,000.00
2. Rotary sieve	(1,036.20 m², stainless steel)	325,600.00	1	325,600.00
3. Equalization tank	(3,345.45 m³, carbon steel)	583,100.00	1	583,100.00
4. Parshall flume	(9′′, stainless steel)	19,000.00	1	19,000.00
5. Bioreactor	(30,666.7 m³, stainless steel)	12,944,200.00	1	12,944,200.00
6. Decanter	(11.29 m, carbon steel)	1,114,700.00	2	2,229,400.00
7. Centrifugal pump	(700.5 m³/h, stainless steel)	39,900.00	3	119,700.00
8. Drum dryer	(2,660 m², stainless steel)	5,258,400.00	1	5,258,400.00
9. Blowers	(360 m³/min, carbon steel)	133,400.00	5	667,000.00
10. Belt filter	(399.96 m², carbon steel)	3,561,400.00	1	3,561,400.00
Total MEC (USD)				25,968,800.00

Table 5 shows that the total amount of the raw materials was summarized as USD 1,017,676.80, wherein the consumption of caustic soda was the main cost. The costs of utilities, based only on power consumption, were estimated as USD 1,417,896.40. Finally, other costs (labor, supervision, payroll charges, maintenance, operating supplies, overheads, taxes, and contingencies) reached USD 3,773,008.70. In this sense, the total WC was estimated at USD 14,320,974.00/year.

Regarding the analysis of the major costs of the process, the major purchases of equipment showed that the bioreactor represents a cost close to 50% of the total facility, followed by the drum-dryer and the belt filter, showing the relationship of these pieces of equipment with their high power consumption. The FCI, depreciation over 10 years, contributed to approximately 56% to the cost of the process. The remaining 44% of the production cost originated in the direct production of the WC. Depreciation charges contributed an approximately 48% to the annual production cost while raw materials, utilities, and labor contributed 7%, 9%, and 5%, respectively, to the production cost.

Based on the determination of cost analysis and the calculation basis of the industry in analysis

(16,000 m³/d), the wastewater treatment cost was estimated at USD 2.66/m³ (USD 0.70/m³ considering only operational costs). Additionally, through the microalgae sludge formation, one can predict a cost of USD 0.03 cent/kg of the dried biomass.

Comparatively, Fig. 4 shows the operational costs of conventional wastewater treatment processes and the costs of the main processes for microalgal biomass production.

Table 4
Fixed capital investment of the process

Item	Factor	Cost (USD)
1. Major purchased equipment (MEC)	1	25,968,800.00
2. Installations	0.2	5,193,760.00
3. Instrumentation and control	0.4	10,387,520.00
4. Piping	0.4	10,387,520.00
5. Electrical	0.09	2,337,192.00
6. Buildings	0.11	2,856,568.00
7. Services	0.14	3,635,632.00
8. Land	0.06	1,558,128.00
9. Engineering and supervision	0.13	3,375,944.00
10. Contractor's fee (0.05 Σ items 1–8)	0.05	3,116,256.00
11. Contingency	0.08	2,077,504.00
Total fixed capital, *A*		70,894,824.00
Depreciation (Σ items 1–7, 9–11)/10 years		6,933,669.60
Property tax (0.01 depreciation)	0.01	69,336.70
Purchase tax (0.16 items 1–10/10)	0.16	1,109,387.10
Total fixed capital per year, *B*		8,112,393.40

Table 5
Working capital of the process

Raw materials	Total quantity	Cost (USD)
1. Caustic soda (USD 0.348 kg)	0.464 kg/m³	867,686.40
2. Flocculants (USD 2.79 kg)	160 kg/d	149,990.40
Total raw materials, *C*		1,017,676.80
Utilities		
3. Power consumption (0.02 FCI)	kWh	1,417,896.40
Total utilities, *D*		1,417,896.40
Others		
4. Labor (USD 8.50/h, 3 shifts)	5 workers	685,440.00
5. Supervision (0.2 labor)		137,088.00
6. Payroll charges (0.25 labor + supervision)		205,632.00
7. Maintenance (0.04 MEC)		1,038,752.00
8. Operating supplies (0.004 *C*)		4,070.70
9. General plant overheads (0.55 labor + supervision + maintenance)		1,023,704.00
10. Tax (0.16 items 1–3, 7 and 8)		556,543.34
11. Contingency (0.05 items 1–3)		121,778.66
Total others, *E*		3,773,008.70
Total working capital, *F* (*B* (Table 3) + *C*+ *D* + *E*) (USD)		14,320,974.00

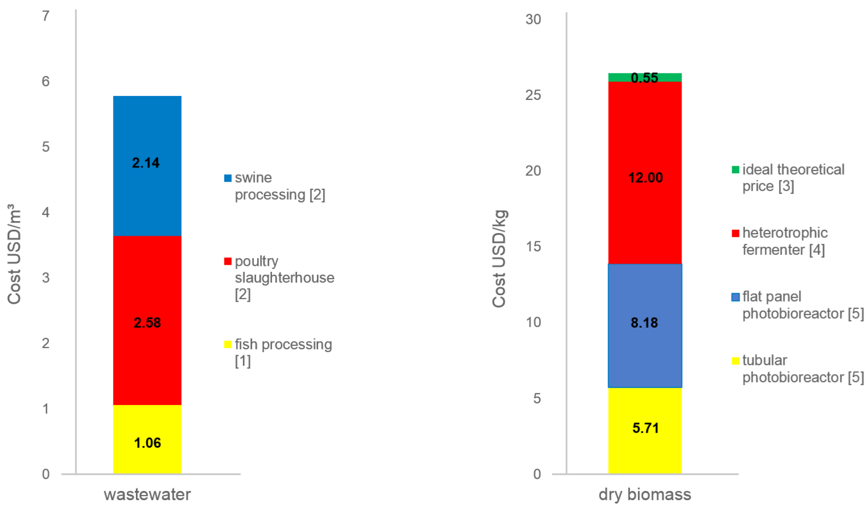

Fig. 4. Comparative costs of the wastewater treatment processes and dried microalgal biomass.
Note: [1] – Cristóvão et al. [29], [2] – Asselin et al. [30], [4] – Wijffels et al. [17], [5] – Lee [14], and [6] – Norske et al. [15].

The conventional technologies for wastewater treatment have operational costs estimated between USD 1.06/m³ to USD 2.58/m³ [29,30]. In particular, for meat processing wastewater, chemical treatment followed by activated sludge with extended aeration are the most usual treatments, with higher operational costs than those estimated in this study. The application of microalgal heterotrophic bioreactors could represent substantial savings per cubic meter of treated wastewater, and furthermore, it generates sludge with commercial value, viable to the exploitation of bioproducts. The low production cost of this biomass (USD 0.03/kg) makes it viable to exploit low added value products, which is currently an infeasible scenario. The production costs of the microalgal biomasses are estimated at USD 5.71/kg for the tubular photobioreactor and USD 8.18/kg for the flat panel photobioreactor [15]. Additionally, the production cost of the heterotrophic fermenters is close to USD 12.00/kg [14]. According to Wijffels et al. [17], the production cost of microalgae biomass may not be higher than USD 0.55 cent/kg (ideal theoretical price) for manufacture of bulk products such as biofuels, which makes this process highly attractive in a commercial point of view.

3.3. Applicability of the process

The feasibility of the process was determined based on the estimate of EE, profitability, rentability, and period of return on investment (Table 6).

The wastewater treatment generates a substantial amount of microalgal biomass of rich composition, similar to commodity products such as soybeans. Soybeans have an average international price in the market estimated at USD 0.48 cent/kg [31], and therefore, the commercial value of microalgal biomass was compared with the price of soybeans, resulting in USD 480/ton.

The net profit was estimated at USD 227,583,522.00 with a profit margin of 94%. The profitability of the process reports that, each year, the industry recovers approximately 321% of the amount invested, and when the revenue reaches the value of USD 71,610,933.30, the payment of the total costs is made. The time of return on investment was estimated at 0.29 years, which means when this period of operation is achieved, the industry recovers the invested capital. These values are highly attractive, since most companies use a value of 12% as minimum acceptable rate of return [32]. This rate is usually determined by evaluating existing opportunities in the expansion of operations, rate of return for investments, and other factors deemed relevant by management. However, companies operating in industries with more volatile markets might use a slightly higher rate in order to offset risk and attract investors [33]. In this sense, the feasibility analysis of the process showed that heterotrophic microalgal bioreactors applied to poultry and swine slaughterhouse wastewater treatments have a wide economic margin to be explored industrially and commercially.

Table 6
Economical feasibility indicators of process

Parameter	Value
Economic equilibrium (USD)	71,610,933.30
Profitability (%/year)	94.00
Rentability (%/year)	321.00
Period of return on investment (year)	0.29

Additionally, the feasibility of the process demonstrates that this microalgal biomass produced in the agroindustrial wastewater has an economic margin that allows for work with fine chemical products but also commodities from microalgae, clearly showing the benefit-cost relationship for both of them.

The heterotrophic microalgal bioreactor is associated with improvements in the productive process, since it complies with the general guidelines for intensive processes, combining more than one function. It requires lower power densities during operation, confirming the high performance of the bioreactor, snapping it into the category of multifunctional reactors [22]. The cultivation of microalgae in wastewater offers combined advantages for the wastewater treatment and simultaneously the production of a valuable biomass. This bioreactor serves as an alternative to reduce the high costs of conventional secondary and tertiary treatments. Inherent in the treatment process, microalgal sludge is generated with a minimum cost of production, since it is a resultant product of an intensive process based on inputs of negligible cost (agroindustrial wastewater).

The current agroindustrial wastewater treatment systems utilize processes operating in multiple unit operations, which require high energetic demand, thus impacting finances throughout the production chain. Furthermore, these systems are still linked to expensive processes, with high capital and operation costs, besides the massive generation of biological sludge, with a low potential of reuse. The microalgal heterotrophic bioreactor not only offers a low-cost alternative for conventional wastewater treatment processes, but also produces biomass with reuse potential; thus, bioproducts with commercial value can be marketed. The process conducted from the use of a heterotrophic microalgae bioreactor contributes to the maturation of the technology, in order to possibly explore these technological routes.

Finally, one should consider the scale limitations of these estimates, currently supported exclusively by lab-scale experiments. In any case, it is of paramount importance to base any performance and economic estimates on field data coming from pilot plants of suitable size, to finally reach an industrial scale. There is a clear need for further studies about this theme, integrating the biological aspects with engineering ones and producing field experimental data from pilot plants, in order to achieve a rapid development of the technology needed for application at the industrial level.

4. Conclusion

The emerging microalgae industry continues its march toward industrial application. The agroindustrial wastewater treatment with the parallel production of microalgal biomass could contribute to the consolidation of this technology.

The multifunctional heterotrophic microalgal bioreactor simultaneously converts the three main pollutants of the poultry and swine slaughterhouse wastewater, reaching removal efficiencies of 97.6%, 85.5%, and 92.4% for COD, N–TKN, and P–PO_4^{-3}, respectively. In addition, a microalgal sludge productivity of 0.27 kg/m^3/d is obtained, potentializing reuse in multiple production platforms.

The economic analysis showed a cost of USD 2.66/m^3 of treated industrial wastewater, and as a consequence of this process, the production cost of microalgal sludge was USD 0.03/kg of dehydrated biomass.

The feasibility analysis for the industrial applicability of the proposed technology shows that if the commercial value of microalgal biomass is estimated at USD 480/ton, a profit margin of 94% can be obtained.

Acknowledgments

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Symbols

μ_{max}	—	Maximum specific growth rate
C	—	Oxygen concentration at time $t = t_i$, mg/L
C^*	—	Oxygen concentration in saturation, mg/L
C/N	—	Carbon/nitrogen ratio
C_0	—	Critical oxygen concentration, mg/L
COD	—	Chemical oxygen demand, mg/L
d_1	—	Diameter of bench-scale reactor, m
d_2	—	Diameter of full-scale reactor, m
EE	—	Economic equilibrium
FCI	—	Fixed capital investment
FS	—	Fixed solids, mg/L
H_1	—	Height of bench-scale reactor, m
H_2	—	Height of full-scale reactor, m
HDT	—	Hydraulic detention time
ICM	—	Index contribution margin
KL_a	—	Volumetric mass transfer coefficient, min^{-1}
MEC	—	Major equipment costs
N/P	—	Nitrogen/phosphorous ratio
P	—	Profitability
PO_4^{-3}	—	Total phosphorus, mg/L
PRI	—	Period of return on investment
P_X	—	Average cellular productivity
Q_1	—	Air flow rate of bench-scale reactor, m^3/min
Q_2	—	Air flow rate of full-scale reactor, m^3/min
R	—	Rentability
RE	—	Removal efficiency
r_S	—	Consumption rate
SS	—	Suspended solids, mg/L
t	—	Time, min
TCI	—	Total capital investment
TKN	—	Total nitrogen, mg/L
TS	—	Total solids, mg/L
V_1	—	Reactor volume at bench-scale, m^3
V_2	—	Reactor volume at full-scale, m^3
VS	—	Volatile solids, mg/L
WC	—	Working capital
$Y_{X/COD}$	—	Biomass yield coefficient

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