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Solar-powered algal production on vegetable processing industry wastewater at pilot scale

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Abstract

This paper proposed a sustainable treatment scheme for effluents from fruit and vegetable processing industries with high organic load that combined heterotrophic microalgae cultivation with microalgae spray drying producing end-products of commercial interest (biofertilisers and/or animal feed). A pilot plant was operated with feedstock from a fruit and vegetable processing industry and its final products were assessed. The pilot plant was powered by renewable energy (solar energy supported by biomass), which minimized the carbon footprint and operating costs of the process. Through the ultimate analysis of the produced algae, it was evident that in all cases it could be commercialized as a solid NPK organic fertilizer being in line with the respective EU and Spanish legislation framework. As far as the animal feed perspective is concerned, the end-product of the pilot plant could be efficiently included in the feed of various animals, substituting a significant part of the animal feed required. The results from the implementation were used for the design of a full-scale implementation of the innovative treatment scheme, proving that 1.26 ton/d of microalgae could be produced, which could be later used as fertiliser and/or animal feed from the daily wastewater production of a medium sized fruit and vegetable processing company. From an environmental perspective, the proposed solution provides a gold standard example of the circular economy concept, since 1.15 kg CO_2 equivalent per kg of sludge avoided could be saved. Additionally, the use of renewable energy (solar and biomass) will result in a saving of 0.531 kg of CO_2 emissions per kWh consumed. Conclusively, the proposed treatment scheme could meet circularity and sustainability since the end-products quality permits their integration into new value chains.

Keywords Algae cultivation · Circular economy · Fruits and vegetables industry · Wastewater valorisation

Introduction

Globally, the sector of fruit and vegetable processing industries (FVPI) is growing progressively as a result of population growth, the newly-adopted healthy eating habits and the advances in the management of the supply chain and the production processes (Valta et al. 2017). The FVPI covers the production of canned fruit and vegetables, juices, pre-cut vegetables, prepared salads, frozen fruits and frozen vegetables along with dehydrated or dried food. This industrial sector presents high water consumption and subsequent high wastewater production (Swartz et al. 2021). Major water use and waste generation points are among others the washing stages of the raw materials, peeling and pitting, blanching, fluming, sorting, and transferring the products in the industrial plant. Reducing size, coring, slicing, dicing, pureeing, juicing process steps, filling and sanitizing activities also add

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to the wastewater generation. The effluents from this industry contain high organic and nutrient loads. However, their composition can be affected by a series of factors like the commodity processed, the process units applied, the daily production efficiency, the seasonality and the crops growing conditions (Islam 2020; Swartz et al. 2021). The types of wastewater treatment technologies used for FVPI usually consist of the conventional array of physical, chemical and biological treatment schemes. Anaerobic and oxidative processes have also been employed (Islam 2020). Nevertheless, more sustainable treatment solutions that may include the production of added-value products such as microalgae are sought.

Cultivation of microalgae on diverse wastewater streams (municipal, industrial or agricultural) aiming at removing pollutants as well as producing biomass has been extensively studied (Cai et al. 2013; Kwon et al. 2020). Microalgae enable the effective recovery of nitrogen and phosphorus contained in wastewater, via their concentration in biomass, offering a different approach to the treatment of wastewater (Spolaore et al. 2006) while generating a valuable side biomass stream with high nutritional content. In some cases, it is highlighted as a more efficient and environmentally friendly way of treating wastewater associated with less greenhouse gas emissions than conventional wastewater treatment techniques (Perera et al. 2019).

The production of microalgae coupled with wastewater treatment and nutrient removal has been widely studied in the literature (Mulbry et al. 2007; Ruiz-Marin et al. 2010; Cai et al. 2013; Gouveia et al. 2016; Kwon et al. 2020). It is mentioned that about 1 kg of dry microalgae biomass can be produced per m^3 of sewage, explaining why microalgae cultivation has been used as a nutrient recovery technology (Spolaore et al. 2006). It is often mentioned that the use of consortia of algae and bacteria and not individual microorganisms, provides better results in nutrients removal from wastewaters. To achieve greater efficiency and performance of the treatment system, it is necessary to select the appropriate combination of strains, in terms of compatibility for growth rate, size and stability (Perera et al. 2019).

Microalgae may be utilised for the production of value-added products because of the high content of carbohydrates, proteins, lipids, antioxidants and vitamins. At present, the biomass harvested may be used as a component for the production of animal feedstock, biofertilisers, biofuels (Severo et al. 2019), bioactive compounds, food (Wang et al. 2023), biomedical products (Severo et al. 2022), biomaterials (Mathiot et al. 2019), pharmaceuticals (Ibrahim et al. 2023), etc. (Liu and Hong 2021).

The aggregation of different types of microalgae in modern agriculture, as soil conditioners and biofertilizers has been suggested in order to improve the physico-chemical properties of soil (Castro et al. 2017). More specifically, the inoculation of algal biomass to soil has been proven to enhance soil fertility and quality, increase soil organic content, enrich soil nutrients, improve utilization of micro and macronutrients by plants and promote the plant growth by phytohormones release and protection from diseases and pests (Mahapatra et al. 2018).

On the other hand, microalgae biomass has a rich biochemical composition and nutritional value that allows its integration to animal diet. Currently 30% of the global algal production is consumed in animal feedstuff (Alam et al. 2020). Among the nutritional elements that microalgae can offer are proteins, lipids (most importantly polyunsaturated fatty acids, PUFA), amino-acids, vitamins and minerals and pigments. In most cases, their amino acids profile is comparable to other conventional protein sources, while their overall composition could be competitive to regularly used feedstuffs in animal feed industry.

In this context, this paper aims to demonstrate the technical and economic feasibility of an innovative concept for fruit and vegetables processing industry wastewater treatment on pilot scale based on heterotrophic microalgae culture to substitute, in the long term, the traditional aerobic digestion as preferable method for the treatment of these streams since instead of waste sludge and nutrients losses, valuable algae-based marketable products (e.g. biofertilisers, animal feed) are produced. This way, the environmental impact of this sector will be decreased. Furthermore, managers of FVPI shall be provided with a cost-effective process for on-site treatment of streams rich in organic matter, nutrients and salts.

Materials and methods

Wastewater

The wastewater used in this study was produced in a vegetable processing company whose production is based on fresh endives, sweet corncobs (boiled and vacuum-wrapped) and beetroot (boiled, peeled and vacuum-wrapped). In addition, it offers other vegetables such as carrots, leeks, boiled lentils, chickpeas and beans, which are ready to eat. It is located in Sanchonuño (Segovia, Spain) and around 65,030 tons of vegetables are processed annually generating 29,400 tons of end products. The water consumed is around 160,000 m^3/year and the electricity consumption is of 8.5 GWh per year. In addition, the total daily production of effluents is estimated between 400–800 m^3 per day.

The mean values and the respective range of the physicochemical characteristics of the wastewater from the corn processing line of the FVPI are presented in Table 1. The latter was considered as the most appropriate and representative waste stream for the pilot system operation.

Table 1 Physico-chemical characteristics of wastewater

Parameter	Average	Min	Max
pH	6.90	4.40	12.16
Conductivity (mS/cm)	2.54	1.21	6.28
TSS (mg/L)	1281	543	3042
Volatile suspended solids (VSS) (mg/L)	899	260	2688
Total dissolved solids (TDS) (mg/L)	2354	1130	3383
TS (mg/L)	3563	2063	6425
COD (mg/L)	5392	1113	9818
BOD_5 (mg/L)	2524	1345	5362
$N–NH_4$ (mg/L)	9.70	0.39	36.90
TP (mg/L)	39.02	0.25	60.83
Total organic Nitrogen (TOC) (mg/L)	1415	215	2970
TN (mg/L)	196.25	136.6	270.9
$NO_3–N$ (mg/L)	< 2		
$NO_2–N$ (mg/L)	< 0.3		
TKN (mg/L)	94.4	46.4	270.9
Phosphate (PO_4) (mg/L)	48	14	118
Na (mg/L)	354	243	676
K (mg/L)	172	140	363
Mg (mg/L)	34	21	45
Ca (mg/L)	29	21	52
Zn (mg/L)	0.260	0.160	0.839
Cu (mg/L)	0.037	0.021	0.131
Cr (mg/L)	0.078	0.015	0.156
Mn (mg/L)	1.45	1.40	1.47
Fe (mg/L)	9.71	9.44	11.30
Pb (mg/L)	< 0.010		
Ni (mg/L)	0.011	0.009	0.022
Cd (mg/L)	0.003	0.003	0.003
Co (mg/L)	0.009	0.009	0.009
As (mg/L)	0.020	0.018	0.022
Toxicity (Eqtox/m^3)	29.167	28.000	30.000
Escherichia coli (CFU/g)	2336.667	2300.000	2420.000
Salmonella spp.	Not detected		

Algae strain

Initial algal culture used for the inoculation of the raceway pond was a mixture of *Scenedesmus sp.* and *Chlorella sp.* Algae were previously adapted on biogas digestate with a high level of nutrients. The choice of algal strain was made based on preliminary research [experimental and bibliographic (Hidalgo et al. 2015, 2018)]aiming to overcome challenges such as effective growth in wastewater, not artificial or pretreated.

Methods of analysis

All analyses were performed according to UNE (Una Norma Española) standard methods which is the Spanish Association for Standarisation and Certification, and the Spanish representative in the international and European organisations ISO/IEC and CEN/CENELEC. Escherichia coli was measured by sowing in depth method based on BRD 07-07-12-04 validated by AFNOR against the standard ISO 16649–2:2001. The NREL laboratory analytical protocols were applied in order to characterize the produced algae (Sluiter et al. 2005a, b, 2008, 2012; Sluiter and Sluiter 2010; Mafe et al. 2015).

Pilot plant

The pilot plant was placed in the facilities of the wastewater treatment plant of the FVPI (Sanchonuño, Spain). It is composed by two 40ft length containers (Fig. 1).

The pilot plant consisted of the following main components:

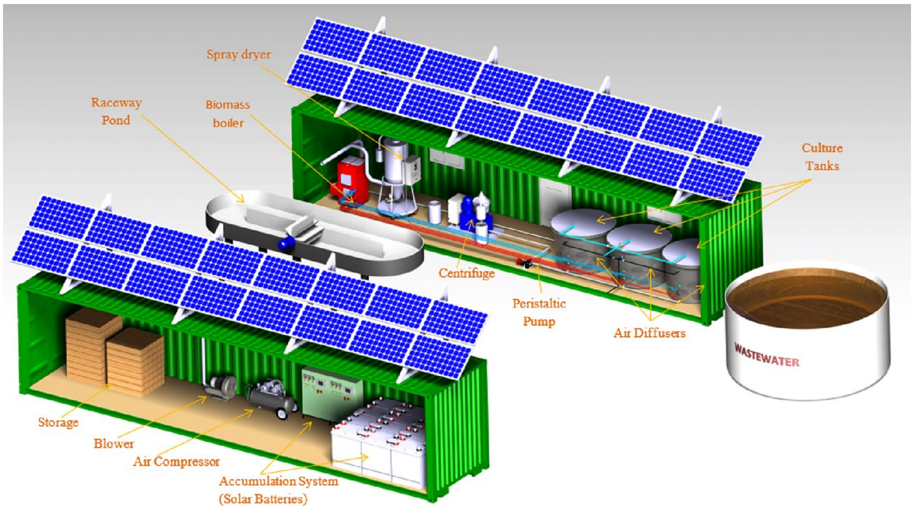

Fig. 1 3D design of the pilot plant

Wastewater Storage and homogenisation tank

Wastewater to be treated proceeding from the hosting facilities was stored in a 2 m^3 tank to provide a homogenized input stream to the treatment process. A pH monitoring and control system was used in order to neutralise the pH of the wastewater when necessary, since the microalgae need the water to be at a neutral pH (7–8).

Raceway pond

The inoculum batch culture was grown autotrophically before placed into the wastewater environment. The pond included mixing system (paddlewheel), sensors (T, pH) and inlets of nutrients and water. For the design of the pond, an inoculum to wastewater ratio of 0.2–0.3 ‰ was considered. In the raceway, the microalgae cultivation is continuous.

Culture tanks

3 tanks of 2 m^3 each were operated continuously for a given residence time (3–8 days). The reactors counted on an air diffusion system in the bottom, fed by a blower capable of providing 28 m^3/ h of air. This air provided a soft mixing inside the tank, allowing microalgae growth. The most important parameters regulating algal growth are pH and temperature, which were, therefore, continuously monitored.

Centrifuge

A vertical centrifuge (ALFA LAVAL, model CLARA 15) was used to increase the concentration of algal biomass. The microalgae cultivated in the raceway pond was concentrated and sent to the cultivation tanks as inoculum when necessary. Given the batch mode operation, upon completion of the residence time, the treated effluent was centrifuged to concentrate microalgae produced to a final concentration of 1.5%. The separation efficiency is influenced by changes in the viscosity (separating temperature). The treated effluent was characterised in order to be evaluated for irrigation, cleaning, etc. purposes.

Inoculum tank

In this tank, the concentrate of raceway algae pond was stored prior to feeding the cultivation tanks. A concentration of 15 g/L microalgae was targeted.

Stirred storage tank

In this tank the stream that leaves the centrifuge, rich in microalgae (about 1.5%), was stored before its subsequent step to spray drying. This tank was mechanically agitated at low velocity including both agitator and baffles. The latter are utilised to increase mixing efficiency and turbulence. The tank's impeller had 4 blades, ensuring proper mixing.

Spray dryer

Microalgae solution was sprayed inside the dryer with counter-current air at, approximately, 180 ℃ to produce a microalgae powder. Moisture evaporated rapidly from the surface of the algae and the dry particles were collected in a storage system (bag or similar) while the hot air stream (at approx. 90 ℃) was driven to the head of the process for the surplus heat to be reused. Atomization was the most crucial stage in this process. The extent of atomization defines the drying rate and thus the dryer capacity, so special attention was paid to the atomizers design.

Photovoltaic system

The system consisted of a generator field of photovoltaic modules and batteries (7 kWp), grouped electrically according to the ideal configuration to obtain the maximum use energy in the conditions of location. In case that there is not enough solar radiation, the plant was supported by energy from a biomass boiler.

Description of experiments

During the operation of the pilot plant, a series of tests were performed in triplicate so as to optimise the treatment process. More specifically, the effect of residence time (3-8d) on the pilot performance was studied. The effluent characteristics, the microalgae yield and composition were assessed.

Daily monitoring of each culture tank was performed. After centrifugation, the concentration of the microalgae obtained was measured. The final effluent was characterised in terms of pH, conductivity, COD, total solids (TS), total suspended solids (TSS), microalgae density, total nitrogen (TN), ammonia (N-NH_4), nitrate (NO_3–N) and nitrite (NO_2–N) nitrogen, total phosphorous (TP), manganese (Mn) and iron (Fe). For microalgae powder received after drying the following parameters were measured: mass flow, total Kjeldahl nitrogen (TKN), total phosphorus, potassium (K), protein, moisture, organic matter and lipids.

Results and discussion

Wastewater characteristics

The high fluctuations in the pollution load of the wastewater are more than evident. The alleviation of these fluctuations constitutes a major challenge for any wastewater treatment plant. The composition of FVP effluents, their quality and quantity are strongly dependant on several factors such as type of product processed, process applied, technology used, seasonal weather variations, etc. The methods used to clean and disinfect the production lines have also an impact on their composition (Puchlik and Struk-Sokołowska 2017). In general it is reported that because of the diversity and nature of the processed raw materials, wastewater from FVPI are hard to characterise (Puchlik and Struk-Sokołowska 2017). In this context, Chen et al. (2019) have reported BOD_5 concentrations from 500 to 6100 mg/L and COD from 806 to 7732 mg/L for FVPI wastewater, values also indicating high fluctuations but very close to those observed in the present study. In another study of Puchlik and Struk-Sokołowska (2017), the COD values reported ranged from 270 to 5260 mg/L and the pH from 4.9 to 7.7 in industries producing several assortments (pickles, pulps, salads) values that lie within the results of this study. However, it is worth mentioning that the composition of the effluent of the peeling beet process, another waste stream of the FVP plant presents much higher COD ranging from 25,985 to 53953 mg/L and could create peaks in the organic load of the wastewater treatment plant.

Performance data

Treated effluent

On average, the characteristics of the treated effluent for all the experimental trials (Mean Values) and all residence times are presented in Table 2.

Regarding the efficiency of the system in terms of COD, TS, TN and TP in relation to the residence time, Fig. 2 illustrates this dependence.

In general, in literature, the absorption of nitrogen on several types of waste streams fluctuates from 24 to 100%, of phosphorus from 25 to 100% and of COD from 23 to 95% (Geremia et al. 2021). It is obvious from Fig. 2 that the treatment of FVPI wastewater via a microalgae-based system was able to efficiently remove organic load and nutrients at pilot scale. Nevertheless, high fluctuations are also observed for all parameters, and this could be attributed to the fluctuations of the characteristics of the influent wastewater (Table 1). Regarding COD, there is a slight increase of COD removal with the increase of residence time (from 72.71% for 3d to 86.36 for 8d), but this cannot stand as a statistical important improvement taking into consideration the standard deviations of each residence time. The same applies for total solids removal as well that in all cases is than 50%. As far as nutrients removal is concerned, the applied treatment train achieved high efficiencies. For a residence time of 3 days, the highest nitrogen removal was achieved (74.23 ± 5.33%), implying that the algal species was able to assimilate all the nitrogen sources available, since according to reports, microalgae may produce proteins, phospholipids and nucleic acids with increased productivity by assimilating simple organic nitrogen, ammonia nitrogen, nitrate and nitrite from wastewater (Liu and Hong 2021). For phosphorous removal, the efficiencies are higher and do not seem to be affected by the residence time. These high efficiencies could be attributed to the fact that more than 40% of the total phosphorus of the influent wastewater was in the form of phosphates that is the form of phosphorus that is absorbed most selectively by microalgae in order to synthesize proteins, phospholipids, nucleic acids and ATP (Liu and Hong 2021).

In view of the above, a residence time of 3 days could be considered optimum since it increases the viability of the process, minimizing the installed capacity in terms of working volume.

Table 2 Average characteristics of treated effluents

	Mean values	Residence time (*d*)					
		3	4	5	6	7	8
pH	8.15 ± 0.59	7.92 ± 0.60	8.27 ± 0.38	8.15 ± 0.21	7.97 ± 0.67	8.27 ± 0.56	8.68 ± 0.73
Conductivity (mS/cm)	3.51 ± 0.50	3.47 ± 0.43	3.15 ± 0.19	3.19 ± 0.25	3.52 ± 0.58	3.76 ± 0.57	3.29 ± 0.44
COD (mg/L)	2129.90 ± 1353.28	2869.64 ± 1168.31	1540.16 ± 943.31	2248.72 ± 751.34	2653.31 ± 1982.09	1499.06 ± 856.30	1019.85 ± 986.97
TS (g/kg)	4.04 ± 2.14	4.84 ± 1.67	4.07 ± 1.74	2.97 ± 0.55	4.77 ± 3.41	3.43 ± 1.77	2.39 ± 0.20
TSS (mg/L)	2285 ± 1890	3105 ± 1455	2495 ± 1645	1375 ± 425	3010 ± 3120	1550 ± 1485	745 ± 5
NO_3–N (mg/L)	7.86 ± 11.78	7.50 ± 12.08	16.67 ± 14.43	12.50 ± 17.68	4.17 ± 10.21	4.55 ± 10.11	16.67 ± 14.43
NO_2–N (mg/L)	1.57 ± 2.36	1.50 ± 2.42	3.33 ± 2.89	2.50 ± 3.54	0.83 ± 2.04	0.91 ± 2.02	3.33 ± 2.89
NH_4–N (mg/L)	22.14 ± 31.65	11.00 ± 14.49	8.33 ± 14.43	12.50 ± 17.68	42.50 ± 55.57	30.45 ± 31.26	8.33 ± 14.43
TN (mg/L)	31.00 ± 27.49	21.36 ± 14.10	29.33 ± 3.79	28.00 ± 4.24	40.86 ± 50.91	36.00 ± 27.53	28.67 ± 3.21
TP (mg/L)	0.14 ± 0.13	0.14 ± 0.07	0.08 ± 0.03	0.09 ± 0.03	0.20 ± 0.24	0.15 ± 0.11	0.09 ± 0.00
Mn (mg/L)	0.80 ± 0.03	0.79 ± 0.04	0.83 ± 0.02	0.79 ± 0.01	0.80 ± 0.02	0.80 ± 0.02	0.80 ± 0.02
Fe (mg/L)	0.84 ± 0.02	0.83 ± 0.03	0.86 ± 0.02	0.82 ± 0.01	0.85 ± 0.01	0.84 ± 0.02	0.84 ± 0.01

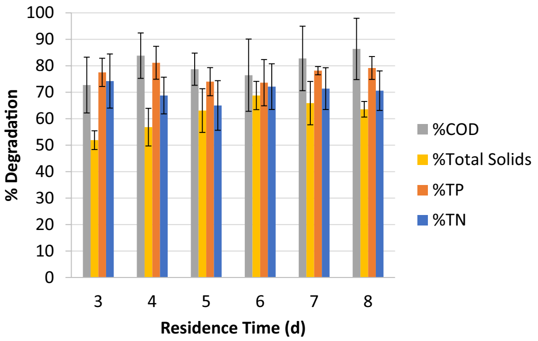

Fig. 2 Influence of residence time on the wastewater treatment efficiency

Table 3 Characteristics of the effluents in comparison to EU 2015/1787 and Royal Decree 140/2003 requirements

Parametric Value according to EU 2015/1787 and Royal Decree 140/2003	
pH	> 6.5 < 9.5For the food industry. the minimum value may be reduced to 4.5 pH units
Conductivity (ms/cm)	2.50
NO_3–N (mg/L)	50
NO_2–N (mg/L)	0.5
[NO_3–N]/50 + [NO_2-N]/3	< 1
N–NH_4 (mg/L)	0.5
Mn (mg/L)	0.05
Fe (mg/L)	0.2

According to Satpal and Khambete (Satpal and Khambete 2016), α microalgae-based wastewater system has a very high removal efficiency for nutrients, which may reach 78–99%, which was also verified in the present study. Additionally, it was reported that such treatment systems also succeed to remove 40–65% of COD and BOD. Even high efficiencies over 70% were observed in our study for very low residence times (3d).

In view of reusing the treated effluent for irrigation purposes, the crucial parameter according to the current EU and Spanish legislation is the Total Suspended Solids parameter, given that the microbial load is negligible. EU standards require concentrations lower than 60 mg/L for all cases, while Spanish standards requirements are lower than 35 mg/L. The concentration of the suspended solids exceeds by fold the limit concentrations. For this reason, an additional post-treatment step should be incorporated in the valorisation scheme in order to achieve the standards for water reuse. Technological alternatives that could be adopted include filtration, membrane-based techniques such as reverse osmosis, air flotation units such as DAF, sedimentation after coagulation etc.

On the other hand, in order to evaluate the possible reuse of the treated effluent of the algae pilot plant, its characteristics should be compared with the minimum requirements set by the European and the Spanish legislation framework for the quality of water in the food processing industries. In Table 3, these legislation limits are presented.

As it is observed, for all indicator parameters apart from pH and nitrates, the measured values of the pilot effluent exceed by fold the limit values. Additionally, the organic load (2129.90 ± 1353.28 mg/L COD), the total solids concentration (4.04 ± 2.14 g/kg) and the total phosphorus content (0.14 ± 0.13 mg/L) should also be taken into consideration. Conclusively, the possibility of recycling the treated effluent back to the production line of the vegetable industry could not be considered as a viable strategy.

Algae

The main end-product of the pilot plant that was delivered after the spray dryer process was the produced algae. The mean values of these characteristics are presented in Table 4 for the harvested algae in relation to the residence time of the wastewater in the treatment tanks.

The algal species used showed good biomass production (1.72 ± 0.69 g/L) higher than that reported by Geremia et al. (2021) for *Scenedemus obliquus* and *Scenedesmus sp*. (1.36 ± 0.27 g/L and 1.24 ± 0.04 g/L) (Geremia et al. 2021). In addition to the production of biomass, nitrogen removal of 92–97% and phosphorous of almost 100% were also reported for these strains, values slightly higher than those observed in the present study.

Regarding the evaluation of the use of the produced algae as fertilizer, Table 5 presents the limits set by both EU and

Table 4 Mean values of the characteristics of the algae harvested in the pilot system

		Residence Time (d)					
	Mean values	3	4	5	6	7	8
Microalgae concentrated to spray dryer (g/kg)	28.33±9.59	29.30±9.48	33.42±3.90	21.38±6.89	24.54±10.73	28.90±11.64	30.34±5.89
Spray dryer efficiency (%)	64.28±9.30	59.65±8.22	69.08±10.98	55.12±6.57	66.52±9.43	69.62±7.41	58.79±9.07
Dry microalgae (g/m^3 treated ww)	1724.74±691.66	1576.78±421.48	2655.56±823.50	1091.92±82.85	1447.03±631.27	1787.38±740.39	2055.56±851.36
TKN (%)	5.31±0.27	5.33±0.21	5.23±0.16	5.36±0.34	5.38±0.13	5.43±0.35	4.91±0.04
Potassium (K_2O) (%)	1.48±0.10	1.51±0.11	1.54±0.04	1.47±0.14	1.39±0.01	1.50±0.08	1.35±0.08
TP (P_2O_5) (%)	2.49±0.16	2.45±0.04	2.55±0.17	2.83±0.24	2.44±0.07	2.54±0.15	2.27±0.16
Protein (%)	31.60±1.59	31.70±1.23	31.12±0.93	31.89±1.07	31.98±0.80	32.28±2.08	29.21±0.25
Lipid (%)	14.15±0.75	14.39±0.34	14.15±0.96	14.74±1.80	14.09±0.29	14.46±0.32	12.30±0.00
Ash (%)	26.00±0.97	25.50±0.31	26.37±1.07	25.78±0.29	25.62±0.71	25.76±0.34	28.41±0.00
Carbohydrate (%)	31.28±6.27	34.26±0.52	29.61±7.50	34.76±4.50	34.04±0.13	32.34±4.69	16.32±0.00
Organic matter (%)	74.00±0.97	74.50±0.31	73.64±1.07	74.22±1.12	74.38±0.71	074.24±0.34	71.59±0.00
Moisture (% dw)	9.56±0.17	9.51±0.24	9.55±0.12	9.81±0.08	9.54±0.18	9.53±0.14	9.70±0.00

Table 5 Fertilisers standards in EU and Spanish legislation

Parameter	Solid NPK Organic fertilizer (EU)	NPK Animal and vegetal origin (Spanish Legislation)
Dry matter	≥ 40%	
Organic carbon content	≥ 15%	
C/N		≤ 15
N	≥ 1%	≥ 1%
P_2O_5	≥ 1%	≥ 1%
K_2O	≥ 1%	≥ 1%
Nutrients sum $N + P_2O_5 + K_2O$	≥ 4%	≥ 4%

Spanish legislation regarding solid organic fertilizer with multiple nutrients content.

From the data presented in Tables 4 and 5, it is evident the produced algae in all cases could be commercialized as a solid NPK organic fertilizer.

Similarly, Khan et al. (Khan et al. 2019) examined wastewater treatment by the microalgae consortium of *Chlorella minutissima spp., Scendesmus spp., Nostoc muscorum spp.* and evaluated the results also in terms of the suitability of residual algal biomass as biofertilizer for agricultural purposes. They achieved low NPK content (which can preserve nutrients from leaching and surface runoff) and proved the enhancement of soil with macro and micronutrients in levels that could be more profitable and efficient than using conventional fertilizers. Others researchers have assessed the effect of algal biomass on several crops (rice, garlic, tomatoes, onion, lettuce) (Faheed and Abd-El Fattah 2008; Shariatmadari et al. 2013; Garcia-Gonzalez and Sommerfeld 2016; Özdemir et al. 2016; Jaiswal et al. 2018; Dineshkumar et al. 2020), verifying that the application of algal strains as biofertilizers has stimulated elevated crop yields and plant growth (Coppens et al. 2016). Different types of microalgal biomass have been investigated for fertilization purposes. Yadavalli et al. (Yadavalli and Heggers 2013) examined the efficiency of *Chlorella pyrenoidosa spp*. in dairy effluent treatment and applied the algae biomass filtrate as a biofertilizer on rice seeds, proving a significant boost in root's length. Beltran-Rocha et al. (Beltrán-Rocha et al. 2017) used native microalgae consortia of 21 microorganisms for municipal wastewater effluent treatment and biofertiliser production. All treatments resulted in high removal efficiency of nutrients (up to 79% of total nitrogen and up to 94% of total phosphorus) and showed potential for the valorization of algae biomass as biofertilizer because of their substantial protein, lipid and carbohydrate content. Lutzu et et al. (2016) when studying brewery wastewater, *Scenedesmus dimorphus spp*. absorbed over 99% of nitrogen and phosphorous in a very short retention time (7 days). Das et al. (Das et al. 2019) cultivated two microalgae strains (*Scenedesmus sp.* and *Chlorella sp.)* in municipal wastewater in large-scale and the microalgae biomass was used as biofertilizer to grow wheat plant. A rise in the quantity of leaves and average plant size was recorded in both algae cases, when compared to conventional NPK fertilizer. These results were also verified through a lifecycle assessment by Castro et al. (Castro et al. 2017). The microalgal biofertilizer cultivated on wastewater from a meat processing industry had more impact than the conventional fertilizer, in all categories examined, such as climate change, fossil depletion freshwater eutrophication and ecotoxicity, terrestrial ecotoxicity and acidification and particulate matter formation.

Another possible use of produced dried algae is in the animal feed sector. Dried algae can be incorporated into animal feed according to the Catalogue of Feed materials (EU 2017/2017). The inclusion of algal biomass into animal diets has been investigated for decades (Lum et al. 2013). Different sources of cultivated algae have been reported in literature as feed supplements and additives, in the nutrition of a wide range of animals, having positive effect on growth, productivity and dairy products quality (Holman 2012; Holman and Malau-Aduli 2013). Nevertheless, prolonged feeding on algae at higher concentrations has been reported to induce adverse effects (e.g. yellow color of egg yolk or broiler skin) (Spolaore et al. 2006).

In this context, the end-product of the pilot plant could be efficiently included as a feedstuff for several animals, ruminants or monogastric, ranging from farm animals and pets to aquaculture substituting a significant part of animal feed required. The nutritional value of the produced dried algae could be evaluated by direct comparison with the respective values of several algal species and conventional feedstuffs. From the data of Table 6, it is evident that the pilot plant algae product could stand as a balanced feed with nearly 30% protein and 30% carbohydrate contents, and a nearly 14% lipid content. Nevertheless, the absence of contaminants and impurities should be ensured and in-vivo animal trials should be performed prior to any commercialization.

Hintz and Heitman (Hintz and Heitman 1967) supplemented pigs' diet with 10% of sewage grown *Scenedesmus sp.* and *Chlorella sp.* and the results showed comparable effects to the conventional basal diet. Also, Hintz et al. (Hintz et al. 1966) examined the nutritional value of sewage-grown algae on cattle, sheep and lambs. They tested mixtures of algae strains (*Chlorella, Scenedesmus obliquus, S. Quadricauda*) with hay, for animal feeding. They achieved high protein digestibility but lower carbohydrate and non-lipids digestibility. Thus, the valorisation of the algae product as animal feed is very promising.

Energy requirements

Two forms of energy are required for the plant to operate; electrical energy which is provided by the photovoltaic system; and thermal energy, due to the temperature required for algae growth (around 25 °C). The thermal energy is provided by a biomass boiler which operates on biomass pellets with a net calorific value of 18.5 MJ/kg. The boiler efficiency was considered equal to 85%.

During the operation of the pilot plant, the consumption of each of the electrical equipment is presented in Table 7.

In Table 8, the amount of energy provided by the photovoltaic panels as well as from the biomass burner during the operation of the pilot plant is presented.

Table 6 Nutritional characteristics of dried algae produced from the pilot plant, several algal species and conventional feedstuffs

	% Crude protein	% Crude carbohydrates	% Crude lipid
Pilot plant algae product	29.21–32.28	16.31–34.76	12.30–14.74
Conventional feedstuffs			
Fish meal	63		11
Poultry meal	58		11.3
Soybean	37–44	30–39	22–22
Wheat	12.2–14	69–84	2–2.9
Corn	10	85	4
Algae species			
Spirulina platensis	50–66	8–23	2–12
Spirulina maxima	60–71	13–16	6–7
Chlorella sp.	37–58	5–28	13–22
Scenedesmus sp.	48–56	10–52	
Porphyridium sp.	28–39	50–57	
Nannochloropsis sp.	18–34	27–36	24–28

Table 7 Consumption of the electrical components of the pilot plant

Equipment	Energy consumption (W)	Operation (h/d)
Blower	311	24
Peristaltic pump	958	1
Centrifuge	2170	2
Biomass boiler	546	24
Spray drier + compressor	3095	2
TOTAL	7480	

Table 8 Energy required for the operation of the pilot plant

Algaecan waste water treatment		
Energy	Amount	Units
Electricity	2042	(kWh/ m^3 treated WW)
Biomass	66,6	(MJ/ m^3 treated WW)

Design of full-scale implementation

In order for the proposed treatment scheme to have significant added value, it is important to provide insight on how it can be implemented at full-scale. The aim of this section is to provide certain suggestions regarding the steps that need to be followed in order to implement the pilot plant system at full scale.

The design of the full-scale implementation was made considering wastewater flow rate 800m^3/d, which is the wastewater flow rate peak of the FVP plant studied, since treatment facilities must be built to accommodate high hydraulic flows without negatively compromising the treatment efficiencies. As far as wastewater characteristics are concerned, the mean values of the characteristics of Table 1 were taken into account for the design of the plant.

The system should be composed of the following main components:

Wastewater storage and homogenisation tank

The influent wastewater will be stored in a tank with pH control system for equalisation and homogenization reasons. A residence time of 1 day is considered. Thus, the working volume is equal to 960m^3, assuming a safety factor of 1.2. Two tanks of 500 m^3 should be incorporated in the full-scale plant.

Raceway pond

According to the pilot plant operation, descripted above the optimum inoculum to wastewater ratio was 0.25‰ (0.25 kg algae per m^3 wastewater). During the start-up, a minimum residence time of 14 days should be ensured. Two raceway ponds of 100 m^2 pond area each will be incorporated in the full-scale plant. According to marketable products the dimensions should be 3 m width, 33.8 m length and 30 cm depth, resulting in a total volume of 30.3 m^3.

Culture tanks

According to the performance data of the pilot plant operation, a residence time of 3 days should be applied. Blowers capable of providing sufficient air to maintain a soft mixing inside the tank, allowing microalgae growth should be placed in the bottom of the culture tanks. Critical parameters that should be monitored during the process are pH and temperature. Thus, a working volume of 2880 m^3, assuming a safety factor of 1.2 could meet the needs for the FVPI wastewater treatment. Three culture tanks of 1000 m^3 are proposed. Each reactor will count on an air diffusion system in the bottom, fed by a blower capable of providing over 46,000 m^3/h of air. Commercial products could meet this specification.

Centrifuge

A commercial centrifuge that will continuously operate will be included in the treatment train. The selected equipment should be able to process from 15 to 140 m^3/h depending on the solids content of the influent with centrifugal force over 1650 *g*, speed over 1800 rpm and motor power over 132 kW.

Inoculum tank

Given that the daily needs of each cultivation tank in inoculum are around 15m^3 (15 g/L microalgae concentrate obtained from raceway after centrifugation), a tank of 50m^3 is sufficient.

Stirred storage tank

From the data of the pilot plant operation for a residence time of 3d, the efficiency of the system in terms of dry microalgae production per volume of treated wastewater is 1.576.78 ± 421.48 g/m^3. Thus, the influent flow rate of 800m^3/d would produce 1.26tn/d of dried microalgae. The latter corresponds to 85m^3/d algae solution of 1.5% concentration in the stirred storage tank after centrifuge. Thus, a tank of 200m^3 could be used assuming safety factor (1.2) and residence time of 2d. This tank should be mechanically agitated at low velocity.

Spray dryer

Commercially available spray dryers that could satisfy the plant's needs should present minimum water evaporation capacity 3.000–4.500 kg/h. Two stage spray dryers could be used, each one with an evaporation capacity of 2.400 kg/h and a consumption of 47 kW/h and 2.350.000 kcal/h.

Microalgae powder storage tank

According to the operational data of pilot pilot plant and assuming an apparent density for dried microalgae equal to 0.64 g/mL, a storage tank of 10 m^3 should be included in the system to feed the downstream packaging equipment.

Packaging equipment

For the case of dried microalgae, it was assumed that it will be packed in 5 kg bags. In a single basic line, the machine unit may do automatic material measurement, manual bag feeding, and automatic bag mouth stitching. A typical commercial packaging equipment may fill 8–15 bags/min of 5–60 kg per bag with a weighing error 0.2–2% and 3 kW host power.

Photovoltaic system

For the estimation of energy needs of the system, meteorological statistical data of the local area for the months of operation (July to September) were considered. A 120 kW solar system could be used, which includes 333–480 panels generating around 13,500 kWh/mo and could be mounted on rooftop or ground up to 800 m^2.

Figure 3 presents a simplified flow diagram of the full-scale implementation of proposed treatment train in FVPI. The flow rates, the characteristics of the influent and effluent along with the daily production of the microalgae are presented. The dimensioning of the equipment is also evident.

From Fig. 3, it is evident that 1.26 ton/d of microalgae could be produced, which could be later used as fertiliser and/or animal feed. The price of the produced microalgae products could be considered equal to ten euros per kilogram (€10/kg) for both biofertilizer and animal feed use, taking into account four critical factors: (a) product quality, (b) market demand for algae and competing product prices, (c) production and distribution costs, and (d) results from preliminary market research.

Regarding the capacity of the unit, the plant is expected to work 330 days a year (excluding maintenance works), with an 8-h shift per day.

Based on the aforementioned, the economic benefit from the use of microalgae as a fertilizer or as animal feed is 15.75€/m^3. Of course, this value does not include the depreciation of capital cost and the operational expenditures.

Nevertheless, this circular and resource efficient concept should be compared with the current management schemes. The system currently applied in the FVPI studied is a conventional double-stage activated sludge treatment process including pre-treatment (coarse filtration, homogenization and neutralization), biological treatment (primary decantation, recirculation of sludge, aeration, secondary decanting, and secondary recirculation of sludge) and sludge treatment (sludge thickener, sludge dehydration). The treated wastewater is disposed in the local wastewater treatment plant. Even though the discharge meets the parameters set by law, the cost of treatment ranges from 2 to 2.5€/m^3.

From an environmental perspective, the proposed solution provides a gold standard example of the circular economy concept. More specifically, the calculated savings are 1.15 kg CO_2 equivalent per kg of sludge avoided. This is achieved as the energy used in this process is 100% from renewable energy: a photovoltaic system and a biomass

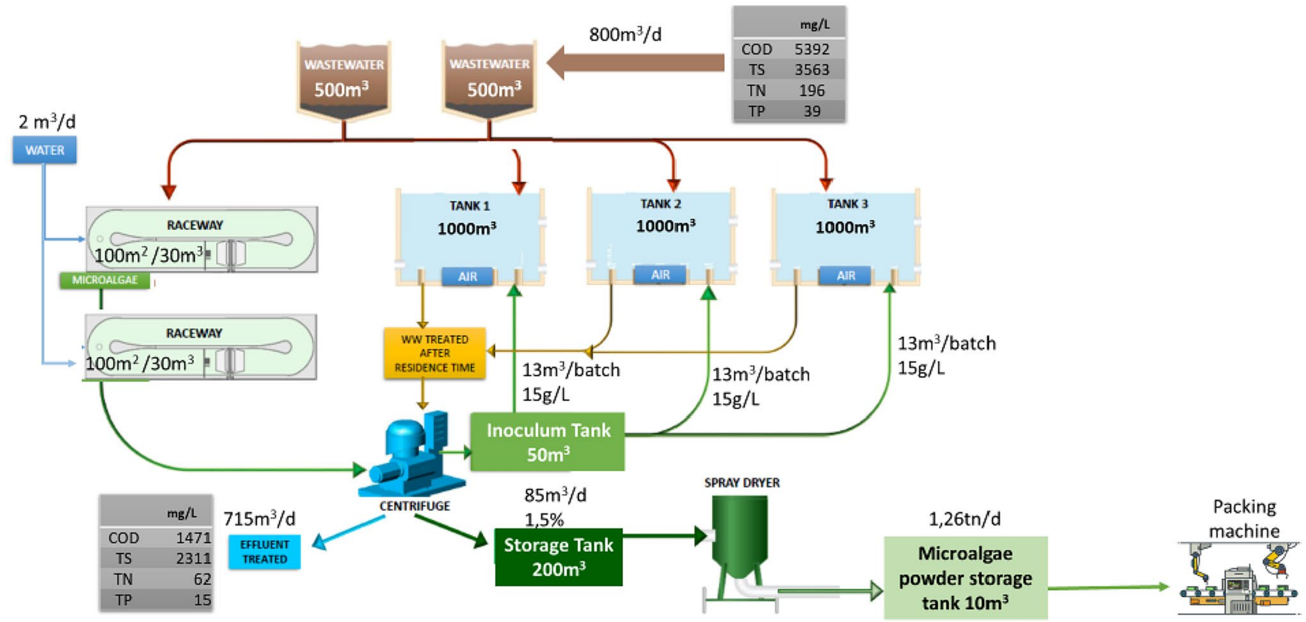

Fig. 3 Flow diagram of full-scale implementation of proposed treatment train in FVPI

boiler. Given the additional aspect of microalgae CO_2 absorption during growth and biomass production rate from wastewater, the environmental sustainability of the process, in comparison with existing solutions, is very high. The use of renewable energy (solar and biomass) will result in a saving of 0.531 kg of CO_2 emissions per kWh consumed.

Another aspect to be noticed is the nutrient reduction achieved through uptake by the biomass. This avoids the use of high environmental impact chemicals such as ferric chloride for phosphorus removal and avoids energy-intensive aeration for ammonia reduction.

The proposed technology will help European authorities to accomplish the priority EU Directives on environmental regulations. Among them, Directive 2008/1/EC on Integrated Pollution Prevention and Control (IPPC) Directive intends to ensure environmental prevention as a whole through protecting its elements, water, air, and land. The proposed technology aims to maximize the use of energy from renewables and the valorization of the by-products. Moreover, it will help the EU authorities to comply with Directive 2000/60/EC Water Framework Directive, prevention of water from deterioration of its status, 80/68/EEC protection of groundwater against pollution caused by certain dangerous substances by eliminating the risk of leachate intrusion into soil and water, 1999/31/EC on the Landfill of Waste and Directive 2009/28/EC on Promotion of the Use of Energy from Renewable Sources in the European Union.

Concluding remarks

Conclusively, within this study a successful demonstration of the technical feasibility of an innovative concept for FVPI wastewater treatment based on heterotrophic microalgae culture was performed aiming to substitute, in the long term, the traditional aerobic digestion. By this scheme, instead of waste sludge and nutrients losses, added-value microalgae are produced.

Although the cultivation of microalgae is becoming attractive given the ability of some microalgal strains to produce added-value products, energy consumption and scalability are a few of the main issues with this technique. Furthermore, currently, the cost of producing value-added products using microalgae is higher than that of other sources. The approach for growing microalgae and valorising them has not yet reached commercialization because of the high costs associated with downstream processing. However, by using solar radiation and biomass as energy sources and avoiding traditional costs associated with aerobic sludge management as proposed in the present study, the cost of FVPI treatment could be decreased significantly. This reduction could be even higher if the potential incomes from algae-based products selling are considered, since the produced algae are of high-quality meeting the market standards of biofertilisers and animal feed. Thus, this biorefinery approach could provide FVP sector with a promising and sustainable cost-effective process for on-site treatment of streams rich in organic matter, nutrients and salts.

Author contributions JMMM: Investigation; Project administration; Writing—review & editing, LG: Investigation; Supervision, DH: Funding acquisition; Project administration, KM: Funding acquisition; Project administration; Supervision, EMB: Formal analysis; Data curation; Writing—original draft; Writing—review & editing, SM: Formal analysis; Data curation; Writing—original draft; Writing—review & editing.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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