water

MDPI

Article

Sludge Treatment Wetland for Treating Microalgae Digestate Grown in Agricultural Runoff: A Technical, Economic, and Environmental Assessment

Eva Gonzalez-Flo [1,*], Antonio Ortiz [2], Carlos A. Arias [3], Rubén Díez-Montero [2,4], Norbert Kohlheb [5], Ulf-Henning Schauser [6], Joan García [2] and Peder K. S. Gregersen [7]

[1] GEMMA-Group of Environmental Engineering and Microbiology, Department of Civil and Environmental Engineering, Escola d'Enginyeria de Barcelona Est (EEBE), Universitat Politècnica de Catalunya-BarcelonaTech, Av. Eduard Maristany 16, Building C5.1, E-08019 Barcelona, Spain
[2] GEMMA-Group of Environmental Engineering and Microbiology, Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya-BarcelonaTech, c/Jordi Girona 1-3, Building D1, E-08034 Barcelona, Spain
[3] Department of Biology, Aarhus University, 8000 Aarhus, Denmark
[4] GIA-Group of Environmental Engineering, Department of Water and Environmental Sciences and Technologies, Universidad de Cantabria, Avda. Los Castros s/n, 39005 Santander, Spain
[5] Helmholtz-Zentrum Fuer Umveltforschung GMBH–UFZ ("UFZ"), 04318 Leipzig, Germany
[6] N.A.T., Ingenieurökologisches Planungsbüro, 24340 Eckernförde, Germany
[7] Center for Recirkulering v/Peder S, 6870 Gregersen Ölgod, Denmark
* Correspondence: eva.gonzalez.flo@upc.edu; Tel.: +34-934137352

check for updates

Citation: Gonzalez-Flo, E.; Ortiz, A.; A. Arias, C.; Díez-Montero, R.; Kohlheb, N.; Schauser, U.-H.; García, J.; Gregersen, P.K.S. Sludge Treatment Wetland for Treating Microalgae Digestate Grown in Agricultural Runoff: A Technical, Economic, and Environmental Assessment. *Water* **2023**, *15*, 2159. https://doi.org/10.3390/w15122159

Academic Editors: Krzysztof Jóźwiakowski, Magda Kasprzyk and Piotr Bugajski

Received: 29 March 2023
Revised: 1 June 2023
Accepted: 5 June 2023
Published: 7 June 2023

Abstract: The management and disposal of wastewater treatment sludge can be a costly and resource-intensive process. To provide a cost-effective and sustainable alternative, Sludge Treatment Wetlands (STW) have emerged as a viable solution for enhancing sludge quality through dewatering and biodegradation. In this study, the effectiveness of a full-scale STW for stabilizing and dewatering digested microalgal biomass from a domestic and agricultural wastewater treatment system was evaluated. The properties of the treated digestate in the STW were assessed after 35 weeks of operation and a resting period of 4 weeks. The dry matter content was found to be 12.8%, and the average macronutrient content was K: 3.8 mg/g DW, P: 4.9 mg/g DW, and Ca: 95 mg/g DW. The highest contents of micronutrients were for Fe: 7.8 mg/g DW and Mg: 7.6 mg/g DW, while heavy metals and pathogen contents were below the EC limits for sewage sludge reuse in agriculture. The STW was found to be a cost-effective and environmentally friendly option for treating mixed wastewater-based sludge for land application. The STW outperformed reference systems using centrifuge dewatering techniques, particularly in terms of eutrophication potential and acidification potential. However, the STW's economic performance was slightly worse than that of the dewatering system in terms of unit production cost. This study is the first in the literature to investigate the use of STW for treating digested microalgae and its possible reuse in arable land, suggesting that STW infrastructures have great potential for the development of sustainable and eco-friendly sludge treatment technologies.

Keywords: digestate land application; digestate reuse; microalgae biomass; sustainable technology; vertical flow system

1. Introduction

Achieving sustainability, as outlined in the sustainable development goals, requires the integration of circular economy principles. This is particularly important in the context of water, which has multiple recycled uses and is closely linked to other material flows such as nutrients, carbon, and metals [1]. The sludge generated during wastewater treatment serves as a concentrated source of these elements and materials, presenting a valuable opportunity for resource recovery from wastewater [2]. Additionally, resources like phosphorous, potassium, and carbon are frequently limiting factors for sustainable and restorative agriculture, which can be addressed by using recycled materials from sludge.

Furthermore, the need for environmental and hygiene considerations has led to an increase in the amount of wastewater that requires to be treated, particularly due to the rapid growth of the population. Consequently, this surge in wastewater treatment activities leads to a corresponding escalation in sludge production [3]. Managing and disposing of sludge generated from wastewater treatment is a costly and resource-intensive process. Therefore, the development of sludge treatment technologies that are both cost-effective and environmentally friendly poses a challenge, particularly when dealing with different types of wastewater.

Sludge Treatment Wetlands (STW) present a promising alternative for improving the quality of sludge through dewatering and biodegradation. This technology offers the potential to recover valuable resources, including nutrients, organic matter, and even energy [2–4]. Planted reed beds have been used for this purpose in Germany and Denmark since the late 1980s [5], and there are facilities in Denmark with the capacity to process 200 to 3000 tons of dry matter per year [6,7].

In the last years, there has been a growing interest in the utilization of unconventional fertilizers for sustainable agriculture. Unconventional fertilizers include a wide range of organic and inorganic materials that are not traditionally used as fertilizers but can provide beneficial nutrients to plants [8]. These fertilizers can be derived from different waste streams, including sludge from wastewater treatment [9,10]. The use of unconventional fertilizers offers potential benefits for sustainable agriculture. Firstly, they serve as an alternative to synthetic fertilizers, thereby mitigating environmental pollution and persistent changes in soil ecology and physicochemical conditions [11]. Secondly, fertilizers derived from waste streams can contribute to waste management and aligns with the principles of circular economy [12].

Research has shown that the nutrient-rich sludge from wastewater treatment can be effectively processed and transformed into valuable biofertilizers [12]. Sludge contains significant amounts of essential nutrients such as nitrogen, phosphorus, and potassium, as well as organic matter, which are vital for plant growth [13].

The present work has tested the treatment of digested microalgal biomass using a full-scale STW system. The primary objectives were biomass stabilization, dewatering, and nutrient recovery for potential biofertilizer applications. The microalgae were grown in photobioreactors fed with a mixture of domestic wastewater and agricultural runoff [14]. The STW system consisted of a vertical flow constructed wetland planted with *Phragmites australis*. The filter media consisted of layers of gravel and sand of varying sizes to retain the dry matter on the surface and allow for continuous percolation of water, thus reducing the risk of clogging.

The primary objective of this study was to evaluate the efficiency of the STW in terms of technical, economic, and environmental performance. The changes in the dry matter content, heavy metals concentrations, nutrient levels, mineral content, and organic substances content of the digested biomass after dewatering and stabilization in the STW were measured to accomplish this objective. These parameters are crucial factors for determining the suitability of the treated digestate for land application, as outlined in the European Sludge Directive [15] and as recommended by the EU's Environment DG [16]. An economic and environmental life cycle assessment was performed, and the STW was compared to conventional dewatering technologies. To the best of our knowledge, this is the first study investigating the use of STW for treating digested microalgal biomass.

2. Materials and Methods

2.1. Experimental Setup

The STW was part of an experimental microalgae-based treatment plant built and operated in the framework of the European H2020 INCOVER project, located in the

Agròpolis Campus of the Universitat Politècnica de Catalunya-BarcelonaTech, in Viladecans (Barcelona) (41.288 N, 2.043 E UTM) (Figure 1).

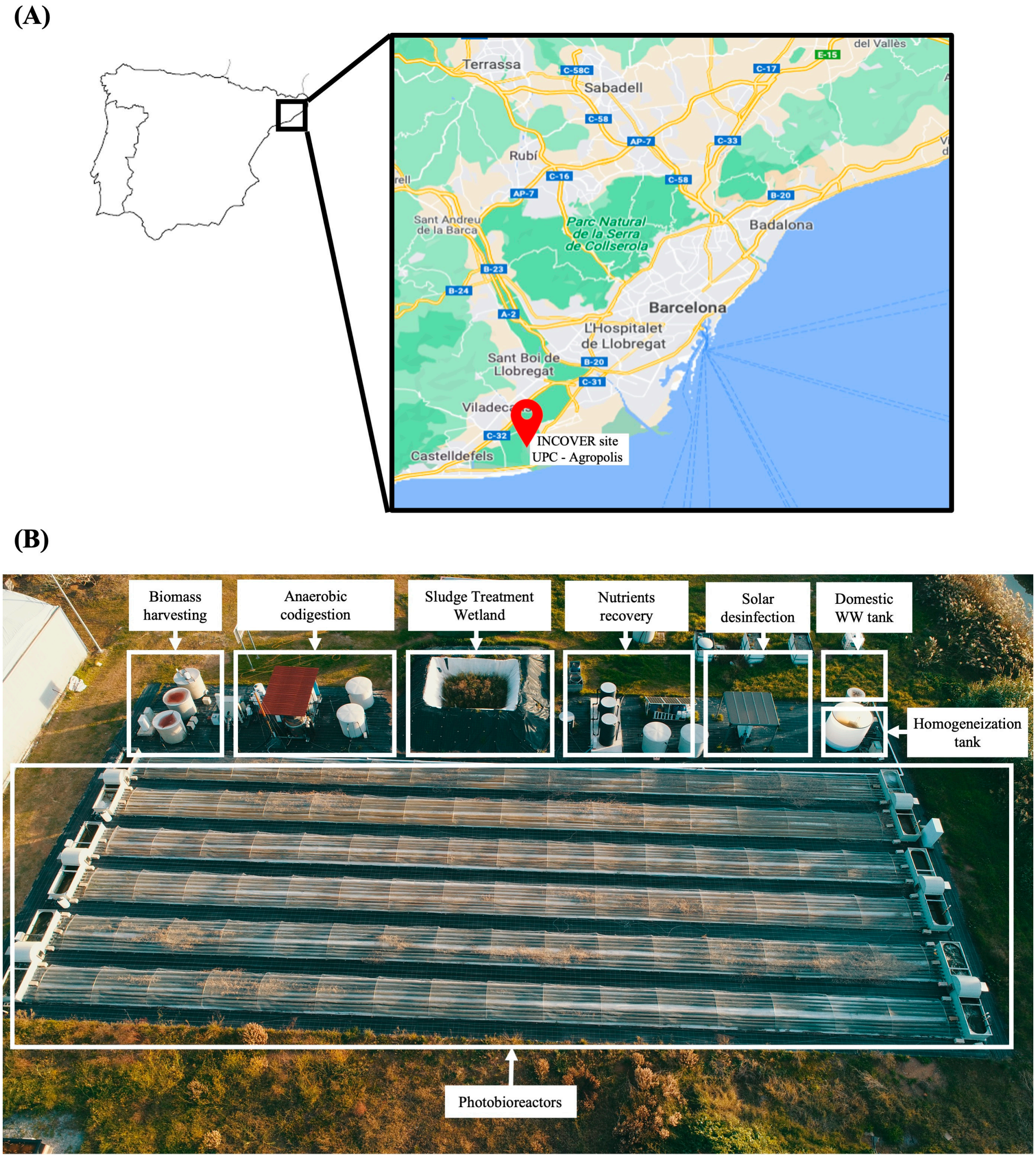

Figure 1. Location map of the facilities (**A**,**B**) global top view with unit processes of the INCOVER site demonstration-scale plant.

The microalgae-based treatment plant comprised several components: (1) a set of photobioreactors for wastewater treatment and microalgal biomass production, along with a biomass harvesting unit, (2) an anaerobic digestion plant to generate biogas using the harvested microalgal biomass, (3) an STW to dewater and stabilize the digested biomass, and (4) a tertiary treatment system for reclaiming water through ultrafiltration, disinfection, and nutrients recovery. Briefly, the microalgae production system consisted of three semi-closed, horizontal tubular photobioreactors at a demonstrative scale (11.7 m^3 each), which were fed with a mixture of agricultural runoff (90% v/v) and partially treated domestic wastewater (10% v/v). More information on the demonstrative-scale plant can be found in [14,17,18]. The biomass produced in the photobioreactors was harvested using a lamella settling tank (700 L) and thickened in two gravity thickeners (200 L each) [19,20]. The thickened biomass was then digested with secondary sludge in an anaerobic digester (800 L) at 35 °C and an average hydraulic retention time of 32 days. The biogas generated was stored in a gasometer for subsequent upgrading to biomethane. The digested biomass was stored in a 200 L tank and intermittently fed to the STW [14].

The STW was constructed in July 2017 and had an effective surface area of 6 m^2. It was designed as a single planted reed bed. Due to a lack of information on digestate production during the design period, the facility was oversized six to eight times larger than what would normally be needed for the load that eventually was fed to the system. The bed bank had a height of 1.50 m, allowing the STW to be filled with up to about 1 m of sludge. The wetland was constructed on top of the soil due to the high level of the water table during winter (Figure S1A,B).

To prevent bank soil erosion, the structure of the STW was protected with a 300 g/m^2 geotextile covered with a 1 mm light-density polyethylene liner. To further protect the liner, an additional layer of geotextile was placed on top. The outer part of the STW was lined with a thin woven polyethylene (PE) gardening liner.

At the bottom of the STW bed, corrugated drainage pipes were installed and surrounded by a 20 cm layer of gravel Ø 16–32 mm, followed by an upper 20 cm additional layer of Ø 2–8 mm. On top of these two layers, a thin layer (5 cm) of washed sand Ø 1–4 mm was added (Figure S1C–E). before planting, this sand layer was amended with a mixture of digested biomass and sand. Approximately 11 kg of harvested biomass from the lamella settling tank creates a favorable environment for the initial plant development (Figure 2).

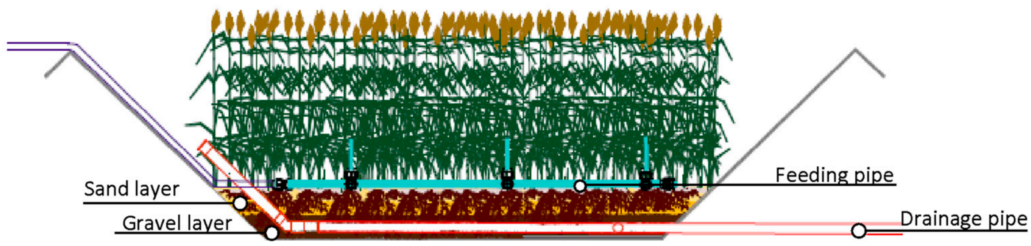

Figure 2. Schematic longitudinal view of the STW bed. The gravel layer has two different materials (20 cm of Ø 16–32 mm gravel and on top 20 cm of Ø 2–8 mm gravel).

The drainage system for percolating liquid discharge was installed and immersed within the coarsest gravel at the bottom of the STW bed. Vertical pipes for aeration were also connected to the drainage system to improve aeration in the bed.

In February 2018, the STW was planted with common reed (*Phragmites australis*) at a density of 10 plants/m^2. A system was built to feed and distribute the digestate using 50 mm polyethylene pressure pipes with pipe risers (Figure 3). The start-up phase for the STW began after the bed was planted and finished at the end of April 2018. The bed was saturated with nutrient-rich water to ensure the establishment of the plants until they were healthy and strong enough to handle the loading of digested material. No replanting was necessary.

The operational phase began on 1 May 2018, and ended on December 2018. During this phase, approximately 200 L of volume was discharged to the bed every 7–9 days, corresponding to the time required to fill up the digestate storage tank. As a result, the STW had a resting time of approximately 7–9 days between each feeding event. It is worth noting that the 200 L were discharged in just a few minutes. After the last feeding, a resting period of 4 weeks was implemented from 20 December–16 January to allow for the stabilization and dewatering of the digested biomass.

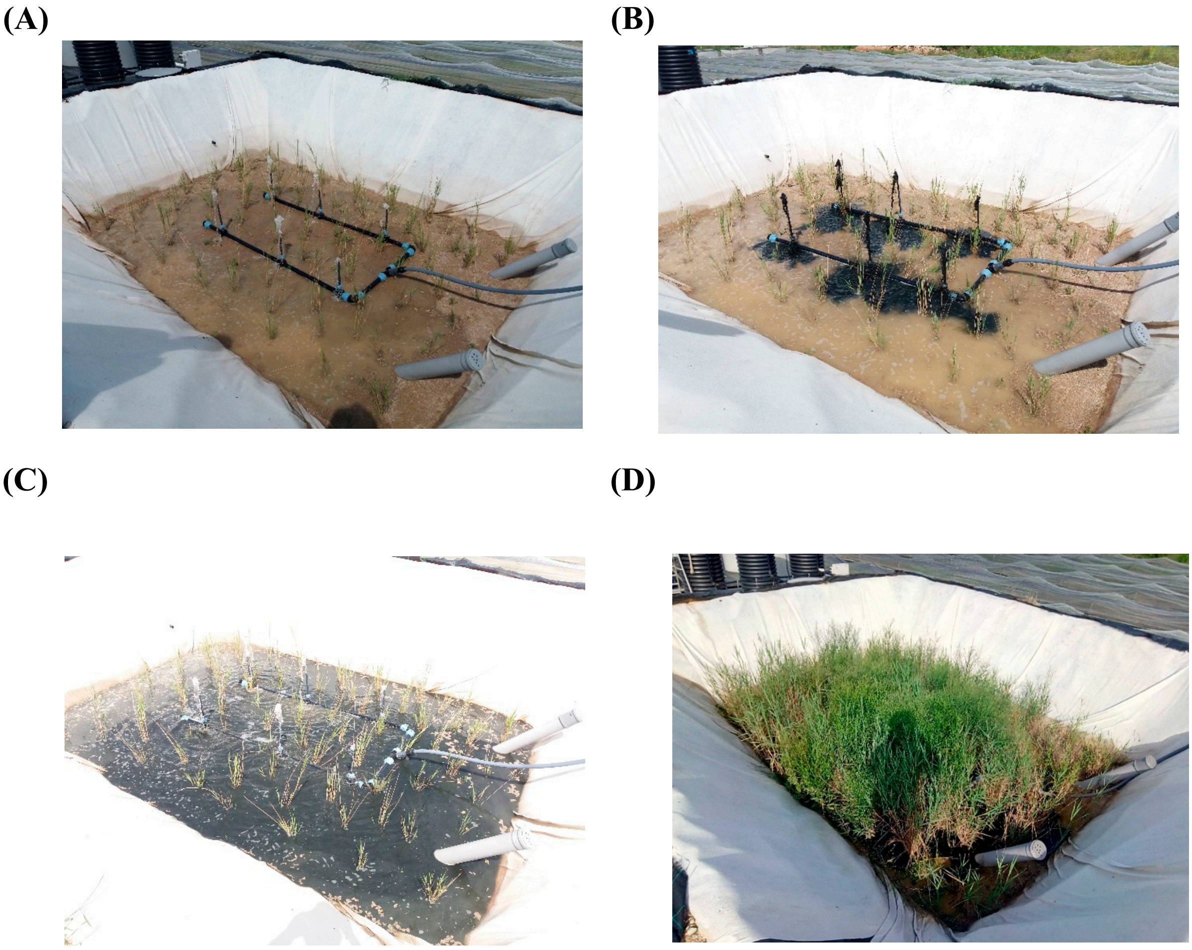

Figure 3. Image showing the top of the bed of the STW and the digestate distribution system. Before feeding (**A**), first feeding (**B**), after feeding (**C**), and after several months of operation (**D**). Note the black color due to digested biomass which was poured onto the nutrient-rich water. Images credits: Center for Recirkulering v/Peder Gregersen.

2.2. Sample Collection and Characterization

Samples of the digestate stored in the 200 L tank were collected and analyzed using conventional methods following the procedures outlined in the Standard Methods [15]. The parameters evaluated include total and volatile solids (TS and VS), total nitrogen (TN), total carbon (TC), heavy metals, and fecal bacteria indicators (*Salmonella* spp. and *Escherichia coli*) as stated in the European Sludge Directive (Council Directive 86/278/EEC). Digestate samples were mostly taken every 7–9 days.

After the resting period following the operational phase, three samples of the digestate retained on the top of the bed were taken with a shovel. These samples were taken from three different surface locations (triplicates) and analyzed for the same parameters as the fresh digestate. It is important to mention that these samples were collected just one month after the conclusion of the operational phase. The analysis included the determination of macronutrients, heavy metals, and pathogens in accordance with Standard Methods [21]. It is worth noting that these analyses were conducted on dried biomass, and therefore, the results are expressed on a dry matter basis (DM).

2.3. Sustainability Assessment

A comparative LCA and LCC analysis was performed comparing three scenarios:

- The first scenario contains the STW and field application of the dried digestate (30% of dry matter (DM)) with transport.

- The second scenario comprised dewatering with a centrifuge and field application of the dewatered digestate. The dry matter content of digestate after dewatering reached 30% as well.
- The third scenario consists of the centrifuge dewatering step that is followed by digestate incineration and, finally, land application of ash.

The life cycle assessment (LCA) model based on the ISO 14040:2006 standard [22–24] was built applying a cradle-to-gate LCA approach to capture material and energy flow both from the infrastructure and operation phases of the life cycle. The functional unit (FU) was set to 1 m^3 of influent digestate to the STW, and all necessary inputs were referenced to it. The life span of the STW was defined as 40 years. Using the CML2001–January 2016 characterization model, global warming potential (GWP), eutrophication potential (EP), acidification potential (AC), human toxicity potential (HTP), and primary energy use (PE) were applied to depict the environmental performance of the wetland. The calculation was made using the LCA software, GaBi8© with GaBi Professional, GaBi Construction Materials, GaBi Food and Feed, and Ecoinvent databases.

The economic analysis was based on dynamic life-cycle costing (LCC) calculations using indicators of capital expenditures (CAPEX), operational expenditures (OPEX), and unit production costs (UPC), where total discounted costs were divided by the FU. The interest rate for discounting was set to 0.25%. Real data for the investment cost were collected when the STW was built; however, planning and construction costs were not considered. The operation costs were calculated using an electricity price of 0.1 EUR/kWh, a transport cost of 0.13 EUR/km (for treated digestate field application), land costs of 1.05 EUR/m^2, and personnel costs of 400 EUR/year for the first operation year and 100 EUR/year for the other years. Note that a personnel cost of 2000 EUR/year was considered in the case of a dewatering centrifuge used for scenario comparison. The amount of electricity consumed in the STW was metered, and the transport distance for treated digestate disposal was set to 50 km. The economic calculation of the reference system was partly based on real costs and partly taken from the literature. Mechanical dewatering with a centrifuge was calculated using real planning costs for machinery, energy, and personnel; however, the cost of incineration and field application was defined by [25].

Scenarios 2 and 3 were used as reference systems for comparison. All three scenarios evaluated the fertilizing effect of the digestate or ash by measuring the phosphorous, potassium, and nitrogen content. The resulting nutrient content of the dewatered biomass, based on the experimental results, was used for the LCA and LCC evaluation, mainly the phosphorous content was 4.9 g/kg DM, the potassium content was 3.8 g/kg DM, and the nitrogen content was 1.8 g/kg DM.

For scenario 1, the nitrogen content was not considered, and for incineration, the ash share of digestate DM was set to 45% [26]. The fertilizing effect was converted to conventional fertilizers, such as superphosphate, potassium chloride, and ammonium nitrate, using the conversion rates of 0.4364 for superphosphate and 0.5244 for potassium chloride. This is the reason why there can be negative values for EP and AP. All steps of the scenarios considered the necessary transport efforts.

The reference flow of the STW scenario was defined by the treatment capacity of the 50 m^2 active surface, which is 65 kg DM/m^2 year digestate in dry matter. This makes 5652 m^3 of digestate for 40 years of a lifetime for the total active surface, assuming 1 t/m^3 density and 2.3% DM content.

In the case of the second and third scenarios, the hydraulic capacity of the centrifuge was considered as 292,000 m^3 of digestate for 40 years of lifetime. For calculating the environmental impact of the STW, the inventory summarized in Table 1 was used.

Table 1. Inventory of the STW system.

Material or Energy Flow		Amount
Infrastructure	Excavation, m^3	50.08
	Steel, kg	1.57
	PE tube, kg	34.76
	PE liner, kg	113.98
	PP tube, kg	5.85
	PP geotextile, kg	36.00
	Rubber, kg	0.20
	Bitumen, kg	0.30
	Pump, kg	82.00
	Sand, kg	7680.00
	Gravel, kg	43,200.00
	Earth, kg	72,115.20
	Land occupation, m^2	2000.00
Operation	Transport, km	2557.73
	Electricity, MJ	953.33
Credits	Superphosphate equivalent, kg	2840.7
	Potassium chloride, kg	1412.5

The inventory data for the two reference scenarios are summarized in Table 2.

Table 2. Inventory of the reference scenarios used for comparison.

Material or Energy Flow		Amount
Dewatering	Excavation, m^3	18.278
	Transport, km	2335.72
	Gravel, kg	20246.4
	Concrete, kg	22,496
	Concrete working, kg	22,496
	Glass fibre reinforced plastic, kg	637.71
	Steel, kg	1462.63
	Pump, kg	111.75
	PAM, kg	58,788.756
	Polymer dosing unit, PEHD, kg	320
	Polymer dosing unit, PVC, kg	200
	Polymer dosing unit, steel, kg	80
	Agitator TIMSA, steel, kg	120
	Agitator TIMSA, motor, kg	40
	Land occupation, m^2	2000
	Electricity, MJ	2,035,123.2
Centrifugal decanter	Steel, kg	800
	Steelworking, kg	800
	Electric motor, kg	200
	Electricity, MJ	2,312,640
Incineration	Unit process for municipal sludge, kg	22,445,455.4
	Transport, km	1,468,799.1
Spreading of ash	Unit process, kg	3,022,200
	Transport, km	151,110
Crediting ash	Superphosphate	163,932.17
	KCl	81,111.111
	Ammonium nitrate	35,713.781

Table 2. *Cont.*

Material or Energy Flow		Amount
Spreading of dewatered sludge	Unit process, kg	22,445,455.42
	Transport, km	1,122,272.771
Crediting sludge	Superphosphate	163,932.172
	KCl	81,111.111
	Ammonium nitrate	35,713.781

3. Results

3.1. STW Performance Characterization

The digestate that was supplied to the STW had a dry matter content ranging from 0.5% to 5.0% TS, as shown in Figure 4. Note that the dry matter typically had values between 2 to 4% TS, with an overall average of 2.3% TS. The volatile content of the dry matter remained relatively stable throughout the operation, with an average ratio of volatile solids to total solids of 0.45.

Figure 4. Evolution of dry matter (percentage of total solids) and ratio volatile solids/total solids of the digestate fed to the STW.

The STW loading period lasted 35 weeks (from 2 May 2018–20 December 2018). During the loading period, a total of 5230 L of digested biomass were applied to the STW.

Regarding the dewatering capability of the STW, the samples collected after the four-week resting period showed a significant increase in the dry matter content. In particular, the dry matter percentage of the digestate raised from an average of 2.3% TS in the fresh digestate to 12.7% TS in the accumulated digestate. Despite this increase, the digestate was still too wet for transport and handling, such as spreading on land. An optimal level for handling would be 20% or greater. It is known from previous studies that are using STW with *Phragmites australis* to treat digestate directly from active sludge treatment systems can result in dry matter percentages greater than 30% TS [7]. Probably the plants were not sufficiently developed in the system to achieve such a level of dryness. Additionally, it is important to note that it cannot be compared this result with previous studies due to the lack of literature on STWs fed with microalgae digestate. The accumulated digestate had an organic carbon content of 53.25% ± 0.09 and an inorganic carbon content of 46.75% ± 0.09.

During the loading period, the STW average total nitrogen influent concentration was 1360 mg/L, and the average ammonium concentration was 363 mg/L (Figure 5). The high concentration of nitrogen is linked to the origin of the digestate, which was microalgae biomass that is well-known to have a high protein content [27].

The assessment of macronutrient content in retained digestate samples is an important step in determining their potential value for agricultural use. In this particular case, the analysis showed that the digestate had a high average content of calcium (95 ± 1.33 g/kg DW), as well as relatively high concentrations of phosphorus (4.9 ± 0.05 g/kg DW) and potassium (3.8 ± 0.28 g/kg DW), all of which are essential macronutrients for plant growth [28,29]. Calcium is particularly important for cell wall structure and root development, while phosphorus and potassium are important for energy transfer and osmotic regulation. The presence of these macronutrients in the digestate suggests that it has the potential to be a valuable resource for agricultural purposes, as it can serve as a source of essential plant nutrients and contribute to sustainable agriculture practices [30].

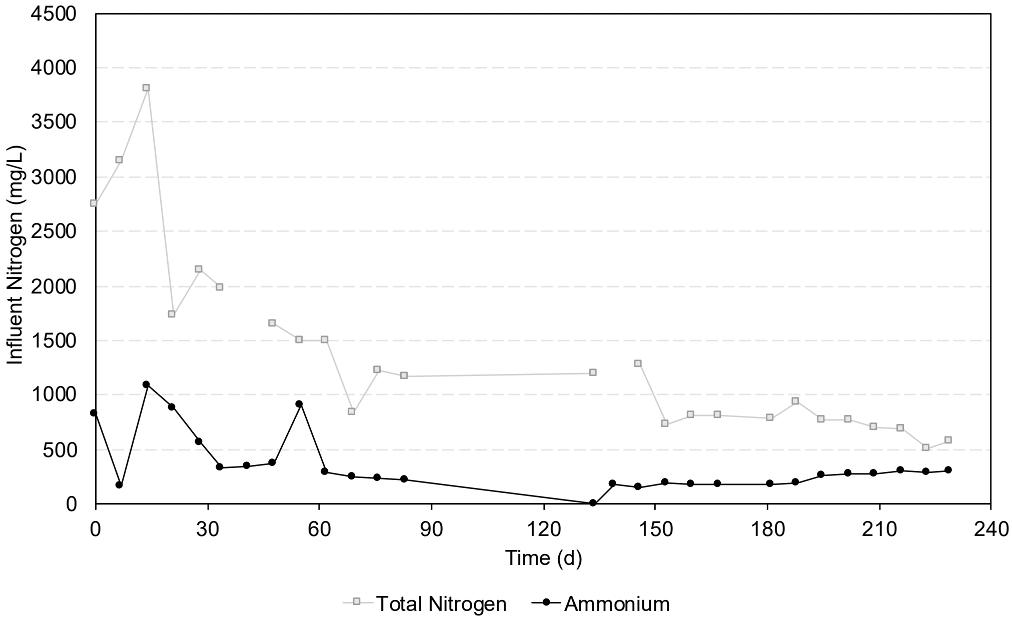

Figure 5. STW influent total nitrogen and ammonium (both expressed as N).

The microelements sodium (8.19 ± 2.41 g/kg DW) and magnesium (7.61 ± 0.39 g/kg DW) were within the ideal range for agricultural reutilization of digestate. The ideal content of magnesium and sodium for agricultural reuse is between 0.2–2% and 0.4–4% by dry weight. However, it is important to observe that these ranges will vary depending on the application and soil type [31]. Moreover, it is essential to determine the specific concentration of magnesium and sodium in the digestate, given their crucial role in human and animal nutrition [32]. Stabilized digestate, achieved through biological processes, can serve as a valuable resource for agricultural applications. It contains a wealth of essential nutrients, particularly magnesium and sodium, which play a crucial role in various biological processes. These processes include photosynthesis, cellular respiration, regulation of water and acid-base balance, and the enhancement of soil nutrient availability and water retention. Moreover, the use of digestate can help mitigate the presence of harmful substances in the soil, thereby contributing to improved soil quality [31,33].

The determination of heavy metals in the dewatered sludge is also important in order to ensure both its potential as a mineral resource for farming and the absence of environmental risk. The retained digestate was analyzed for heavy metals, such as copper, zinc, iron, and manganese, and their concentrations were compared to the regulatory limits.

Results of the concentration of heavy metals in the retained digestate after the resting period, are shown in Table 3. The regulatory limits for heavy metals in sewage sludge reuse in agriculture are set by the Council Directive 86/278/EEC. The results showed that all regulated heavy metals were within the permissible limits, indicating that the reuse of digestate in agriculture is safe (European Parliament, 1986).

Table 3. Concentration of heavy metals of the digestate retained on the STW. Limit values set by Council Directive 86/278/EEC are also shown.

	Cu	Zn	Fe	Mn	Ni	Cd	Cr	Pb
Council Directive 86/278/EEC limits (mg/kg)	1000–1750	4000	-	-	300–400	20–40	-	750–1200
STW (mg/kg DW)	50 ± 0	291.5 ± 0.70	7873 ± 144	290 ± 2.82	31 ± 1.41	0.7 ± 0	26 ± 1.27	11.85 ± 0.35

The dewatered digestate was also tested for pathogens after the operation period. The results revealed no presence of *Salmonella* spp. and *Escherichia coli*, and therefore, the retained digestate met the EU regulation. This is likely due to the anaerobic digestion process and the long retention time in the bed of the STW.

Additionally, the thickness of the dewatered digestate layer was measured to be 3 cm (Figure 6). The layer exhibited cracks, likely caused by shrinkage of the material, and small open areas were observed around the stems of the *Phragmites australis*, which could facilitate drainage during future loadings.

Figure 6. View of the retained digestate layer laying on the bed of the STW. Note the extensive crack on the left-hand bottom of the picture. Images credits: Center for Recirkulering v/Peder Gregersen.

3.2. Environmental Impact LCA

The results of LCA are depicted in Figure 7. When comparing the scenario of using STW for digestate dewatering and field application to the reference systems of the centrifuge and field application and centrifuge and incineration (Scenarios 2 and 3, respectively), the environmental performance of STW was considerably better in all of the checked impact categories. Notably, it significantly outperforms the reference systems in terms of eutrophication potential (EP) and acidification potential (AP). It is worth noting that the compared systems differ significantly in their maximum processing volumes: STW size is 5652 m^2, assuming it is filled up to 1 m^3 per m^2, whereas conventional dewatering systems may have higher capacities, up to 292,000 m^3.

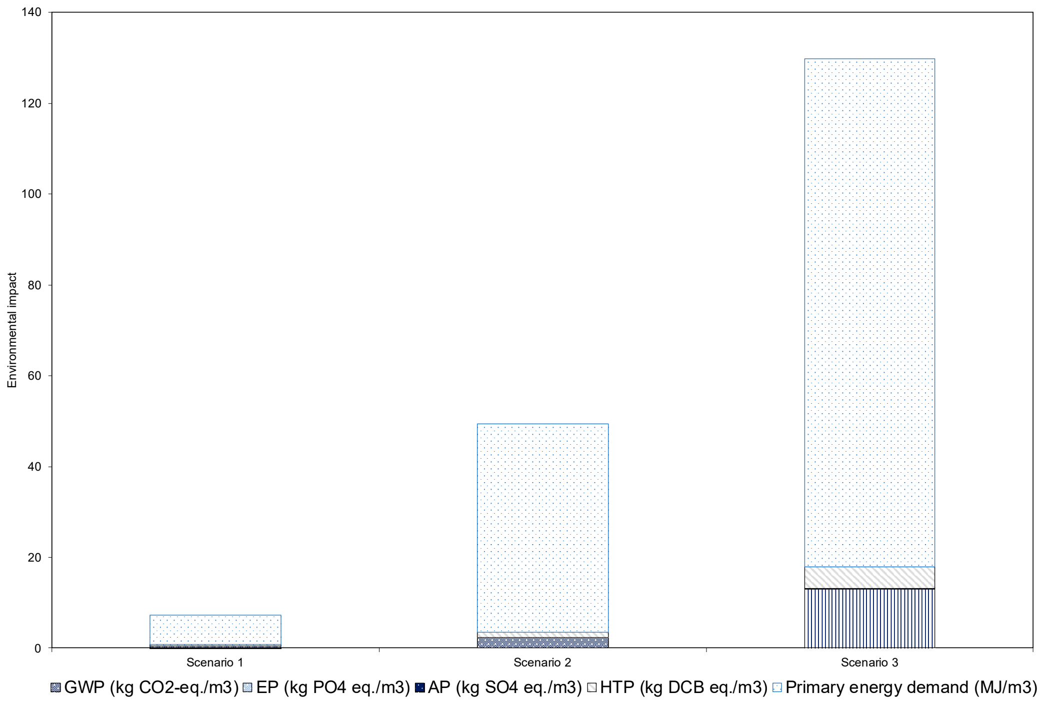

Figure 7. Results of the LCA for the impact categories of global warming potential (GWP), eutrophication potential (EP), acidification potential (AC), human toxicity potential (HTP), and primary energy use (PE).

3.3. Economic Impact LCC

The economic performance of the STW (Table 4), measured in terms of unit production cost (UPC), is slightly worse compared to the case of dewatering. This is primarily due to the significant difference in scale between the two systems. Unfortunately, CAPEX and OPEX values for the reference system were not available in the literature. The most expensive system found in the study is the one that employs incineration and field application, i.e., scenario 3, which costs 5.66 EUR/m^3 of treated digestate.

Table 4. Capital expenditures (CAPEX), operational expenditures (OPEX), and unit production costs (UPC).

	CAPEX EUR	OPEX (EUR/Year)	LCC, Discounted Total Costs (EUR/Lifetime)	Unit Production Cost (EUR/m^3)
STW	4296.69	126.16	9852.86	1.74
Dewatering	122,947.25	8565.61	444,423.22	1.52
STW and field application	n.a.	n.a.	20,973.30	3.71
Dewatering and field application	n.a.	n.a.	1,018,923	3.49
Dewatering, incineration, and field application	n.a.	n.a.	1,653,159	5.66

4. Discussion

The study evaluated the performance of Sludge Treatment Wetlands (STW) in stabilizing and dewatering digested microalgal biomass from a domestic and agricultural wastewater treatment system. The dewatering capability of the STW was assessed after a four-week resting period, and it showed a significant increase in the dry matter content. The digestate dry matter percentage increased from an average of 2.3% TS in the fresh digestate to 12.7% TS in the accumulated digestate. However, the digestate still had a moisture content that was too high for easy transport and handling, such as spreading on land. Previous studies have shown that STWs with *Phragmites australis* can achieve dry matter percentages greater than 30% TS when treating digestate directly from active sludge treatment systems. It is possible that the plants in this study were not sufficiently developed to reach such levels of dryness. It is important to note that there is a lack of literature on STWs fed with microalgae digestate, making it difficult to compare the results with previous studies.

The stabilized digestate had a relatively high content of macro- and micro-nutrients and a high content of carbon that could serve as a valuable source for gardening or agriculture. It can supply the needed nutrients as well as serve as a soil conditioner. The micro- and macro-nutrients and the carbon are valuable sources for organic farming, where phosphorus and potassium are essential. However, it is important to consider specific applications and soil types when determining the optimal concentrations of macro and micronutrients.

Conversely, to maintain consumer trust in organic products, heavy metals must be below background loads in the soil. The concentrations of heavy metals observed in this study are low and do not exceed the limits decreed by the European Sewage Sludge Directive. It is worth noting that the digestate in the bed in a full-scale facility would be retained in the STW for at least 20 years of operation, and processes of degradation or accumulation of heavy metals can occur and must be monitored. This highlights the importance of finding sources of digestate contribution with low heavy metal concentrations in order to eliminate them and deliver wastewater to a facility from which the treated material can be reused as a soil conditioner. Furthermore, no presence of *Salmonella* spp. and *Escherichia coli* was detected in the dewatered digestate after the operation period, meeting EU regulations. This can be attributed to the anaerobic digestion process and the long retention time in the STW.

The loading rate to the STW was lower than the one planned due to the lower production of digestate from the microalgae-based system. The expected loading for the system in the first year was 35 kg/m^2·year of dry weight (DW). But the actual load was only 3 kg/m^2·year. This means that the load was less than 10% of the expected load for the first year of operation.

The environmental impact of using the Sludge Treatment Wetland (STW) for digestate dewatering and field application was assessed through a Life Cycle Assessment (LCA), comparing it to reference systems using centrifuge dewatering techniques and incineration. Although STW demonstrated superior environmental performance compared to the reference systems, its slightly higher unit production cost raises questions about its overall economic viability. Furthermore, it is important to consider the potential long-term benefits of using STW. While it may have a higher initial cost, STW's improved environmental performance may lead to cost savings in the future by reducing the need for costly environmental remediation measures.

Ultimately, the choice of wastewater treatment system will depend on a range of factors, including the specific needs of the facility, available resources, and local environmental regulations. It is important to carefully evaluate these factors when selecting a treatment system to ensure that it is both effective and sustainable in the long term.

5. Conclusions

The obtained digestate from the anaerobic digestion of microalgal biomass in a microalgae-based wastewater treatment system underwent additional stabilization and dewatered in an STW. The distribution system efficiently and uniformly discharged the digestate onto the surface of the STW. The dewatering process resulted in a reduction of the digestate volume by 10.4%. The digestate was mineralized, resulting in a soil-like structure, as expected. According to the nutrients and heavy metals analysis, the material could be used as a nutrient source and could improve agricultural soil structure when used as a soil amendment. During the test, the reeds developed well and grew healthy, covering the entire bed to contribute to the treatment process. Regarding the sustainability assessment, it is noteworthy that STW outperformed reference systems in terms of environmental impact. However, its economic performance was comparatively weaker, suggesting the possibility of further improvement.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15122159/s1, Figure S1. Images depicting the construction and feeding process of the Sludge Treatment Wetland (STW).

Author Contributions: Conceptualization, C.A.A., R.D.-M., N.K., U.-H.S., J.G. and P.K.S.G.; Methodology, C.A.A., R.D.-M., N.K., U.-H.S., J.G. and P.K.S.G.; Validation, E.G.-F., A.O., C.A.A., R.D.-M., U.-H.S., J.G. and P.K.S.G.; Formal analysis, E.G.-F. and N.K.; Investigation, A.O., R.D.-M. and N.K.; Resources, C.A.A., U.-H.S., J.G. and P.K.S.G.; Writing—original draft, E.G.-F.; Writing—review & editing, A.O., C.A.A., R.D.-M., N.K., U.-H.S., J.G. and P.K.S.G.; Visualization, E.G.-F., A.O. and R.D.-M.; Supervision, J.G.; Project administration, R.D.-M. and J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission (H2020 project INCOVER, GA 689242). E. Gonzalez-Flo would like to thank the European Union-Next Generation EU, Ministry of Universities and Recovery, Transformation and Resilience Plan for her research grant [2021UPF-MS12]. A. Ortiz would like to thank the European Union Next-Generation EU, Ministry of Universities and Recovery, Transformation and Resilience Plan for his research grant [2022UPC-MSC-94120].

Data Availability Statement: Data available on request.

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

Abbreviations

Symbol and Abbreviations	Description
AC	acidification potential
LCA	life cycle assessment
Cd	cadmium
CAPEX	capital expenditures
Cr	chromium
Cu	copper
DM	dry matter
DW	dry weight
EC	European Commission
EU	European Union
EP	eutrophication potential
FU	functional unit
GWP	global warming potential
HTP	human toxicity potential
Fe	iron
Pb	lead
LCC	life-cycle costing
Mn	mangesium
Ni	niquel
OPEX	operational expenditures
PE	primary energy use
STW	Sludge Treatment Wetlands
TC	total carbon
TN	total nitrogen
TS	total solids
UPC	unit production costs
VS	volatile solids
Zn	zinc

References

1. United Nations Environment. The United Nations world water development report, 2017: Wastewater: The untapped resource. *J. Chem. Inf. Model. UNESCO* **2017**, 689–1699. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000247153 (accessed on 20 February 2023).
2. Tarantini, M.; Buttol, P.; Maiorino, L. An environmental LCA of alternative scenarios of urban sewage sludge treatment and disposal. *Therm. Sci.* **2007**, *11*, 153–164. [CrossRef]
3. Uggetti, E.; Ferrer, I.; Molist, J.; García, J. Technical, economic and environmental assessment of sludge treatment wetlands. *Water Res.* **2011**, *45*, 573–582. [CrossRef]
4. Uggetti, E.; Ferrer, I.; Llorens, E.; García, J. Sludge treatment wetlands: A review on the state of the art. *Bioresour. Technol.* **2010**, *101*, 2905–2912. [CrossRef]
5. Brix, H. Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds. *Water* **2017**, *9*, 160. [CrossRef]
6. Nielsen, S. Sludge reed bed facilities: Operation and problems. *Water Sci. Technol.* **2005**, *51*, 99–107. [CrossRef] [PubMed]
7. Nielsen, S. Sludge treatment reed bed facilities—Organic load and operation problems. *Water Sci. Technol.* **2011**, *63*, 941–947. [CrossRef]
8. Luo, H.; Duan, M.; He, L.; Yang, S.; Zou, Y.; Tang, X. A New Organic-Inorganic Compound Fertilizer for Improving Growth, Yield, and 2-Acetyl-1-Pyrroline Biosynthesis of Fragrant Rice. *Agriculture* **2021**, *11*, 1121. [CrossRef]
9. Dharminder; Singh, R.K.; Kumar, V.; Pramanick, B.; Alsanie, W.F.; Gaber, A.; Hossain, A. The use of municipal solid waste compost in combination with proper irrigation scheduling influences the productivity, microbial activity and water use efficiency of direct seeded rice. *Agriculture* **2021**, *11*, 941. [CrossRef]
10. Fršťák, V.; Pipíška, M.; Koperová, D.; Jagerhofer, R.; Soja, G.; Bell, S.M. Utilization of Sewage Sludge-Derived Pyrogenic Material as a Promising Soil Amendment. *Agriculture* **2022**, *12*, 360. [CrossRef]
11. Mahapatra, D.M.; Satapathy, K.C.; Panda, B. Biofertilizers and nanofertilizers for sustainable agriculture: Phycoprospects and challenges. *Sci. Total Environ.* **2022**, *803*, 149990. [CrossRef] [PubMed]
12. Pajura, R.; Masłoń, A.; Czarnota, J. The Use of Waste to Produce Liquid Fertilizers in Terms of Sustainable Development and Energy Consumption in the Fertilizer Industry—A Case Study from Poland. *Energies* **2023**, *16*, 1747. [CrossRef]
13. Bora, R.R.; Richardson, R.E.; You, F. Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: A comprehensive review. *BMC Chem. Eng.* **2020**, *2*, 8. [CrossRef]
14. García, J.; Ortiz, A.; Álvarez, E.; Belohlav, V.; García-Galán, M.J.; Díez-Montero, R.; Álvarez, J.A.; Uggetti, E. Nutrient removal from agricultural run-off in demonstrative full scale tubular photobioreactors for microalgae growth. *Ecol. Eng.* **2018**, *120*, 513–521. [CrossRef]
15. Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, when Sewage Sludge is Used in Agriculture. Available online: https://www.legislation.gov.uk/eudr/1986/278/contents (accessed on 20 February 2023).
16. EC 2000 Water Framework Directive 2000/60/EC of the European Parliament and of the Council Establishing a Framework for the Community Action in the Field of Water Policy. Available online: https://eur-lex.europa.eu/eli/dir/2000/60/oj (accessed on 20 February 2023).
17. Uggetti, E.; García, J.; Álvarez, J.A.; García-Galán, M.J. Start-up of a microalgae-based treatment system within the biorefinery concept: From wastewater to bioproducts. *Water Sci. Technol.* **2018**, *78*, 114–124. [CrossRef]
18. Díez-Montero, R.; Vassalle, L.; Passos, F.; Ortiz, A.; García-Galán, M.J.; García, J.; Ferrer, I. Scaling-Up the Anaerobic Digestion of Pretreated Microalgal Biomass within a Water Resource Recovery Facility. *Energies* **2020**, *13*, 5484. [CrossRef]
19. Ortiz, A.; García-Galán, M.J.; García, J.; Díez-Montero, R. Optimization and operation of a demonstrative full scale microalgae harvesting unit based on coagulation, flocculation and sedimentation. *Sep. Purif. Technol.* **2021**, *259*, 118171. [CrossRef]
20. Ortiz, A.; García, J.; Uggetti, E.; Díez-Montero, R. Optimization of multi-stage thickening of biomass in a demonstrative full–scale microalgae-based wastewater treatment system. *Sep. Purif. Technol.* **2022**, *281*, 119830. [CrossRef]
21. APHA; AWWA; WPCF. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; APHA, AWWA, WPCF: Washington, DC, USA, 2001.
22. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
23. Gargalo, C.L.; Cheali, P.; Posada, J.A.; Carvalho, A.; Gernaey, K.V.; Sin, G. Assessing the environmental sustainability of early stage design for bioprocesses under uncertainties: An analysis of glycerol bioconversion. *J. Clean. Prod.* **2016**, *139*, 1245–1260. [CrossRef]
24. Guinée, J.B.; Heijungs, R.; Huppes, G.; Zamagni, A.; Masoni, P.; Buonamici, R.; Ekvall, T.; Rydberg, T. Life Cycle Assessment: Past, Present, and Future. *Environ. Sci. Technol.* **2011**, *45*, 90–96. [CrossRef] [PubMed]
25. Roskosch, A.; Heidecke, P. *Klärschlammentsorgung in der Bundesrepublik Deutschland*; Umweltbundesamt: Dessau-Roßlau, Germany, 2018.
26. Wiechmann, B.; Dienemann, C.; Kabbe, C.; Brandt, S.; Vogel, I.; Roskosch, A. *Klärschlammentsorgung in der Bundesrepublik Deutschland, Stand: 01.01.2012. Ed.*; Umweltbundesamt: Dessau-Roßlau, Germany, 2012.
27. Becker, E.W. Micro-algae as a source of protein. *Biotechnol. Adv.* **2007**, *25*, 207–210. [CrossRef] [PubMed]
28. Marschner, P. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: Cambridge, MA, USA, 2011; 651p. [CrossRef]

29. Taiz, L.; Zeiger, E. Plant physiology. 3rd edn. *Ann. Bot.* **2003**, *91*, 750. [CrossRef]
30. White, P.J.; Brown, P.H. Plant nutrition for sustainable development and global health. *Ann. Bot.* **2010**, *105*, 1073–1080. [CrossRef]
31. Saeed, M.; Hassan, A. Magnesium and sodium in sludge stabilized with chemical and biological agents for reuse in agriculture. *J. Environ. Sci. Health Part A Toxic/Hazard. Subst. Environ. Eng.* **2008**, *43*, 1918–1923.
32. Gondek, K.; Filiper-Mazur, B. Yielding and the contents of Calcium, Magnesium and Sodium in maize fertilized with organic materials. *Ecol. Chem. Eng. A* **2009**, *16*, 1284–1292.
33. Oehme, S.; Fuchinoue, Y.; Van Leeuwen, E. Application of Sewage Sludge to Agricultural Land: Nutrient Contents and Fate of Heavy Metals and Pollutants. In *Hazardous Waste Management*; IntechOpen: London, UK, 2012; pp. 1–7. [CrossRef]