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Effect of Electrofiltration on the Dewatering Kinetics of *Arthrospira platensis* and Biocompound Recovery

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Abstract: *Arthrospira platensis* (*A. platensis*) is a microalga with a wide range of commercial uses. One of the main concerns that needs to be addressed in microalgae biorefineries is the costs associated with the harvesting and concentration steps. Filtration has been shown to be an effective technique for concentrating microalgae and recent studies have attempted to enhance membrane filtration by applying an external electric field to the filtration cell. This study consisted of assessing the use of electrically assisted filtration (electrofiltration) at 60 A/m^2 and 1 bar for the dewatering of *A. platensis*, as well as the effect of pretreating the microalgae with ultrasounds (US) on the filtration process. Untreated *A. platensis* exhibited better filtration kinetics than US-treated *A. platensis*, and electrofiltration was found to increase the cake dryness. More protein and pigments were present in the US-treated microalgae solution compared to the untreated microalgae, which led to the presence of higher concentrations of protein and pigments in the filtrate streams after pressure filtration at 1 bar without the application of an external electric field. Electrofiltration was found to consume less energy compared to traditional drying techniques used for *A. platensis*. However, electrofiltration degrades the biocompounds present in the filtrate and cake due to pH changes and other electrophoresis phenomena, which shows the need to optimize the process in future work.

Keywords: microalgae *Arthrospira platensis*; dewatering; filtration; electrofiltration; phycocyanin; protein

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1. Introduction

Arthrospira platensis (*A. platensis*), commercially referred to as *Spirulina*, is a strain of microalgae that is categorized as a type of cyanobacteria. This microalgal strain has been associated with many benefits and potential applications [1–6]. It is mainly known for its ability to produce a blue pigment called phycocyanin that presents many benefits due to its color, antitumor, anti-inflammatory, and antioxidant properties [7]. Even though the phycobiliprotein phycocyanin offers many benefits and can be used in applications such as food and pharmaceuticals, it also presents many limitations. The main issue related to the use of phycocyanin in different contexts is its sensitivity to certain temperatures, pH values, alcohol concentrations, ionic strengths, and light conditions [7–10].

After the cultivation of microalgal cells under the desired conditions to accumulate high concentrations of the biocompounds of interest [11–13], the microalgae needs to be harvested and processed to recover these compounds [14–18]. A dry method of biocompound recovery is most often used. It includes the concentration of microalgal suspension by flotation [19–23] or centrifugation [24–27] and eventually by further dewatering by cross-flow microfiltration [28–32]. This is followed by drying the concentrated suspension to obtain a microalgal powder, which would then undergo a selective solvent extraction to recover the compounds of interest from the dried microalgae [33–35]. Alternatively, a wet pathway for microalgae compound recovery can be applied, including preliminary cell disruption,

followed by solid–liquid extraction and selective separation of valuable compounds. Both dry and wet processing methods have their own significant shortcomings. While the dry way of microalgae processing is highly energy consuming, the wet processing pathway includes a complex separation stage to purify the obtained solution [33,34,36,37].

Dead-end filtration can be used to better dehydrate different sludges and to increase the filter cake dryness [38–40]. Preliminary mechanical concentration of a microalgae suspension by dead-end filtration can decrease the energy consumption required for the subsequent thermal drying of the filter cake. This can increase the global effectiveness of the dry way of microalgae processing. In spite of existing examples of the industrial implementation of filtration equipment [41–45], dead-end filtration of microalgae suspensions is poorly studied [32,46–49]. The high specific cake resistance of the microalgal filter cake leads to a low filtration velocity. This factor hinders the implementation of filtration techniques in microalgae processing. Electrofiltration has been found to enhance filtration velocity. The use of electrofiltration and electrodewatering has been studied for different industrial sludges [38,39,50–59] and biopolymers [60,61]. Two studies assessed the use of electrically assisted filtration of the microalgae *Chlorella vulgaris* by cross-flow filtration under a constant or periodic electric field [62] and the use of a cylindrical filter press at a pressure of 0.6 MPa for 1 h [63].

The aim of this work is to compare the behavior of dead-end filtration and electrofiltration, without any additional mechanical pressure, to improve the dewatering of the microalgae *Arthrospira platensis* while causing minimal damage to biocompounds of interest. Untreated and ultrasound-treated (US) microalgae suspensions were used for dead-end filtration and electrofiltration. The US-treated *A. platensis* was used to extract more biocompounds from wet biomass and create a more difficult to filter feed solution. Filter cakes obtained by the filtration of untreated *A. platensis* were freeze dried and the obtained powder was qualitatively and quantitatively assessed. This allowed us to study the effect of the order of the processing steps for the recovery and purification of bioactive compounds from *A. platensis*. Filtration characteristics of the filter cakes (specific cake resistance and cake dryness) as well as qualitative and quantitative attributes of the electrically treated and untreated filtrates were evaluated.

2. Materials and Methods

2.1. Arthrospira platensis Suspensions

The microalgae *A. platensis* was used in this study. The algae was purchased from SAS TAM- Cyane (Plougastel-Daoulas, France), as a frozen algae paste (≈14 ± 1.2% dry weight content) to prevent its spoilage during its transportation to Compiègne, France. The frozen *A. platensis* paste was stored at −20 °C. The pastes were thawed at ambient temperature and diluted with deionized water to prepare algal solutions with a concentration of 5% by weight dry matter (henceforth %). The feed solution had a pH of 7.06 ± 0.3, a conductivity of (1.62 ± 0.12) mS/cm, and a zeta potential of −17.3 ± 0.9 mV (Zetasizer, Malvern Panalytical Ltd, Malvern, UK). An *A. platensis* feed solution that did not undergo further treatment was used for control experiments hereby referred to as untreated.

Scanning electron microscopy (SEM, Quanta FEG 250, FEI, Eindhoven, The Netherlands) was used to monitor any changes in the microstructure of the algal cells, with an applied voltage of 20 kV. The SEM image of the untreated feed solution is shown in Figure 1a.

To study the effect of preliminary cell disruption on the filtration and electrofiltration behavior as well as its effect on the extractability of biocompounds, *A. platensis* suspensions were pretreated by an ultrasonic processor at 400 watts for 20 min (UP-400S, Hielscher Ultrasonics, GmbH, Teltow, Germany). *A. platensis* cells were disrupted into cell debris after the US pretreatment as shown by the SEM image in Figure 1b. The untreated and US-treated solutions had the same pH values of 7.7 ± 0.1, whereas the electrical conductivity increased from (1.03 ± 0.12) mS/cm to (2.49 ± 0.24) mS/cm after the US treatment due to the release of cellular compounds.

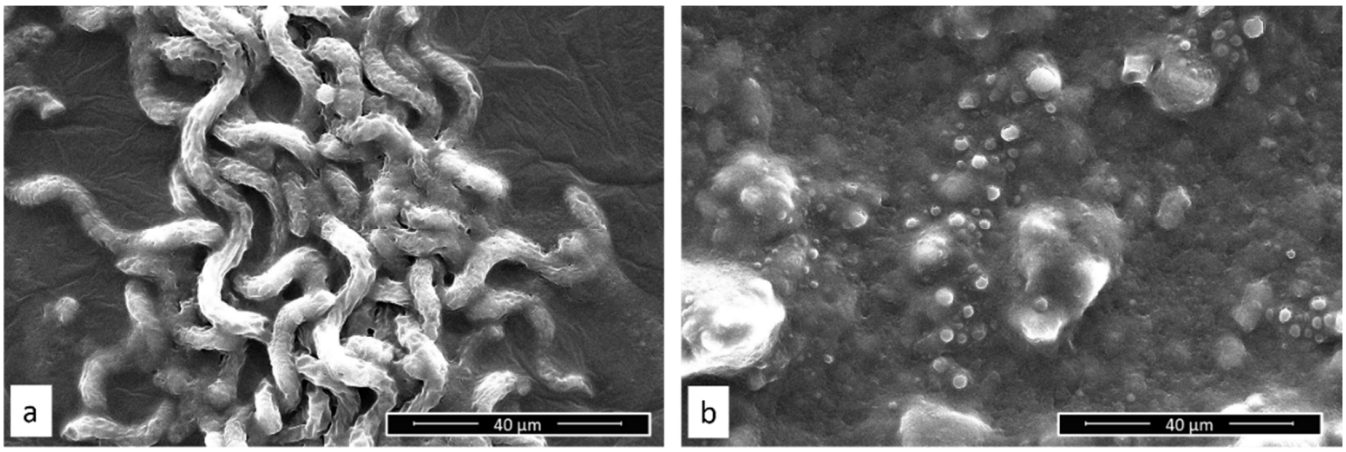

Figure 1. SEM images of the untreated (**a**) and US-treated (**b**) suspensions of *A. platensis* microalgae.

2.2. Dead-End Filtration and Electrofiltration

Two types of dead-end filtration experiments were carried out: pressure filtration at a constant pressure of 1 bar and electrofiltration at a constant electric current of 60 A/m^2 and the same pressure of 1 bar. The filtration equipment (Figure 2) consisted of a 1 L feed tank connected to a pressurized air system, a stainless-steel support with a screw to secure the independent parts of the system together, and a polypropylene filtration cell (circular cross section 24.6 cm^2, volume 49.2 cm^3) equipped with a feed inlet and valve. Both sides of the filtration cell were covered with a disposable PVDF membrane (Nafion MV020T, Millipore, Burlington, MA, USA) with a pore size of 0.2 µm. Prior to use, the membranes were activated by soaking them in deionized water for 30 min. The wire mesh electrodes made of titanium (anode) and inox (cathode) were placed on the outer side of the filtration cell in a way that would prevent them from being in direct contact with the filter cake.

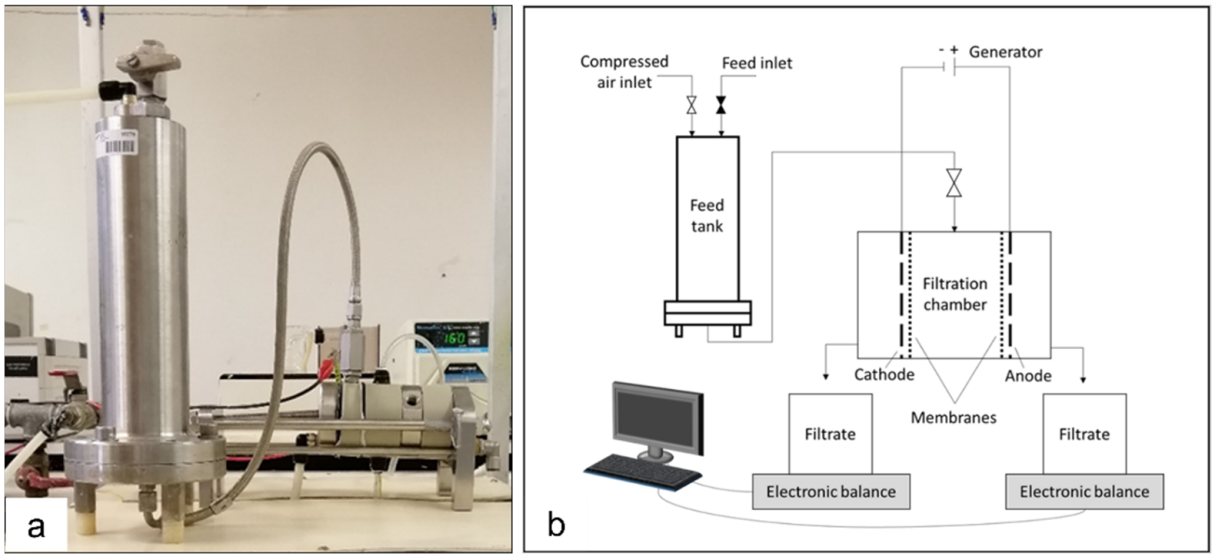

Figure 2. Picture of the dead-end filtration/electrofiltration cell and feed tank (**a**) and a schematic representation of the dead-end filtration/electrofiltration equipment (**b**).

The filtration time of 150 min was needed to fill the filtration cell by the cake in filtration conditions. The graph t/V vs. V curve presented in Figure 3 deviates from the straight line at the filtration time $t > \sim$150 min indicating that the filtration cell is completely filled by

the cake. This was assessed based on Ruth–Carman's filtration model [44] as presented in Equation (1):

$$\frac{t - t_0}{V - V_0} = \frac{\propto \cdot \mu \cdot C_0}{2A^2 \Delta P}(V + V_0) + \frac{R_m \cdot \mu}{A \cdot \Delta P} \quad (1)$$

where t is the time (s), V is the total volume of filtrate (m^3), α is the specific resistance of filter cake (m/kg), A = 49.2 cm^2 is the total cross sectional filtration area, $\mu = 10^{-3}$ Pa.s is the filtrate viscosity, C_0 is the concentration of the feed solution (kg/m^3), ΔP is the applied pressure (Pa), R_m is the filter media resistance (m^{-1}), and V_0 (mL) is the initial volume of filtrate recuperated at the time t_0 (s) needed to attain stabilized filtration regime. The specific resistance of the filter cake α obtained by filtration at 1 bar was found to be equal to 1.94 × 10^{13} m/kg for the untreated sample (Figure 3) and 3.87 × 10^{15} m/kg for the US-treated sample. Similarly, the high specific cake resistances of the order of 1.0 × 10^{14} m/kg were recorded for the filtration of powdered *Chlorella vulgaris* microalgae [32].

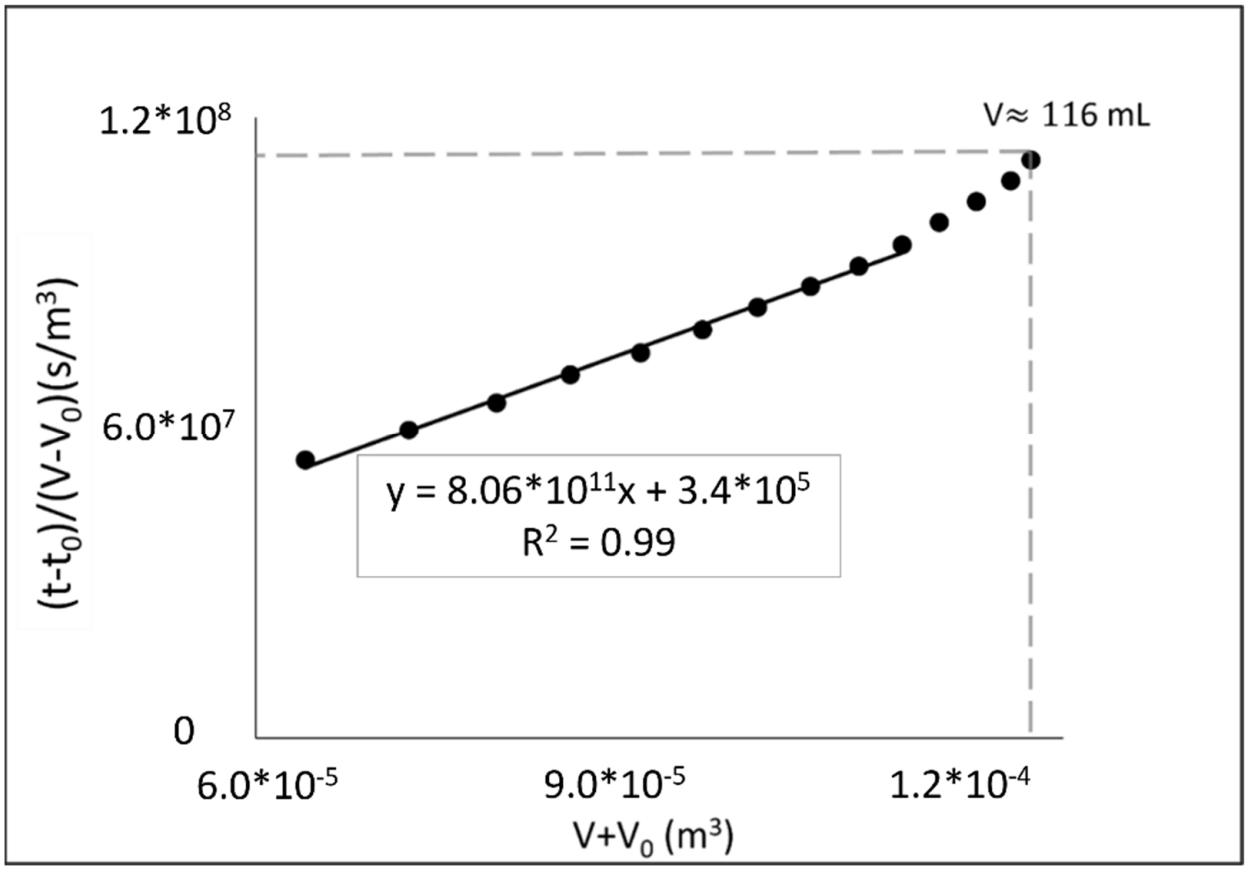

Figure 3. Typical example of filtration data for the untreated *A. platensis* samples.

The increase in the specific cake resistance α after US treatment is related to the disruption of *A. platensis* cells.

The same experimental setup was used for both filtration and electrofiltration experiments. Filtrates from each outlet of the filtration cell were collected in separate beakers. The electricity supply was set using the EV261 direct electric current generator (0–1 A, 0–600 V, Consort, Turnhout, Belgium) and was monitored using a multimeter (FLUKE 45). The filtration rates were obtained by continuously measuring the mass of the obtained filtrates with two electronic balances (METTLER PM6000, max weight: 6000 g, resolution: 0.01 g and SARTORIUS (max weight: 600 g, resolution: 0.1 g). The filtrate masses, and the applied currents and voltages were recorded by the HPVEE filtration acquisition software (Electronic Service, UTC, Compiègne, France). The interval between each measurement was fixed at 60 s. The temperature at the electrodes was measured using flexible K-type

thermocouples, connected to a 4-channel thermometer (Extech Instruments, Nashua, NH, USA). The pH and conductivity of the filtrate were measured using a Consort multimeter.

2.3. Freeze Drying the Filter Cake

For the experiments using untreated microalgae, the filter cakes obtained by both filtration and electrofiltration were freeze-dried. The samples were initially frozen at −20 °C, they were then placed on a pre-cooled shelf at ≈−20 °C in a SMH 15 freeze-dryer (Usifroid, Maurepas, France) and freeze-dried until each sample reached a constant weight, indicating that they were completely dry.

2.4. Filtrate and Filter Cake Characterization

Filtrates and dispersed filter cake samples were centrifuged at 13,500× *g* RCF for 10 min; then, the supernatants were collected and analyzed. The freeze-dried cakes were hand pulverized into a finer powder; then, the obtained powder was dispersed into deionized water and vortexed.

2.4.1. Protein Characterization

The protein content of the samples was determined using Bradford's method [64], where 100 µL of the supernatant was vortexed with 1 mL of Bradford dye reagent (Alfa Aesar, Thermo Fisher Scientific, Bremen, Germany). Then, the mixture was incubated for 10 min in the dark at room temperature and the absorbance was measured at 595 nm (Biochrom Libra S32, Biochrom Ltd., Cambridge, UK). The blank consisted of 100 µL of deionized water with 1 mL of Bradford dye reagent. The calibration curve was obtained using Bovine Serum Albumin (BSA) as a standard and the results were expressed as milligrams BSA equivalent per gram dry algal biomass (mg BSA equivalent/g d.m.).

2.4.2. Pigment Characterization

The phycobiliprotein content was determined by applying a slightly modified version of the formulas developed by Bennett and Bogorad [65], as shown in Equations (2)–(4):

$$C_{C-PC} = [A_{620} - (0.474\ A_{652})]\ /\ 5.34 \quad (2)$$

$$C_{APC} = [A_{652} - (0.208\ A_{620})]\ /\ 5.09 \quad (3)$$

$$C_{PE} = [A_{562} - (2.41\ C_{C-PC}) - (0.849\ C_{APC})]\ /\ 9.62 \quad (4)$$

where C_{C-PC} is the *C*-phycocyanin concentration (mg/mL); C_{APC} is the allophycocyanin concentration (mg/mL); C_{PE} is the *C*-phycoerythrin concentration (mg/mL); and A_{562}, A_{620} and A_{652} are, respectively, the absorbances of the sample at 562 nm, 620 nm, and 652 nm. The concentrations were then converted to mg/g dry *A. platensis* (hereby, referred to as mg/g d.m.).

2.4.3. Filter Cake Dryness

To determine the dryness of filter cake, the wet cake was placed in an oven at 105 °C for 24 h. The filter cake's dryness was calculated based on Equation (5) [54]:

$$\%dryness = \frac{m_{wet\ cake}}{m_{dry\ cake}} \times 100 \quad (5)$$

where $m_{wet\ cake}$ and $m_{dry\ cake}$ are, respectively, the masses of wet and dry filter cake (g).

2.5. Energy Consumption

The specific energy consumption during electrofiltration was calculated using Equation (6) [54]:

$$E = \frac{1}{M_l} \sum_{j=1}^{Z} \frac{I_j \cdot U_j \cdot \Delta t}{3600} \quad (6)$$

where E is the specific energy consumption (kWh/kg water removed), M_l is the mass of water removed under the influence of an electric field (kg), I_j is the current intensity (A), U_j is the voltage (V), and Δt is the time interval between subsequent measurements (s). j and Z represent the number of measurements, with j being the first measurement when an electric field is applied, thus only taking into account the volume of water removed due to the application of an electric field.

2.6. Statistical Analyses

All the experiments were repeated at least three times. All the results are presented with the calculated standard deviation.

3. Results and Discussion

3.1. Filtration and Electrofiltration Behavior

Filtration and electrofiltration kinetics for the untreated *A. platensis* microalgae are presented in Figure 4. The quantity of filtrate obtained during electrofiltration from the anode side of filter cell was very small (24.93 $\pm$ 7.45 mL), while the quantity of filtrate obtained from the cathode side of the filter cell was considerably larger (116.6 $\pm$ 0.96 mL). This is explained by the negative charge of the microalgae particles, which migrate towards the anode due to electrophoresis forces. As a result, the filter cake is more intensively built near the anode, which in turn decreases the filtration kinetics on the anode side. Simultaneously, electroosmotic forces in the pores of the filter cake push the liquid to flow towards the cathode, thus increasing the quantity of filtrate obtained from the cathode side. Similar observed behavior during electrofiltration has been reported in literature for different types of suspensions [38,50,61,66]. The total quantity of filtrate obtained after 150 min of electrofiltration (EF-total) was higher (141.52 $\pm$ 6.09 mL) than that obtained by pressure filtration (F-total) (111.84 $\pm$ 10.18 mL). It appears that the total quantity of filtrate obtained by electrofiltration and pressure filtration is nearly identical during the first 50 min and then gradually deviates, increasing more rapidly for electrofiltration (Figure 4). This difference in kinetics can be explained by the mechanism of cake formation at the cathode side of filter chamber, which has several stages [67]. Initially, the cake gradually becomes thicker on the cathode side, subsequently decreasing the filtration rate. However, only a rather thin layer of particles is deposited on the cathode side because of the electrophoretic force that pushes the negatively charged microalgae particles towards the anode. When the velocity of cake formation on the cathode side decreases and becomes equal to the electrophoretic velocity, the cake stops growing, and the filtration rate from the cathode side becomes constant. This leads us to speculate that the first stage of more intensive cake formation on the cathode side lasted for about 50 min in our experiments. The cake formation on the cathode side reached a state of equilibrium with the particles flowing towards the anode, which can explain the faster filtration rate obtained by electrofiltration.

The filtration and electrofiltration kinetics for US-pretreated *A. platensis* are presented in Figure 5. US pretreatment reduces the size of the microalgae particles and destroys the cells' structure, as revealed by the SEM imaging (Figure 1b). Consequently, cellular compounds are better extracted after the US pretreatment. However, US pretreatment considerably decreases the filtration rate due to the higher specific resistance of the formed filter cake, which increased by approximately 200 times in our case (from 1.94×10^{13} to 3.87×10^{15} m/kg). Moreover, cell debris and the released intracellular compounds can lead to membrane fouling by pore blocking [48,62,68–70]. During the filtration of *A. platensis* polysaccharides, cell debris, and exopolymeric materials secreted from the microalgal cells were reported to be the main cause of membrane fouling [71,72].

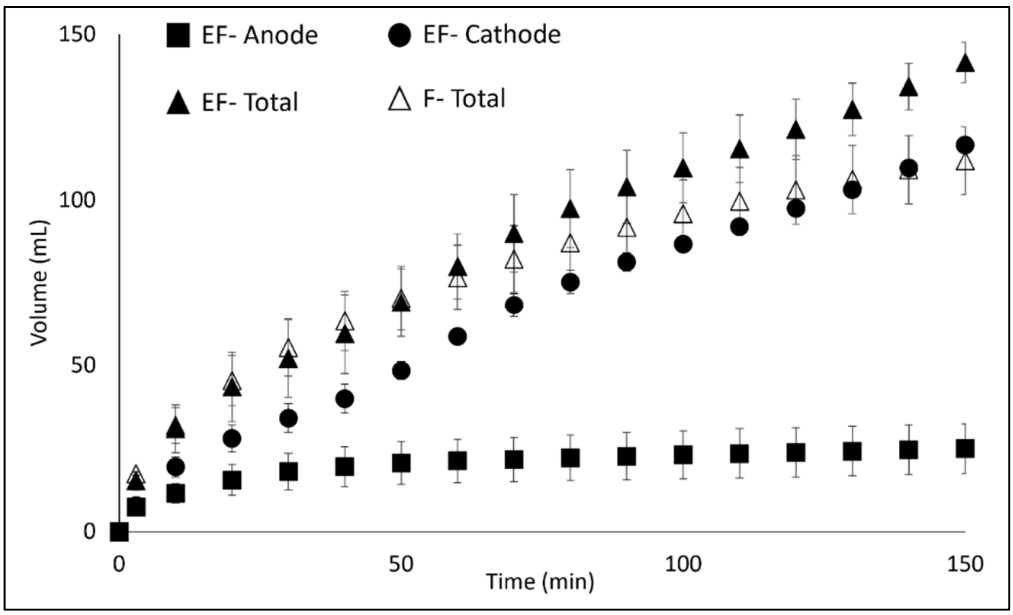

Figure 4. Filtrate volume obtained from the anode side (EF-anode), cathode side (EF-cathode), and both sides (EF-total) during electrofiltration of the untreated *A. platensis* suspension. F-total is the total filtrate volume obtained during pressure filtration.

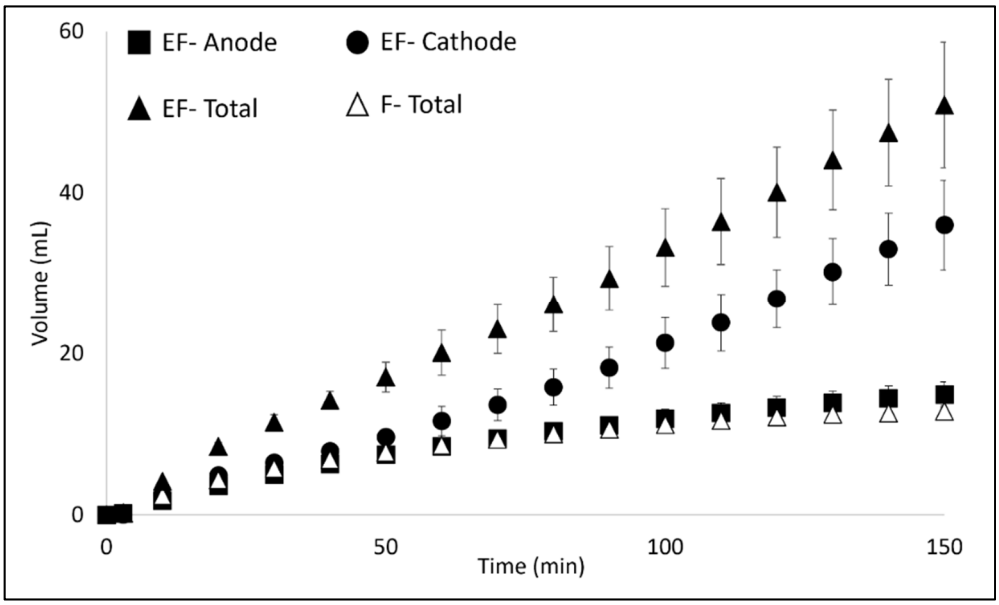

Figure 5. Filtrate volume obtained on the anode side (EF-anode), cathode side (EF-cathode), and both sides (EF-total) during electrofiltration of the US-treated *A. platensis* suspension. F-total is the total filtrate volume obtained during pressure filtration.

The quantity of filtrate obtained during pressure filtration of US-treated *A. platensis* was very small, reaching a total volume of 12.84 ± 0.71 mL. The same volume of filtrate was approximately obtained from the anode side of the filter cell during electrofiltration of US-treated *A. platensis* (EF-anode). Electrofiltration considerably increased the filtration rate from the cathode side of the filter cell (EF-cathode). Consequently, the final total volume of filtrate obtained by electrofiltration (EF-total) was 4 times larger than that obtained by filtration (F-total).

Figure 6 presents the photos of filter cakes formed by filtration and electrofiltration. Filter cakes formed by both filtration and electrofiltration of the untreated microalgae

suspension have a thickness of 2 cm and occupy the entire volume of the filter chamber after a filtration time of 150 min (Figure 6a,b).

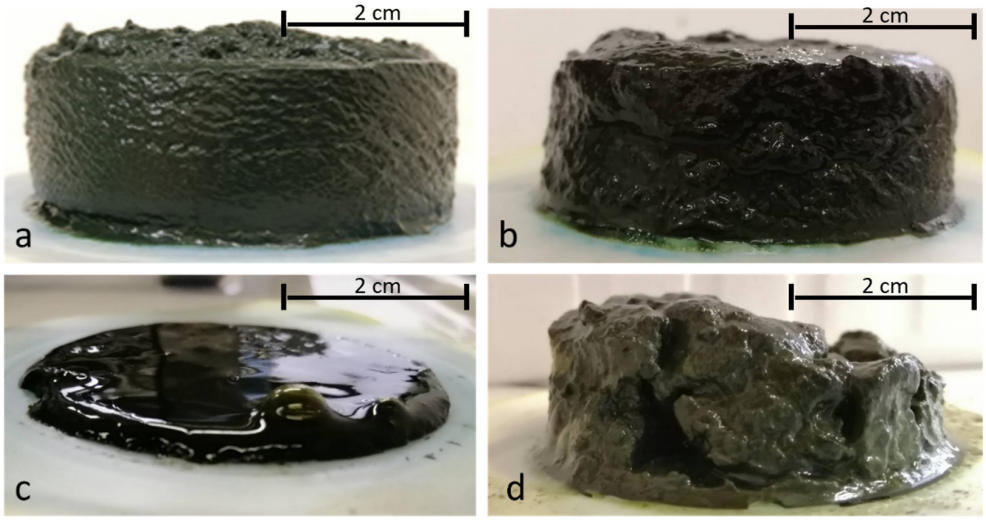

Figure 6. Filter cakes formed from the untreated *A. platensis* suspension by filtration (**a**) and electrofiltration (**b**). Filter cakes formed from the US-treated *A. platensis* suspension by filtration (**c**) and electrofiltration (**d**).

The dryness of the filter cake formed by electrofiltration is somewhat higher (16.04 ± 0.2)% than that of the filter cake formed by filtration (13.0 ± 0.47)%. Filter cakes formed from the US-treated *A. platensis* suspension incompletely occupy the volume of the filter chamber (Figure 6c,d). This is more prominently observed with the filter cake formed by filtration (Figure 6c), which remains in liquid form and has a dryness of (6.75 ± 0.02)%. The filter cake formed by electrofiltration is better structured (Figure 6d) and has a higher dryness (10.07 ± 0.32)%. The difference observed between the cakes formed using untreated and US-treated *A. platensis* can be associated with the difference in the particles' shape and size as clearly illustrated in the SEM imaging (Figure 1a,b). Many studies have investigated the influence of the particle shape and size on filtration kinetics and the properties of the filter cake [66,73–75]. The higher cake dryness reported for the electrofiltration experiments compared to the filtration experiments was expected, since the application of an electric filed during filtration has been proven to increase the cake dryness due to the electrokinetic phenomena that take place [39,40,50,76].

Figure 7 presents the specific energy consumption over time during electrofiltration of the untreated and US-treated *A. platensis* suspension, calculated using Equation (6). It is observed that the energy consumption increases more rapidly during the electrofiltration of US-pretreated microalgae. As a result, the final energy consumption was 0.24 kWh/kg water removed for the electrofiltration of US-pretreated *A. platensis*, while it was limited to 0.07 kWh/kg water removed for the electrofiltration of the untreated *A. platensis*. This is easily explained by the higher electric resistance of the filter cake as well as the higher voltage during the electrofiltration of US-pretreated *A. platensis*. For instance, the initial value of the voltage (at a constant electric current density, I = 60 A/m^2) was U_0 = 4.51 V. At the end of the electrofiltration process at I = 60 A/m^2 the value of the voltage increased up to (38.61 ± 1.77) V and (50.37 ± 5.01) V, respectively, for the untreated and US-pretreated microalgae. A study had also reported that electrically assisted filtration became more efficient with an increase in voltage and/or ionic strength [63]. The temperature increase measured near the electrodes was moderate for both untreated (final temperature reaching up to ≈32 °C) and US-pretreated (final temperature reaching up to ≈35 °C) *A. platensis*.

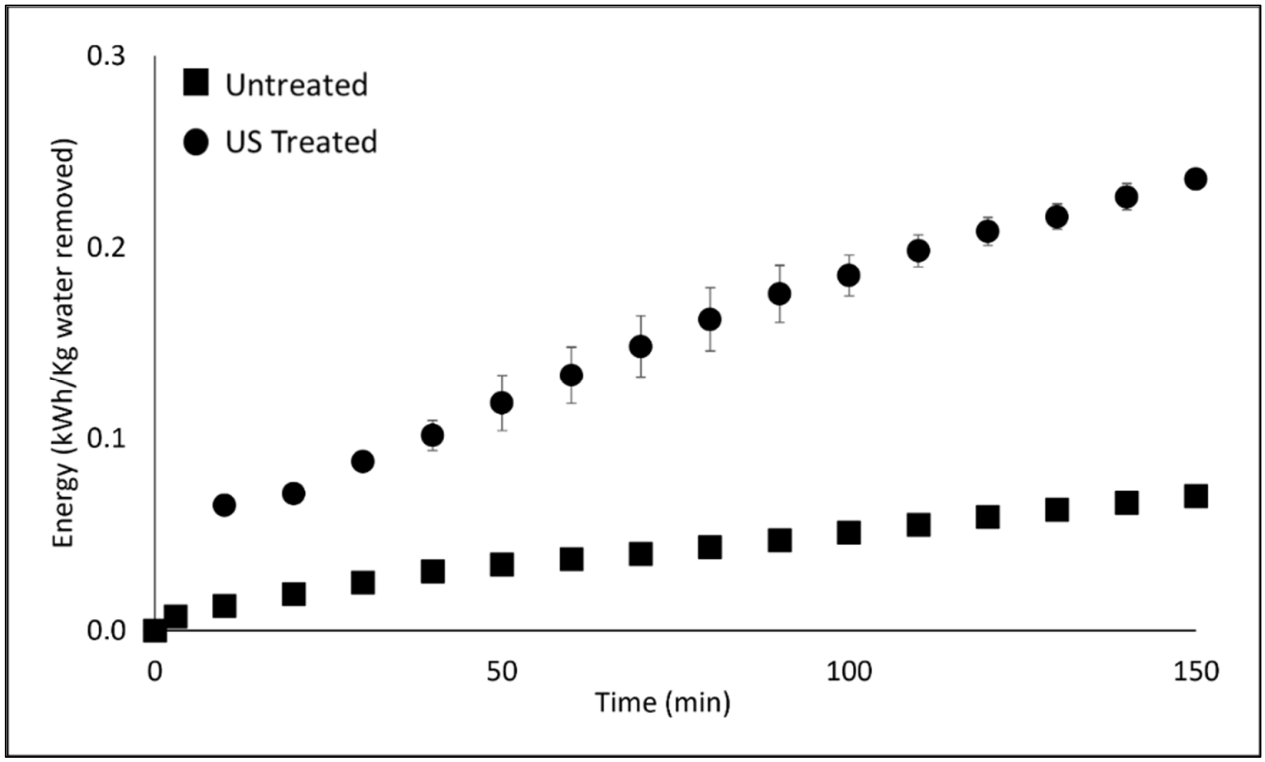

Figure 7. Specific energy consumption over time during electrofiltration of the untreated and US-treated suspension of *A. platensis*.

Data presented in Figure 7 show that electrofiltration consumes less energy for the dewatering of microalgae when compared to thermal processing techniques. For instance, drum drying of microalgae has an energy consumption of 0.9 kWh/kg water removed, and spray drying has an even higher energy consumption of 1.09 kWh/kg water removed [77].

3.2. Qualitative Characteristics of Extract Solutions and Filter Cakes

Table 1 shows the characteristics of the untreated and US-pretreated *A. platensis* feed solutions used for the filtration and electrofiltration experiments. The untreated and US-treated feed solutions had similar pH values which were close to being neutral, whereas the conductivity increased by a factor of 2.4, i.e., from (1.03 ± 0.12) mS/cm for the untreated solution to (2.49 ± 0.24) mS/cm for the US-treated feed solution.

Table 1. Characteristics of the untreated and US-treated *A. platensis*.

Feed Solution	Untreated	US Treated
pH	7.87 ± 0.06	7.38 ± 0.13
Conductivity (mS/cm)	1.03 ± 0.12	2.59 ± 0.3
Protein concentration (mg/g d.m.)	15.69 ± 0.79	27.18 ± 2.38
C-PC concentration (mg/g d.m.)	2.65 ± 0.96	3.17 ± 0.3
APC concentration (mg/g d.m.)	1.07 ± 0.3	2.12 ± 0.33
PE concentration (mg/g d.m.)	0.12 ± 0.08	1.25 ± 0.07

The change in conductivity for US-treated microalgae can be directly related to the release of bioactive compounds from the cells into the medium after cell disruption. This is further proven by the spectrophotometric analyses (Table 1). For instance, after the US treatment the concentrations of protein, phycocyanin concentration (C-PC), allophycocyanin concentration (APC), and phycoerythrin concentration (PE) in the feed solution were, respectively, increased by approximately 1.73, 1.20, 1.98, and 10.4 times.

Table 2 presents the qualitative characteristics of filtrates obtained by filtration and electrofiltration of the untreated and US-pretreated *A. platensis* suspensions. Electrofiltration significantly modified the characteristics of the filtrates obtained from the cathode and anode sides of the filter chamber. The filtrate obtained from the anode side was acidic with a pH, respectively, equal to 2.7 ± 0.02 and 4.05 ± 0.09 for the untreated and US-pretreated *A. platensis*. On the contrary, filtrate obtained from the cathode side was alkaline with approximatively the same pH of 12.1–12.3 for both untreated and US-pretreated *A. platensis* microalgae. The observed pH changes are related to the electrolysis reactions on the electrodes and are in accordance with the findings reported in literature for electrofiltration of microalgal solutions [62] as well as for other types of solutions [50,60,78].

Table 2. Qualitative characteristics of filtrates obtained by filtration (F) and electrofiltration (EF) of the untreated and US-pretreated *A. platensis* microalgae.

		Untreated		US Treated	
		F	**EF**	**F**	**EF**
pH	Anode Cathode	7.43 ± 0.19	2.71 ± 0.02 12.3 ± 0.02	7.73 ± 0.25	4.05 ± 0.09 12.1 ± 0.08
Conductivity (mS/cm)	Anode Cathode	2.19 ± 0.21	5.66 ± 0.76 6.71 ± 0.27	2.98 ± 0.14	10.37 ± 4.24 16.2 ± 1
Protein concentration (mg/g d.m.)	Anode Cathode	1.37 ± 0.27	0.28 ± 0.01 4.88 ± 0.05	15.56 ± 1.5	Negligible 2.71 ± 0.2
C-PC concentration (mg/g d.m.)	Anode Cathode	0.43 ± 0.04	Negligible Negligible	0.21 ±0.02	Negligible Negligible
APC concentration (mg/g d.m.)	Anode Cathode	Negligible	Negligible Negligible	0.17 ± 0.03	Negligible Negligible
PE concentration (mg/g d.m.)	Anode Cathode	Negligible	Negligible Negligible	Negligible	Negligible Negligible

The conductivity of the filtrates obtained by electrofiltration was significantly higher than the conductivity of the filtrates obtained by filtration, especially for US-pretreated *A. platensis*. The quantity of proteins detected in the filtrate obtained by filtration was very low for the untreated microalgae, (1.37 ± 0.27) mg/g d.m., and it significantly increased after the US treatment, (15.56 ± 1.5) mg/g d.m. The PVDF membrane with a pore size of 0.2 µm used in this paper may retain a small portion of protein molecules, as many studies have found that different extents of protein binding can occur when using PVDF membranes [79–82]. The formed *A. platensis* filter cake, which has a significant specific resistance, may also hinder the passage of proteins into the filtrate. The concentration of C-phycocyanin was lower in the filtrate obtained by filtration than in the feed solution. However, the blue was clearly visible for the filtrates obtained by filtration from both the untreated (Figure 8a) and US-treated (Figure 8b) microalgae suspensions. The concentration of other pigments in the filtrate was very low and can be considered negligible. Electrofiltration led to the extraction of different concentrations of protein in the filtrate obtained from the anode and cathode sides of the filter cell. The quantity of proteins obtained in the filtrate on the cathode side was somewhat higher (in comparison with the filtrate on the anode side), but it remained lower than the concentration detected in the feed solution. Other microalgae compounds that are present in the filtrate were detected in negligible amounts, which explains the absence of the blue color for the filtrates obtained by electrofiltration (Figure 8c–f).

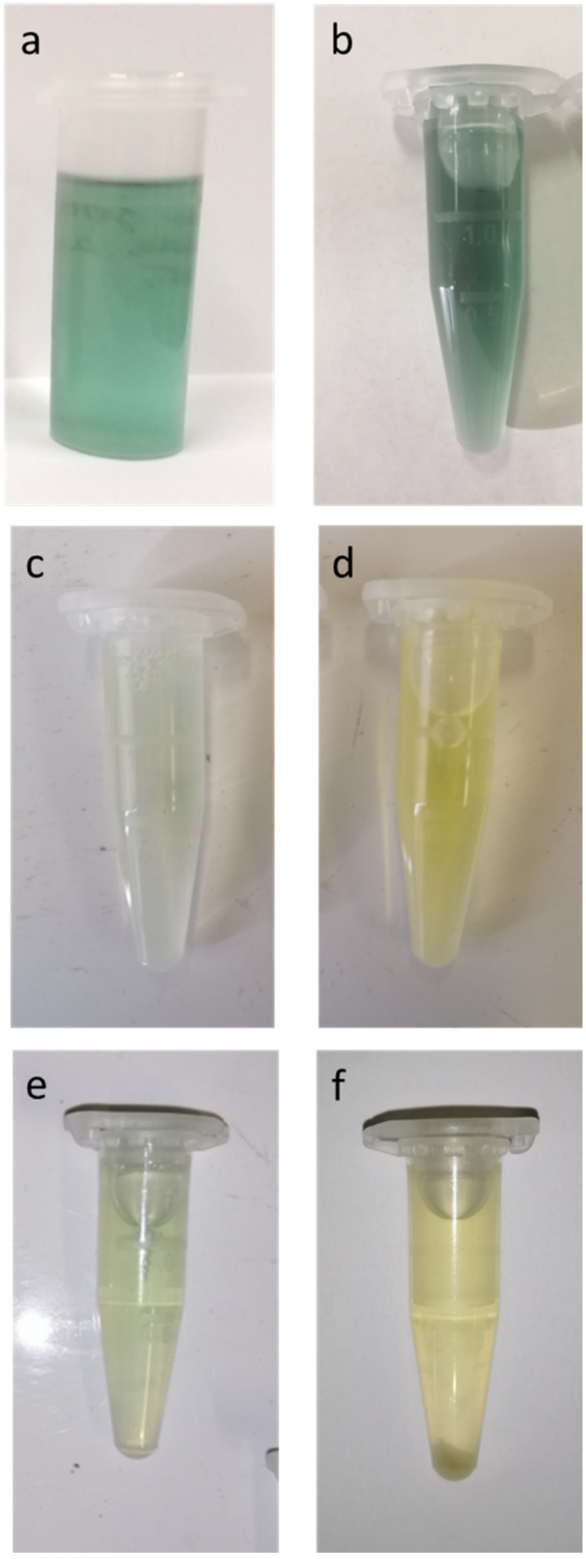

Figure 8. Filtrates obtained by filtration from the untreated (**a**) and US-treated (**b**) microalgae suspensions. Filtrates obtained by electrofiltration from the untreated ((**c**): anode side, (**d**): cathode side) and US-treated ((**e**): anode side, (**f**): cathode side) microalgae suspensions.

The extraction of negligeable amounts of phycoerythrin (PE) was expected, given the initially lower concentration of PE detected in the feed solution compared to the other biocompounds that were extracted. This has been observed in a study extracting

phycocyanin and phycoerythrin from *A. platensis* using protic ionic liquids and it was also associated with the lower concentrations of PE initially present in the algal cells compared to the more abundantly present phycocyanin [83].

The filter cakes obtained by filtration and electrofiltration of the untreated *A. platensis* suspension were analyzed after they had been freeze-dried (Table 3). This helped preserve the residual microalgae compounds within the cake by eliminating the use of high drying temperatures, which have been associated with pigment and protein denaturation [84–87]. It is evident from the data presented in Table 3 that the protein, C-phycocyanin, allophycocyanin, and C-phycoerythrin were conserved in the filter cake obtained by filtration. However, protein and other microalgae compounds were detected in very low concentrations in the freeze-dried filter cake obtained by electrofiltration. This could be explained by protein denaturation for more alkaline and acidic pH values of 11 and 4.5 as interpretated in previous studies [85,88].

Table 3. Qualitative characteristics of freeze-dried filter cakes obtained by filtration and electrofiltration of untreated *A. platensis*.

Cake	Filtration	Electrofiltration
Protein concentration (mg/g d.m.)	164.5 ± 0.57	1.81 ± 0.02
C-PC concentration (mg/g d.m.)	43.2 ± 0.12	0.33 ± 0.01
APC concentration (mg/g d.m.)	18.14 ± 0.06	0.28 ± 0
PE concentration (mg/g d.m.)	0.6 ± 0.41	0.09 ± 0

Figure 9 shows the images of the freeze-dried filter cakes obtained by filtration (a) and electrofiltration (b) from the untreated microalgae. The surface of the freeze-dried filter cake obtained by filtration has a clearly visible blue pigmentation. However, the surface of the filter cake obtained by electrofiltration has brown and dark green tints, as well as a white residue, which could indicate the presence of salts. The visual attributes of the cake obtained by electrofiltration are probably due to the formation of electrolysis products.

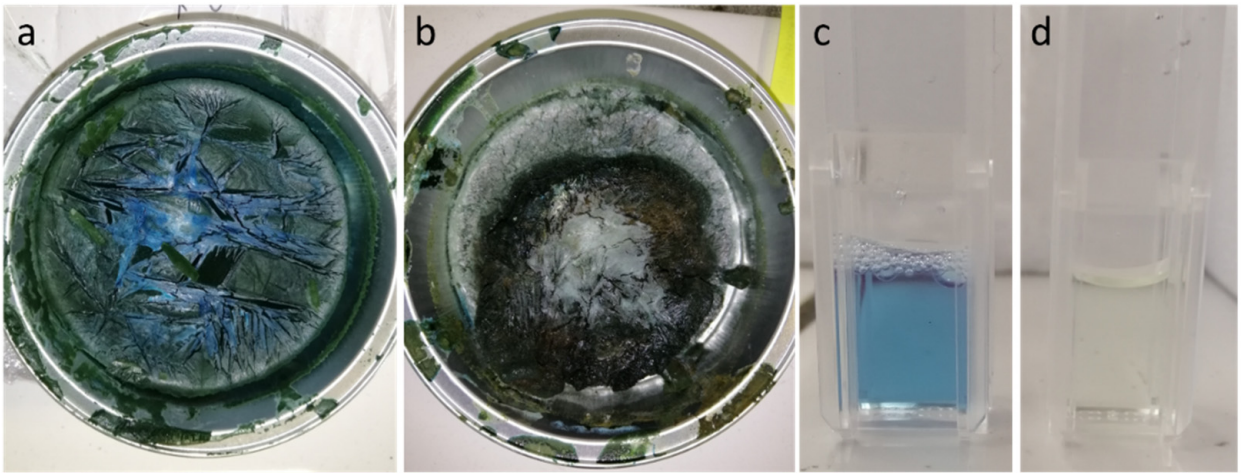

Figure 9. Images of freeze-dried filter cakes obtained by filtration (**a**) and electrofiltration (**b**) from the untreated microalgae and the same freeze-dried cakes dispersed in water for filtration (**c**) and electrofiltration (**d**).

Dispersing the freeze-dried cakes obtained by filtration (Figure 9a) and electrofiltration (Figure 9b) provided further visual evidence that very low amounts of C-phycocyanin were present in the cake formed by electrofiltration compared to the relatively higher amount present in the cake formed by filtration, as quantitatively demonstrated in Table 3.

4. Conclusions

Dead-end filtration of untreated *A. platensis* can efficiently concentrate this microalga and increase the concentration of dry matter from 5 to 13%. Moreover, the obtained filter cake is rich in protein, phycocyanin, and allophycocyanin, whereas the filtrate is poor in these extracts, eliminating the need of additional separation steps. However, the specific resistance of the formed filter cake is rather high (1.94×10^{13} m/kg), which reduces the filtration kinetics.

Ultrasonic (US) pretreatment disrupts *A. platensis* cells and permits a better release of microalgae biocompounds in the filtrate. However, US pretreatment leads to the reduction in the filtration rate due to the formation of a filter cake with a very high specific resistance (3.87×10^{15} m/kg). The lower filtration rate subsequently leads to the formation of a cake with a low concentration of dry matter (6.75%).

Electrofiltration of the untreated *A. platensis* suspension increases the cake dryness (to 16%) and enhances the filtration rate with an energy consumption of 0.07 kWh/kg water removed, which is considerably lower than the energy consumption of thermal drying techniques. However, microalgae biocompounds extracted from the untreated *A. platensis* were denatured during electrofiltration, probably due to the extreme pH conditions and electrolysis phenomena.

Furthermore, electrofiltration of US-pretreated *A. platensis* is also effective for enhancing the filtration rate and increasing the cake dryness (up to approximately 10%). However, this process consumes more energy (0.27 kWh/kg) and does not have any additional advantages in comparison with the electrofiltration of untreated microalgae.

Due to the ability of electrofiltration to enhance the filtration rate and subsequently improve the cake dryness, further studies should be conducted to optimize the processing conditions and prevent the denaturation of biocompounds of interest. More specifically, electrofiltration should be performed at neutral pH conditions, which can be achieved by filtrate recirculation.

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References

1. Batista, A.P.; Niccolai, A.; Fradinho, P.; Fragoso, S.; Bursic, I.; Rodolfi, L.; Biondi, N.; Tredici, M.R.; Sousa, I.; Raymundo, A. Microalgae Biomass as an Alternative Ingredient in Cookies: Sensory, Physical and Chemical Properties, Antioxidant Activity and in Vitro Digestibility. *Algal Res.* **2017**, *26*, 161–171. [CrossRef]
2. Sahin, S.C. The Potential of Arthrospira Platensis Extract as a Tyrosinase Inhibitor for Pharmaceutical or Cosmetic Applications. *S. Afr. J. Bot.* **2018**, *119*, 236–243. [CrossRef]
3. Singh, U.; Singh, P.; Singh, A.K.; Laxmi; Kumar, D.; Tilak, R.; Shrivastava, S.K.; Asthana, R.K. Identification of Antifungal and Antibacterial Biomolecules from a Cyanobacterium, Arthrospira Platensis. *Algal Res.* **2021**, *54*, 102215. [CrossRef]
4. Çelekli, A.; Alslibi, Z.A.; Bozkurt, H. üseyin Influence of Incorporated Spirulina Platensis on the Growth of Microflora and Physicochemical Properties of Ayran as a Functional Food. *Algal Res.* **2019**, *44*, 101710. [CrossRef]
5. Han, P.; Li, J.; Zhong, H.; Xie, J.; Zhang, P.; Lu, Q.; Li, J.; Xu, P.; Chen, P.; Leng, L.; et al. Anti-Oxidation Properties and Therapeutic Potentials of Spirulina. *Algal Res.* **2021**, *55*, 102240. [CrossRef]
6. Almeida, L.M.R.; Cruz, L.F.d.S.; Machado, B.A.S.; Nunes, I.L.; Costa, J.A.V.; Ferreira, E.d.S.; Lemos, P.V.F.; Druzian, J.I.; de Souza, C.O. Effect of the Addition of *Spirulina* sp. Biomass on the Development and Characterization of Functional Food. *Algal Res.* **2021**, *58*, 102387. [CrossRef]

7. Adjali, A.; Clarot, I.; Chen, Z.; Marchioni, E.; Boudier, A. Physicochemical Degradation of Phycocyanin and Means to Improve Its Stability: A Short Review. *J. Pharm. Anal.* **2021**, *12*, 406–414. [CrossRef]
8. Jespersen, L.; Strømdahl, L.D.; Olsen, K.; Skibsted, L.H. Heat and Light Stability of Three Natural Blue Colorants for Use in Confectionery and Beverages. *Eur. Food Res. Technol.* **2005**, *220*, 261–266. [CrossRef]
9. Sarada, R.; Pillai, M.G.; Ravishankar, G. Phycocyanin from Spirulina Sp: Influence of Processing of Biomass on Phycocyanin Yield, Analysis of Efficacy of Extraction Methods and Stability Studies on Phycocyanin. *Process Biochem.* **1999**, *34*, 795–801. [CrossRef]
10. Hsieh-Lo, M.; Castillo, G.; Ochoa-Becerra, M.A.; Mojica, L. Phycocyanin and Phycoerythrin: Strategies to Improve Production Yield and Chemical Stability. *Algal Res.* **2019**, *42*, 101600. [CrossRef]
11. Chaiklahan, R.; Chirasuwan, N.; Srinorasing, T.; Attasat, S.; Nopharatana, A.; Bunnag, B. Enhanced Biomass and Phycocyanin Production of Arthrospira (Spirulina) Platensis by a Cultivation Management Strategy: Light Intensity and Cell Concentration. *Bioresour. Technol.* **2022**, *343*, 126077. [CrossRef]
12. Yu, J.; Hu, H.; Wu, X.; Wang, C.; Zhou, T.; Liu, Y.; Ruan, R.; Zheng, H. Continuous Cultivation of Arthrospira Platensis for Phycocyanin Production in Large-Scale Outdoor Raceway Ponds Using Microfiltered Culture Medium. *Bioresour. Technol.* **2019**, *287*, 121420. [CrossRef]
13. Rosero-Chasoy, G.; Rodríguez-Jasso, R.M.; Aguilar, C.N.; Buitrón, G.; Chairez, I.; Ruiz, H.A. Growth Kinetics and Quantification of Carbohydrate, Protein, Lipids, and Chlorophyll of Spirulina Platensis under Aqueous Conditions Using Different Carbon and Nitrogen Sources. *Bioresour. Technol.* **2021**, *346*, 126456. [CrossRef] [PubMed]
14. Dixon, C.; Wilken, L.R. Green Microalgae Biomolecule Separations and Recovery. *Bioresour. Bioprocess.* **2018**, *5*, 1–24. [CrossRef]
15. Suganya, T.; Varman, M.; Masjuki, H.H.; Renganathan, S. Macroalgae and Microalgae as a Potential Source for Commercial Applications along with Biofuels Production: A Biorefinery Approach. *Renew. Sustain. Energy Rev.* **2016**, *55*, 909–941. [CrossRef]
16. Mehariya, S.; Fratini, F.; Lavecchia, R.; Zuorro, A. Green Extraction of Value-Added Compounds Form Microalgae: A Short Review on Natural Deep Eutectic Solvents (NaDES) and Related Pre-Treatments. *J. Environ. Chem. Eng.* **2021**, *9*, 105989. [CrossRef]
17. Soto-Sierra, L.; Stoykova, P.; Nikolov, Z.L. Extraction and Fractionation of Microalgae-Based Protein Products. *Algal Res.* **2018**, *36*, 175–192. [CrossRef]
18. Käferböck, A.; Smetana, S.; de Vos, R.; Schwarz, C.; Toepfl, S.; Parniakov, O. Sustainable Extraction of Valuable Components from Spirulina Assisted by Pulsed Electric Fields Technology. *Algal Res.* **2020**, *48*, 101914. [CrossRef]
19. Garg, S.; Wang, L.; Schenk, P.M. Flotation Separation of Marine Microalgae from Aqueous Medium. *Sep. Purif. Technol.* **2015**, *156*, 636–641. [CrossRef]
20. Demir, I.; Besson, A.; Guiraud, P.; Formosa-Dague, C. Towards a Better Understanding of Microalgae Natural Flocculation Mechanisms to Enhance Flotation Harvesting Efficiency. *Water Sci. Technol.* **2020**, *82*, 1009–1024. [CrossRef]
21. Kurniawati, H.A.; Ismadji, S.; Liu, J.C. Microalgae Harvesting by Flotation Using Natural Saponin and Chitosan. *Bioresour. Technol.* **2014**, *166*, 429–434. [CrossRef] [PubMed]
22. Xu, K.; Zou, X.; Chang, W.; Qu, Y.; Li, Y. Microalgae Harvesting Technique Using Ballasted Flotation: A Review. *Sep. Purif. Technol.* **2021**, *276*, 119439. [CrossRef]
23. Laamanen, C.A.; Ross, G.M.; Scott, J.A. Flotation Harvesting of Microalgae. *Renew. Sustain. Energy Rev.* **2016**, *58*, 75–86. [CrossRef]
24. Whitelam, G.C.; Lanaras, T.; Codd, G.A. Rapid Separation of Microalgae by Density Gradient Centrifugation in Percoll. *Br. Phycol. J.* **1983**, *18*, 23–28. [CrossRef]
25. Dassey, A.J.; Theegala, C.S. Harvesting Economics and Strategies Using Centrifugation for Cost Effective Separation of Microalgae Cells for Biodiesel Applications. *Bioresour. Technol.* **2013**, *128*, 241–245. [CrossRef]
26. Najjar, Y.S.H.; Abu-Shamleh, A. Harvesting of Microalgae by Centrifugation for Biodiesel Production: A Review. *Algal Res.* **2020**, *51*, 102046. [CrossRef]
27. Japar, S.A.; Azis, N.M.; Sobri, M.; Haiza, N.; Yasin, M. Application of Different Techniques to Harvest Microalgae. *Trans. Sci. Technol.* **2017**, *4*, 98–108.
28. Hung, M.T.; Liu, J.C. Microfiltration of Microalgae in the Presence of Rigid Particles. *Sep. Purif. Technol.* **2018**, *198*, 10–15. [CrossRef]
29. Ahmad, A.L.; Mat Yasin, N.H.; Derek, C.J.C.; Lim, J.K. Crossflow Microfiltration of Microalgae Biomass for Biofuel Production. *Desalination* **2012**, *302*, 65–70. [CrossRef]
30. Ríos, S.D.; Salvadó, J.; Farriol, X.; Torras, C. Antifouling Microfiltration Strategies to Harvest Microalgae for Biofuel. *Bioresour. Technol.* **2012**, *119*, 406–418. [CrossRef]
31. Bamba, B.S.B.; Tranchant, C.C.; Ouattara, A.; Lozano, P. Harvesting of Microalgae Biomass Using Ceramic Microfiltration at High Cross-Flow Velocity. *Appl. Biochem. Biotechnol.* **2021**, *193*, 1147–1169. [CrossRef] [PubMed]
32. Babel, S.; Takizawa, S. Microfiltration Membrane Fouling and Cake Behavior during Algal Filtration. *Desalination* **2010**, *261*, 46–51. [CrossRef]
33. Sarkar, S.; Manna, M.S.; Bhowmick, T.K.; Gayen, K. Extraction of Chlorophylls and Carotenoids from Dry and Wet Biomass of Isolated Chlorella Thermophila: Optimization of Process Parameters and Modelling by Artificial Neural Network. *Process Biochem.* **2020**, *96*, 58–72. [CrossRef]
34. Xu, L.; Wim Brilman, D.W.F.; Withag, J.A.M.; Brem, G.; Kersten, S. Assessment of a Dry and a Wet Route for the Production of Biofuels from Microalgae: Energy Balance Analysis. *Bioresour. Technol.* **2011**, *102*, 5113–5122. [CrossRef] [PubMed]

35. Aslam, A.; Bahadar, A.; Liaquat, R.; Saleem, M.; Waqas, A.; Zwawi, M. Algae as an Attractive Source for Cosmetics to Counter Environmental Stress. *Sci. Total Environ.* **2021**, *772*, 144905. [CrossRef]
36. Corrêa, P.S.; Morais Júnior, W.G.; Martins, A.A.; Caetano, N.S.; Mata, T.M. Microalgae Biomolecules: Extraction, Separation and Purification Methods. *Processes* **2021**, *9*, 10. [CrossRef]
37. Li, X.; Liu, J.; Chen, G.; Zhang, J.; Wang, C.; Liu, B. Extraction and Purification of Eicosapentaenoic Acid and Docosahexaenoic Acid from Microalgae: A Critical Review. *Algal Res.* **2019**, *43*, 101619. [CrossRef]
38. Barton, W.A.; Miller, S.A.; Veal, C.J. The Electrodewatering of Sewage Sludges. *Dry. Technol.* **1999**, *17*, 498–522. [CrossRef]
39. Citeau, M.; Olivier, J.; Mahmoud, A.; Vaxelaire, J.; Larue, O.; Vorobiev, E. Pressurised Electro-Osmotic Dewatering of Activated and Anaerobically Digested Sludges: Electrical Variables Analysis. *Water Res.* **2012**, *46*, 4405–4416. [CrossRef]
40. Loginov, M.; Citeau, M.; Lebovka, N.; Vorobiev, E. Electro-Dewatering of Drilling Sludge with Liming and Electrode Heating. *Sep. Purif. Technol.* **2013**, *104*, 89–99. [CrossRef]
41. Patel, R.; Shah, D.; Prajapti, B.G.; Patel, M. Overview of Industrial Filtration Technology and Its Applications. *Indian J. Sci. Technol.* **2010**, *3*, 1121–1127. [CrossRef]
42. Warring, R.H. *Filters and Filtration Handbook*; Trade & Technical Press Ltd.: Morden, UK, 1981. [CrossRef]
43. Seo, Y. Characterization of Industrial Filtration Systems for Fine Particle. *ARPN J. Eng. Appl. Sci.* **2015**, *10*, 10605–10610.
44. Wakeman, R.J.; Tarleton, E.S. Solid/Liquid Separation: Principles of Industrial Filtration. In *Solid/Liquid Sep. Equip. Sel. Process Des.*, 1st ed.; Elsevier Science: Amsterdam, The Netherlands, 2005.
45. Citeau, M.; Larue, O.; Vorobiev, E. Electric (Electro/Dielectro-Phoretic)—Force Field Assisted Separators. In *Progress in Filtration and Separation*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 325–397.
46. Discart, V.; Bilad, M.R.; Vandamme, D.; Foubert, I.; Muylaert, K.; Vankelecom, I.F.J. Role of Transparent Exopolymeric Particles in Membrane Fouling: Chlorella Vulgaris Broth Filtration. *Bioresour. Technol.* **2013**, *129*, 18–25. [CrossRef] [PubMed]
47. Pfaff, N.M.; Kleijn, J.M.; van Loosdrecht, M.C.M.; Kemperman, A.J.B. Formation and Ripening of Alginate-like Exopolymer Gel Layers during and after Membrane Filtration. *Water Res.* **2021**, *195*, 116959. [CrossRef] [PubMed]
48. De Gouvion Saint Cyr, D.; Wisniewski, C.; Schrive, L.; Farhi, E.; Rivasseau, C. Feasibility Study of Microfiltration for Algae Separation in an Innovative Nuclear Effluents Decontamination Process. *Sep. Purif. Technol.* **2014**, *125*, 126–135. [CrossRef]
49. Mo, W.; Soh, L.; Werber, J.R.; Elimelech, M.; Zimmerman, J.B. Application of Membrane Dewatering for Algal Biofuel. *Algal Res.* **2015**, *11*, 1–12. [CrossRef]
50. Desabres, J.; Equisoain, C.; Loginov, M.; Gésan-Guiziou, G.; Vorobiev, E. Improvement of Anode Lifetime by Flushing during Electrofiltration. *Dry. Technol.* **2018**, *36*, 1145–1157. [CrossRef]
51. Sorensen, P.B.; Moldrup, P.; Hansen, J.A.A. Filtration and Expression of Compressible Cakes. *Chem. Eng. Sci.* **1996**, *51*, 967–979. [CrossRef]
52. Mahmoud, A.; Olivier, J.; Vaxelaire, J.; Hoadley, A.F.A. Electrical Field: A Historical Review of Its Application and Contributions in Wastewater Sludge Dewatering. *Water Res.* **2010**, *44*, 2381–2407. [CrossRef]
53. Khosravanipour Mostafazadeh, A.; Zolfaghari, M.; Drogui, P. Electrofiltration Technique for Water and Wastewater Treatment and Bio-Products Management: A Review. *J. Water Process Eng.* **2016**, *14*, 28–40. [CrossRef]
54. Aoude, C.; Grimi, N.; El Zakhem, H.; Vorobiev, E. Dewatering of *Arthrospira Platensis* Microalgae Suspension by Electrofiltration. *Dry. Technol.* **2022**, 1–13. [CrossRef]
55. Zhang, Q.; Cui, G.; He, X.; Wang, Z.; Tang, T.; Zhao, Q.; Liu, Y. Effects of Voltage and Pressure on Sludge Electro-Dewatering Process and the Dewatering Mechanisms Investigation. *Environ. Res.* **2022**, *212*, 113490. [CrossRef] [PubMed]
56. Wei, S.; Chen, Y.; Wei, X.; Dong, C.; Cai, M.; Song, Z.; Shi, Y.; Jin, M.; Xu, T. Understanding Mechanism of Improved-Dewatering of Waste Activated Sludge by Multi-Stage Pressurized Vertical Electro-Osmotic. *Process Saf. Environ. Prot.* **2022**, *164*, 846–856. [CrossRef]
57. Li, Q.; Zhi, S.; Yu, X.; Li, Y.; Guo, H.; Yang, Z.; Zhang, S. Biodegradation of Volatile Solids and Water Mass Balance of Bio-Drying Sewage Sludge after Electro-Dewatering Pretreatment. *Waste Manag.* **2019**, *91*, 9–19. [CrossRef] [PubMed]
58. Lee, K.; Lee, S.; Lee, J.; Zhang, X.; Lee, S.H. Roles of Soluble Microbial Products and Extracellular Polymeric Substances in Membrane Fouling. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 45–79.
59. Chen, G. Electrochemical Technologies in Wastewater Treatment. *Sep. Purif. Technol.* **2004**, *38*, 11–41. [CrossRef]
60. Käppler, T.; Posten, C. Fractionation of Proteins with Two-Sided Electro-Ultrafiltration. *J. Biotechnol.* **2007**, *128*, 895–907. [CrossRef]
61. Hofmann, R.; Posten, C. Improvement of Dead-End Filtration of Biopolymers with Pressure Electrofiltration. *Chem. Eng. Sci.* **2003**, *58*, 3847–3858. [CrossRef]
62. Kim, D.-Y.; Hwang, T.; Oh, Y.-K.; Han, J.-I. Harvesting *Chlorella* Sp. KR-1 Using Cross-Flow Electro-Filtration. *Algal Res.* **2014**, *6*, 170–174. [CrossRef]
63. Cao, B.; Zhang, Y.; Shi, Y.; Ren, R.; Wu, H.; Zhang, W.; Wang, D.; Zhang, T.; Xiong, J. Extracellular Organic Matter (EOM) Distribution Characteristic in Algae Electro-Dewatering Process. *J. Environ. Manag.* **2020**, *265*, 110541. [CrossRef]
64. Bradford, M.M. A Rapid and Sensitive Method for the Quantitation of Microgram Quantities of Protein Utilizing the Principle of Protein-Dye Binding. *Anal. Biochem.* **1976**, *72*, 248–254. [CrossRef]
65. Bennett, A.; Bogobad, L. Complementary Chromatic Adaptation in a Filamentous Blue-Green Alga. *J. Cell Biol.* **1973**, *58*, 419–435. [CrossRef] [PubMed]

66. Weber, K.; Stahl, W. Improvement of Filtration Kinetics by Pressure Electrofiltration. *Sep. Purif. Technol.* **2002**, *26*, 69–80. [CrossRef]
67. Vorobiev, E.; Jany, S. Étapes de Filtration Frontale Assistée Par Un Champ Électrique. *Entropie* **1999**, *16*, 23–28.
68. Liu, Y.; Su, Y.; Cao, J.; Guan, J.; Zhang, R.; He, M.; Fan, L.; Zhang, Q.; Jiang, Z. Antifouling, High-Flux Oil/Water Separation Carbon Nanotube Membranes by Polymer-Mediated Surface Charging and Hydrophilization. *J. Memb. Sci.* **2017**, *542*, 254–263. [CrossRef]
69. Chong, W.C.; Mahmoudi, E.; Chung, Y.T.; Koo, C.H.; Mohammad, A.W.; Kamarudin, K.F. Improving Performance in Algal Organic Matter Filtration Using Polyvinylidene Fluoride–Graphene Oxide Nanohybrid Membranes. *Algal Res.* **2017**, *27*, 32–42. [CrossRef]
70. Teow, Y.H.; Wong, Z.H.; Takriff, M.S.; Mohammad, A.W. Fouling Behaviours of Two Stages Microalgae/Membrane Filtration System Applied to Palm Oil Mill Effluent Treatment. *Membr. Water Treat.* **2018**, *9*, 373–383. [CrossRef]
71. Rossi, N.; Jaouen, P.; Legentilhomme, P.; Petit, I. Harvesting of Cyanobacterium Arthrospira Platensis Using Organic Filtration Membranes. *Food Bioprod. Process.* **2004**, *82*, 244–250. [CrossRef]
72. Rossi, N.; Derouiniotchaplain, M.; Jaouen, P.; Legentilhomme, P.; Petit, I. Arthrospira Platensis Harvesting with Membranes: Fouling Phenomenon with Limiting and Critical Flux. *Bioresour. Technol.* **2008**, *99*, 6162–6167. [CrossRef]
73. Wakeman, R. The Influence of Particle Properties on Filtration. *Sep. Purif. Technol.* **2007**, *58*, 234–241. [CrossRef]
74. Bourcier, D.; Féraud, J.P.; Colson, D.; Mandrick, K.; Ode, D.; Brackx, E.; Puel, F. Influence of Particle Size and Shape Properties on Cake Resistance and Compressibility during Pressure Filtration. *Chem. Eng. Sci.* **2016**, *144*, 176–187. [CrossRef]
75. Boskovic, L.; Altman, I.S.; Agranovski, I.E.; Braddock, R.D.; Myojo, T.; Choi, M. Influence of Particle Shape on Filtration Processes. *Aerosol Sci. Technol.* **2005**, *39*, 1184–1190. [CrossRef]
76. Larue, O.; Wakeman, R.J.; Tarleton, E.S.; Vorobiev, E. Pressure Electroosmotic Dewatering with Continuous Removal of Electrolysis Products. *Chem. Eng. Sci.* **2006**, *61*, 4732–4740. [CrossRef]
77. Costa, J.A.V.; Freitas, B.C.B.; Rosa, G.M.; Moraes, L.; Morais, M.G.; Mitchell, B.G. Operational and Economic Aspects of Spirulina-Based Biorefinery. *Bioresour. Technol.* **2019**, *292*, 121946. [CrossRef] [PubMed]
78. Hagglund, J.K.; Insley, T.I.; Johnson, T.W. Electrofiltration Process. U.S. Patent US 6,471,746 B2, 2002. Available online: https://patentimages.storage.googleapis.com/63/03/93/47c02b9043c337/US6471746.pdf (accessed on 27 September 2022).
79. Moghadam, M.T.; Lesage, G.; Mohammadi, T.; Mericq, J.P.; Mendret, J.; Heran, M.; Faur, C.; Brosillon, S.; Hemmati, M.; Naeimpoor, F. Improved Antifouling Properties of TiO_2/PVDF Nanocomposite Membranes in UV-Coupled Ultrafiltration. *J. Appl. Polym. Sci.* **2015**, *132*, 1–13. [CrossRef]
80. Mozdzanowski, J.; Speicher, D.W. Microsequence Analysis of Electroblotted Proteins. I. Comparison of Electroblotting Recoveries Using Different Types of PVDF Membranes. *Anal. Biochem.* **1992**, *207*, 11–18. [CrossRef] [PubMed]
81. Fernandez, J.; Mische, S.M. Enzymatic Digestion of Proteins on PVDF Membranes. *Curr. Protoc. Protein Sci.* **1995**. [CrossRef] [PubMed]
82. Zhang, S.; Chen, Y.; Zang, X.; Zhang, X. Harvesting of Microcystis Aeruginosa Using Membrane Filtration: Influence of Pore Structure on Fouling Kinetics, Algogenic Organic Matter Retention and Cake Formation. *Algal Res.* **2020**, *52*, 102112. [CrossRef]
83. Rodrigues, R.D.P.; de Lima, P.F.; de Santiago-Aguiar, R.S.; Rocha, M.V.P. Evaluation of Protic Ionic Liquids as Potential Solvents for the Heating Extraction of Phycobiliproteins from Spirulina (Arthrospira) Platensis. *Algal Res.* **2019**, *38*, 101391. [CrossRef]
84. Böcker, L.; Ortmann, S.; Surber, J.; Leeb, E.; Reineke, K.; Mathys, A. Biphasic Short Time Heat Degradation of the Blue Microalgae Protein Phycocyanin from Arthrospira Platensis. *Innov. Food Sci. Emerg. Technol.* **2019**, *52*, 116–121. [CrossRef]
85. Buecker, S.; Grossmann, L.; Loeffler, M.; Leeb, E.; Weiss, J. Thermal and Acidic Denaturation of Phycocyanin from Arthrospira Platensis: Effects of Complexation with λ-Carrageenan on Blue Color Stability. *Food Chem.* **2022**, *380*, 132157. [CrossRef]
86. Patel, A.; Pawar, R.; Mishra, S.; Sonawane, S.; Ghosh, P.K. Kinetic Studies on Thermal Denaturation of C-Phycocyanin. *Indian J. Biochem. Biophys.* **2004**, *41*, 254–257. [PubMed]
87. Chaiklahan, R.; Chirasuwan, N.; Bunnag, B. Stability of Phycocyanin Extracted from Spirulina Sp.: Influence of Temperature, PH and Preservatives. *Process Biochem.* **2012**, *47*, 659–664. [CrossRef]
88. Chronakis, I.S.; Galatanu, A.N.; Nylander, T.; Lindman, B. The Behaviour of Protein Preparations from Blue-Green Algae (Spirulina Platensis Strain Pacifica) at the Air/Water Interface. *Colloids Surf. A Physicochem. Eng. Asp.* **2000**, *173*, 181–192. [CrossRef]