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Article

An Innovative Low-Cost Equipment for Electro-Concentration of Microalgal Biomass

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Featured Application: This paper features the design and construction of low-cost equipment for the harvesting of microalgal and cyanobacterial biomass under laboratory conditions.

Abstract: Microalgal harvesting is one of the most challenging processes in the development of algal research and development. Several methods, such as centrifugation, flocculation, and filtration, are available at the laboratory scale. However, the requirement of expensive pieces of equipment and the possibility of biomass contamination are recurring gaps that hinder the development of microalgae I+D in different parts of the world. Recently, the electroflotation has been proved as a suitable method for the harvesting of different species of microalgae and cyanobacteria. To this day, there are no companies that sell laboratory-scale electroflotation equipment; this is mainly due to the gap in the knowledge on which factors (time, mixing rate, number of electrodes, and others) will affect the efficiency of concentration without reducing the biomass quality. This paper aims to build an innovative low-cost electroflotation system under 300 USD with cheap and resistant materials. To achieve our goal, we test the interaction of three variables (time, mixing rate, and amount of electrodes) were evaluated. Results showed that an efficiency closer to 100% could be achieved under 20 minutes using >10 electrodes and 150 rpm. We hope this innovative approach can be used by different researchers to improve our knowledge of the concentration and harvesting of algae and cyanobacteria.

Keywords: Dewatering; Response Surface Methodology; Arduino; Aluminum electrodes; microalgae harvesting.

1. Introduction

The R&D on microalgal usage has expanded tremendously over the last two decades. From biofuels to nutraceuticals, this microorganism has led an industrial expansion on novel products for different markets worldwide. Microalgae cells are tiny, usually ranging from one to ten micrometers with a low specific gravity (1–1.1 $g*L^{-1}$) [1], and when is produced on large scale reactors (such as open ponds or PBR) tend to be highly diluted (on the order of 1 g/L up to 2 g/L) [2,3].

Giving its nature, the most troublesome step on microalgae research and production is the concentration and dewatering of produced biomass. This process is a labor-intensive and time-intensive step, which separates the microalgal biomass from water for effective downstream

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processing [4]. Algae concentration and separation from the exhausted media demands large amounts of energy [5]; therefore, extended operation times are required to concentrate significant amounts of biomass.

On a broad view, in the last ten years, over 1100 research papers focused on algal production and metabolites extraction have been published. As far as the author's knowledge, the vast majority of these papers use centrifuges for algae concentration. It does exist other technologies for algal concentration such as flocculation (auto-, bio- or microbial flocculation), flotation, filtration, etc.; however, flocs collected may contain a certain amount of flocculant (organic or inorganic), which in turn may contaminate the final biomass, thus reducing the suitability of produced biomass for some purposes [6].

In 2018, the National Alliance for Advanced Biofuels and Bioproducts (NAABB) in his final report [7] recommended that electroflotation was the most efficient and sustainable method for algae concentration and dewatering. There are three established electrolytic methods: electrocoagulation, electroflotation, and electroflocculation. This physical/chemical process is founded on the principle of the movement of electrically charged particles in an electric field [4] and the in-situ generation of flocculants during metal electrolysis [8].

Briefly, an electric current is applied to the solution between two electrodes; then, metal ions are released from the sacrificial anode through electrolytic oxidation; at the same time, oxygen and hydrogen microbubbles generated at the anode and cathode flow through the suspension [9]. Metal ions react with the pollutants forming flocs, which in turn can be lifted to the surface by the microbubbles or sediment in the lower part of the reactor [6,10,11], which can be easily removed from the system's surface [12].

In 2018 [13], we proposed an Arduino®-based magnetic stirrer for the harvesting of biomass through electroflotation. In this study, we found that short distance between electrodes, medium mixing rates (200 rpm), and 50W can remove up to 100% of algal biomass from 500 mL of culture media. Other authors have studied potential variables such as voltage, pH, time, current intensity, electrode material, temperature, and submerged area of electrodes. Each one of those experiments employed inexpensive materials and equipment found in most laboratories around the world (glass beakers, magnetic stirrer, power supply, and lab stands) [1,3-6,8,13]. Despite its simplicity, there is no available equipment for the concentration and harvesting of algal biomass through electroflotation. The latter may occur because there is no consensus on which are the most critical variables for biomass concentration, which makes it challenging to build equipment that can be used for different species of both microalgae and cyanobacteria.

The aim of this project is to design and build an efficient, low-cost (< 300 USD) electroflotation equipment for the concentration and dewatering of algal biomass. To achieve the above, the interaction of three key factors (number of electrodes, mixing rate, and time) was employed.

2. Materials and Methods

2.1. Strain culture

Scenedesmus sp UFPS_002 was obtained for the INNOValgae collection (Universidad Francisco de Paula Santander, Colombia). The strain growth in 2000 mL tubular glass reactors with a culture volume of 1300 mL containing Bold Basal Medium [14]. The alga was mixed through the injection of air with 1% (v/v) CO_2 at a flow rate of 0.78 L min^{-1}, and light:dark cycle of 12:12 hours at 120 µmol m^{-2} s^{-1}.

2.1. Response Surface Methodology for variables evaluation

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The interaction between three critical variables on the process was evaluated using a 3^3 (3 factors, 3 levels) Non-Factorial Response Surface Design with two central points, on software STATISTICA 7.0 (Statsoft) (Table 1).

Table 1. Variables for electroflotation of algal biomass.

Level	# of electrodes	Mixing (rpm)	Time (min)
-1	2	100	10
0	4	150	15
1	6	200	20

Each of the experiments was performed using 300 mL of 30 days-old algae culture on a 600 mL beaker. Aluminum electrodes (13 cm long, 5 cm wide), with a distance of 5 mm between electrodes and an electric current of 50W (50V, 1 Amp), were employed. To avoid deviations by electrode degradation, every single experiment was performed using new electrodes. All the samples were mixed using an Arduino®-based magnetic stirrer described by [13].

The efficiency (E, expressed as percentage) of cell concentration was determined by optical density (absorbance A at 550 nm) of the culture at the beginning (A_0) and at the end (A_t). Each experiment was measured five times (original and four replicates). The efficiency was obtained by replacing the values obtained in equation 1.

$$E = \frac{A_0 - A_t}{A_0} \% \quad (1)$$

Once the factors affecting the process were obtained, the stability of the method was evaluated by increasing the reaction volume up to 2000 mL. In this stage, the electrodes were reused up to 20 cycles.

At the end of every cycle, the electrodes were washed with deionized water, dried in an oven (100°C, 24 h), and stored in a desiccator until a constant weight was obtained. After the process, the weight of each electrode was recorded and used again until 20 cycles were achieved.

From the results, a system was designed to fit the needs of a microalgae culture laboratory. The following parameters were taken into account:

- maximum efficiency of cell concentration.
- minimum working volume of 500 mL and maximum 2000 mL
- Easy cleaning and maintenance.
- Final cost less than 300 USD.

3. Results

From all the experiments, it was possible to retrieve the concentrated biomass. However, there were significant differences between the experiments. Table 2 present the results for biomass concentration and temperature of the media. There was a considerable increase in temperature (> 35°C) in those experiments with efficiencies below 40%. This increase in the temperature of the medium can have adverse effects on the stability and quality of the biomass. However, test 5 shows efficiency values below 20%, but with a temperature below 30 ° C, this is due to the short time exposed to the process in the experiment (6.6 minutes).

According to [15], the distance between electrodes affects the overall energy consumption in the process. Our findings show that not only the distance but the number of electrodes used can increase energy consumption (fewer electrodes, higher energy consumption).

Table 2. The efficiency of algae concentration and temperature of media.

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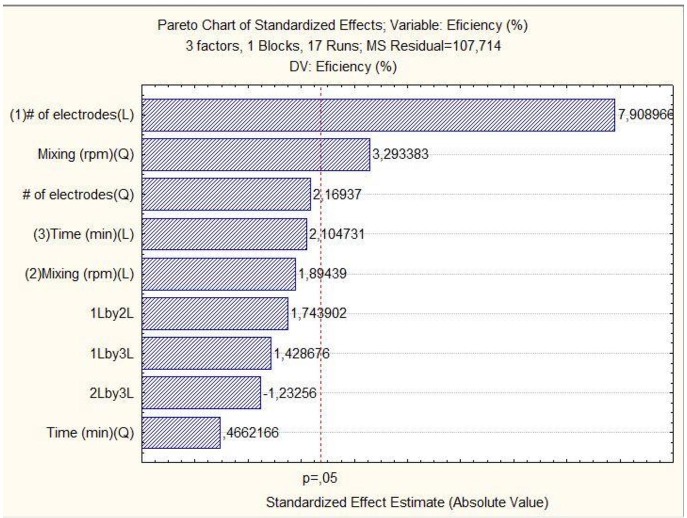
Experiment	# of electrodes	Mixing (rpm)	Time (min)	Efficiency (%)	Temperature (°)
5 (C)	4	150	15	32,07	35,27
1	2	100	10	33,67	32,72
16	4	150	23	38,71	43,55
3	6	100	20	81,27	35,60
15	4	150	6,6	15,48	28,61
8	6	100	10	48,85	29,21
13	4	66	15	38,55	31,53
17 (C)	4	150	15	32,07	35,28
10 (C)	4	150	15	32,07	35,28
12	7	150	15	83,76	36,22
11	1	150	15	0	25
4	6	200	10	79,83	28,39
2	2	200	20	28,13	58,54
9	6	200	20	89,92	31,77
7	2	200	10	34,79	42,20
14	4	234	15	64,99	29,86
6	2	100	20	40,64	36,67

The Pareto analysis (Figure 1a) illustrates that ($p = 0.05$) the number of electrodes and agitation are the variables that most affect the concentration process. These results are consistent with the results presented by [16], where they demonstrated that the number of electrodes and agitation are critical variables for increasing efficiency since they allow to increase the active area of contact with the media and decrease the electrical consumption.



(a)

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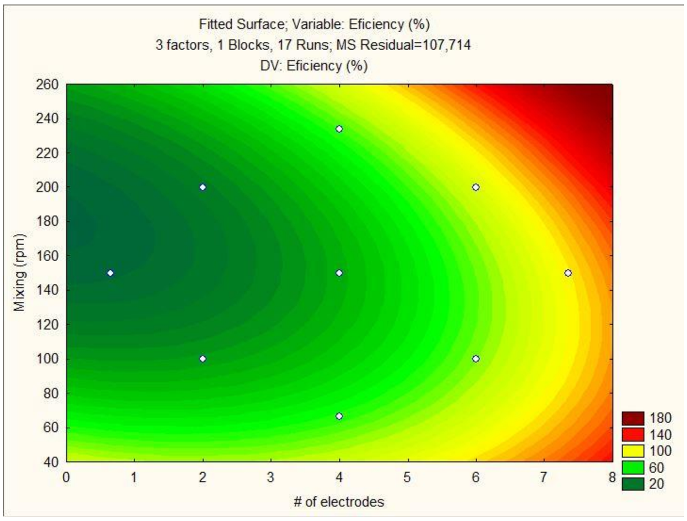

(**b**)

Figure 1. Pareto Analysis of variables (a) and surface response between the most critical variables, mixing and # of electrodes (b).

By analyzing the interaction between mixing and the number of electrodes within the equipment (Figure 1b), Equation 2 was obtained, where X is the number of electrodes, and Y is the mixing. According to Eq 2, to achieve an efficiency close to 100%, medium agitation and more than ten electrodes are necessary (table 3). These operating conditions are consistent with the results obtained by [16], where mixing has a direct relationship with the time of concentration since at speeds between 150-210 rpm, the biomass is aggregated in less time, with an efficiency of 90%. However, they recommend the use of agitation close to 150 rpm to save energy and maintain higher efficiencies.

$$Z = (113{,}9 - 19{,}8 * x) + (1{,}7 * x^2) - (1{,}1 * \mathrm{y}) + (0{,}004 * y^2) + (0{,}064 * \mathrm{x} * \mathrm{y}) + (0{,}524 * 15{,}0 * \mathrm{x}) - (0{,}018 * 15{,}0 * \mathrm{y}) + (13{,}966) \quad (2)$$

Table 3. Variables for optimal electroflotation.

Label	Variable	Value
X	# of electrodes	11
Y	mixing (rpm)	150
Z	Efficiency (%)	>100

The verification of the proposed operating conditions for the efficient concentration of the biomass was tested on a piece of innovative equipment, designed and built for the project. This new equipment has a build-in, Arduino-based magnetic stirrer at the bottom, with a working volume of 2L (figure 2). The design of each section, the size of electrodes, and the electrical blueprint of the magnetic stirrer can be found in appendix A-C. Once the operating conditions (11 electrodes, 150 rpm, 20 minutes) were selected, the stability of the electrodes was evaluated during 20 concentration cycles, using 2 L of *Scenedesmus* sp.

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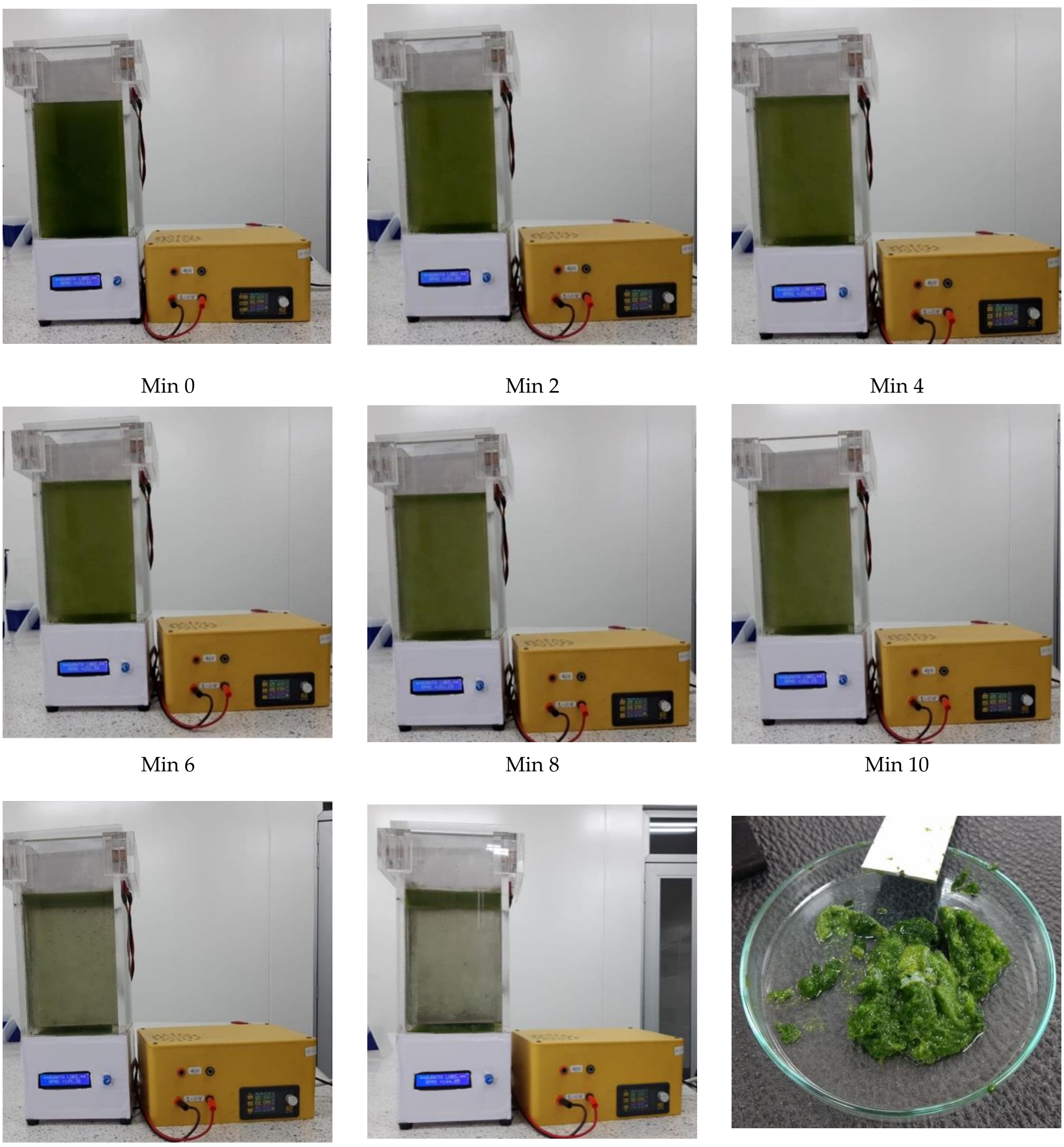

Min 0 | Min 2 | Min 4
Min 6 | Min 8 | Min 10
Min 12 | Min 15 | Harvested biomass

Figure 2. The concentration of biomass using the new equipment for electroflotation.

After 15 minutes, the process reaches an efficiency of 100%, with no increase in the temperature of the media (figure 3). This process was repeated 20 times, according to the results presented in Figure 3, it is possible to determine that, after 20 cycles, the electrodes can lose up to 15% (w/w) of their mass. These results allow inferring that, on average, each electrode will lose 0.57% (w/w) of its weight for each liter processed. However, the efficiency of each of the cycles is above 95% (figure 4), with no reduction in its effectiveness. The above demonstrates that electroflotation is a stable, repeatable process and that the electrodes can withstand several cycles without the need to replace

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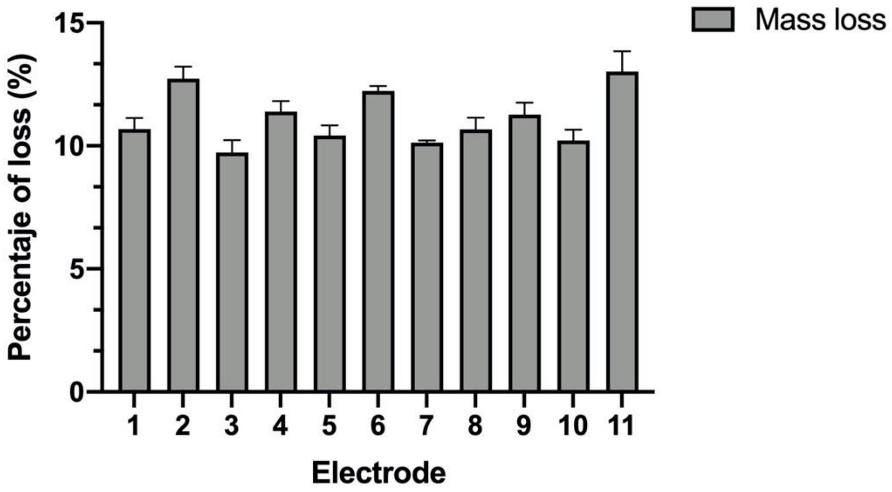
them in short periods. This equipment has a cost of 260 USD. All the parts and were to buy them can be found in Appendix D.



(**a**)

(**b**)

Figure 3. Mass loss of the electrodes (a) and efficiency on electroflotation by the reuse of electrodes (b).

4. Discussion

Throughout the last years, the application of electroflotation for the concentration of microalgae and cyanobacteria has gained strength. One of the most evaluated variables has been the mixing of the media since high speeds (>300 rpm) can damage the cells. However, [17] found that mixing does not affect the efficiency of algal harvesting. However, the appropriate mixture is required to improve the contact of the cells with the electrodes and, in turn, improve the aggregation of flocs since high mixing rates can alter their formation [16]. The only variable that did not affect (either positively or negatively) the efficiency was time. However, long times (> 30 minutes), can increase energy consumption. In our previous work [13], we found that time is a critical variable for an optimal concentration. However, in that research, all the results were obtained using only two aluminum electrodes.

Through the development of this work, an electrical current of 50W was used. [16,18-20] found that at a higher voltage (> 30 V), the time is reduced (<10 minutes). The latter occurs due to an increase in the number of free ions from the sacrificial electrode, which accelerates the shift of cell surface charges, allowing faster flocculation.

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Another variable that directly affects the efficiency is the distance between the electrodes. All the experiments performed employed a length of 5 mm, which, according to [16] is an optimal distance to increase the efficiency of the process and reduce the time. According to [21], distances less than 10 mm affect the formation of gas bubbles around the electrode, and more considerable distances can negatively affect the overall efficiency and increase energy consumption.

Another crucial factor is the electrode material. Table 4 presents a short review of different materials employed for the harvesting of algae and cyanobacteria. The most common material is aluminum. Other materials, such as graphite, require the addition of electrolytes or chemical flocculants such as $Al_2(SO_4)_3$ or chitosan to achieve higher efficiencies (> 92%) [4,16].

Table 4. Electrode materials evaluated for the harvesting of microalgae and cyanobacteria.

Strain	Electrode material	# of electrodes	mixing (rpm)	Time (min)	Efficiency (%)	Author
Chlorella sp. MJ 11/11	Stainless steel	2	---	30	98	[1]
Chlorella sp. 0217	Graphite coupled with chitosan	2	30	3	90	[16]
Chlorella sp. (PTCC 6010)	Al	4	100 (high), 30 (low)	1 (high), 15 (low)	96.8	[5]
Chlorella pyrenoidosa	Al, Zn, Cu, Fe and a non-sacrificial electrode of carbon	3 (2 cathodes, 1 anode)	---	5	95.83	[22]
Chlorella vulgaris	Al	2	---	8	100	[8]
Chlorella vulgaris UTEX 1803	Al and Cu	2	200	25	97 - 88	[13]
Chlorella vulgaris	Al or Fe (Anode) and IrO_2/TiO_2 (cathode)	2	---	30	88	[24]
Desmodesmus subspicatus	Al or Fe Spiral electrode	---	---	20	95.4	[23]
Dunaliella bardawil 30861	Al coupled with sand	2	150	3	97.16	[3]
Dunaliella salina	Al	2	100	7	98.9	[15]
Microcystis aeruginosa	Al	2	200	45	100	[19]
Microcystis aeruginosa	Al and Fe	2	200	50	100	[20]
Phaeodactylum tricornutum	Al or Fe (Anode) and IrO_2/TiO_2 (cathode)	2	---	20	85	[24]
Scenedesmus sp.	Al and graphite	2	---	20	98.5 - 92	[17]
Scenedesmus acuminatus	Mg, Al, Zn, Cu, Fe, and brass	2	100	7.3 - 30.9	90	[18]
Scenedesmus obliquus FR751179.1	Graphite coupled with $Al_2(SO_4)_3$	3 (2 cathodes, 1 anode)	---	60	83	[4]
Tetraselmis sp.	Al	2	---	15	---	[6]

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Scenedesmus sp UFPS_002	Al	11	150	15	100	This paper

5. Conclusions

The present work explores the interaction between critical variables (mixing, number of electrodes, and time) for the efficient concentration and harvesting of microalgal biomass through an electroflotation process. Results have shown that time can be significantly reduced (from 30 to 15 min) as long the ten or more electrodes are active and medium mixing rates (150 rpm). From the data, the innovative equipment has a lower-medium cost (260 USD) with cheap and resistant materials that anyone can build. This new configuration proves that the electrodes can be reused several times, which in turn reduces the cost of the concentration of up to 2 L of algal biomass. We hope this innovative approach can be used by different researchers to improve our knowledge of the concentration and harvesting of algae and cyanobacteria.

Author Contributions: Conceptualization, J.E.C.-R. I.J.C-G and A.Z.; Data curation, A.F.B.-S.; Formal analysis, J.B.G.-M. and A.Z.; Funding acquisition, E.M.S-G, and A.F.B-S.; Investigation, J.E.C.-R. I.J.C-G and E.M.S-G.; Methodology, J.B.G.-M., A.F.B.-S. and A.Z.; Project administration, A.F.B-S.; Resources, J.E.C.-R. I.J.C-G and E.M.S-G.; Software, J.B.G.-M, and E.M.S-G.; Supervision, A.F.B.-S. And A.Z.; Validation, J.E.C.-R. and I.J.C-G.; Visualization, A.F.B.-S. And A.Z.; Writing–original draft, A.F.B.-S. And A.Z.; Writing–review & editing, J.B.G.-M., A.F.B.-S. And A.Z.

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

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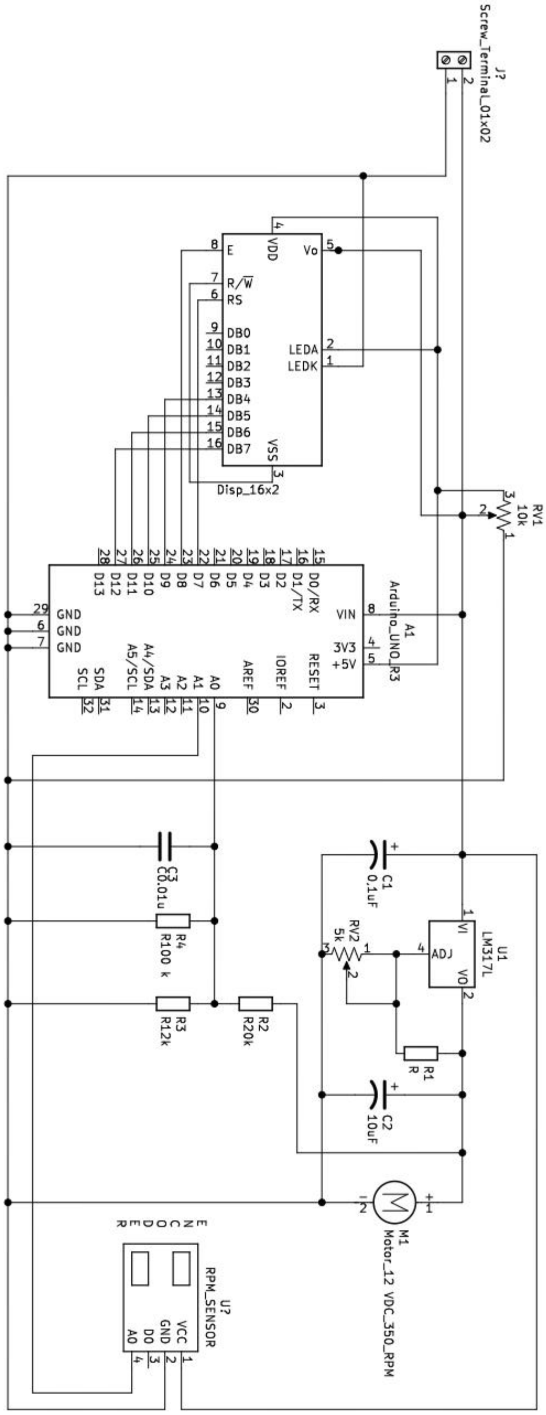
Appendix A. Magnetic stirrer with speed control



Appendix B. Electrodes design

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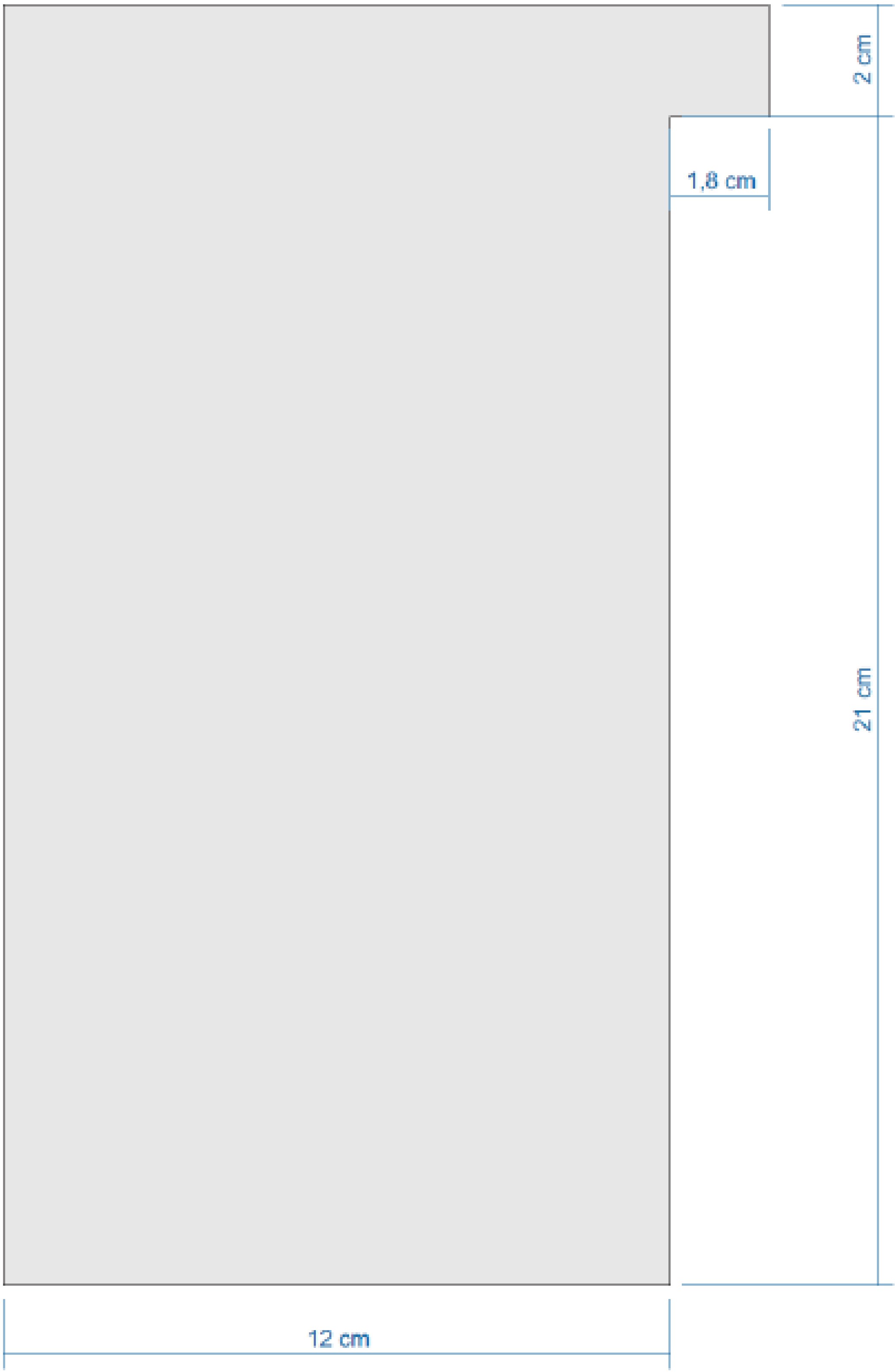

Note: Each electrode was built using 0.1 cm thick aluminum plates.

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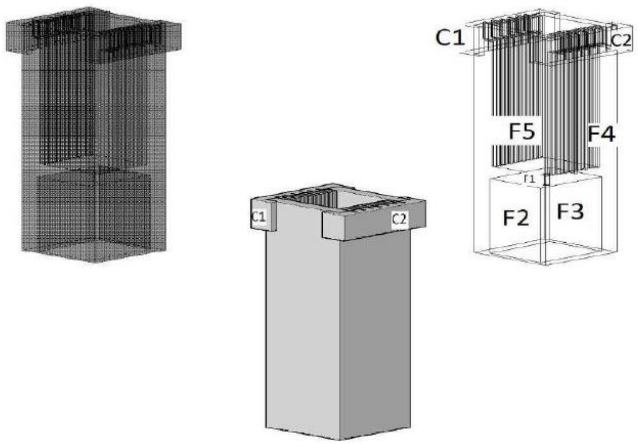
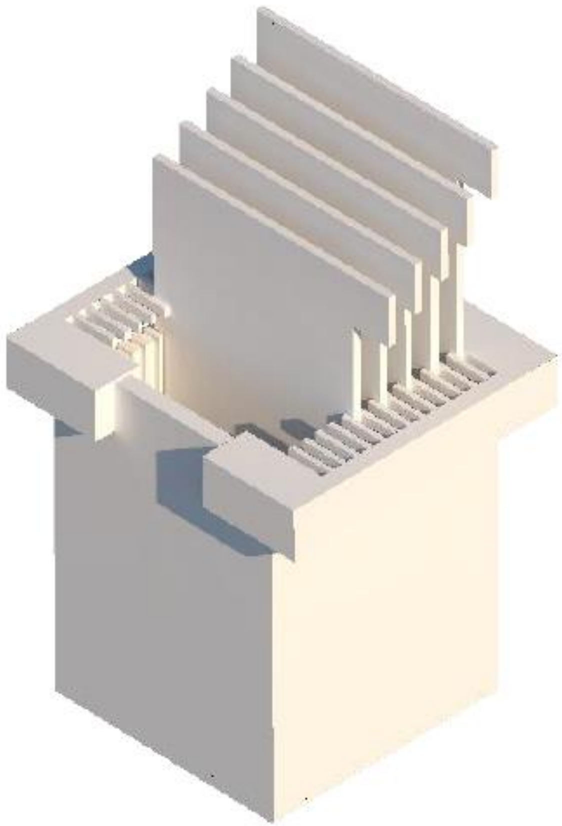
Appendix C. Assembly of the equipment with the electrodes





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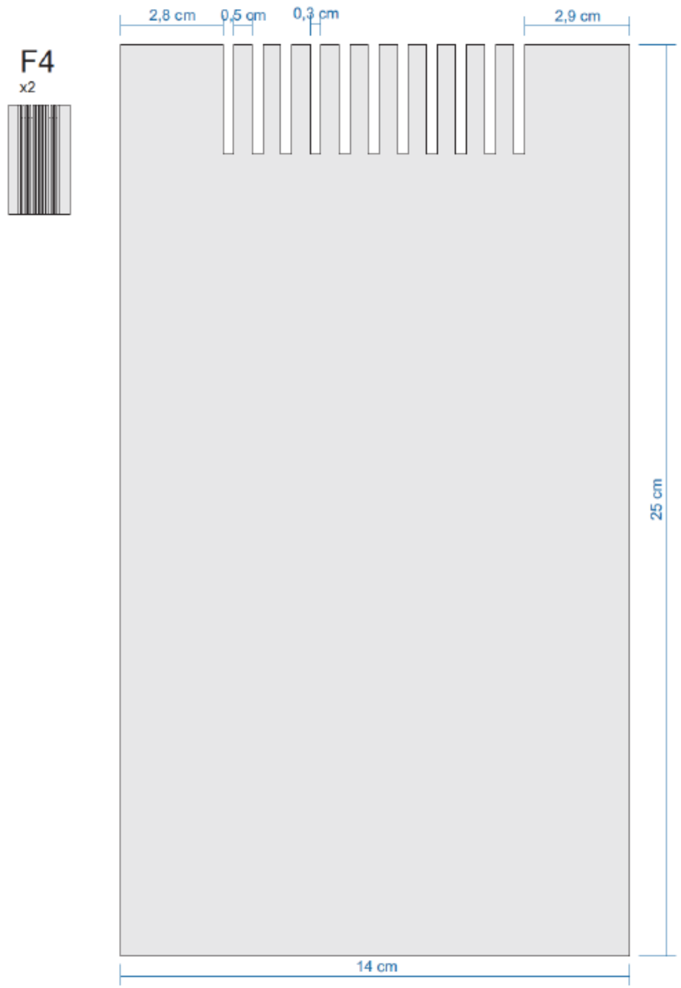
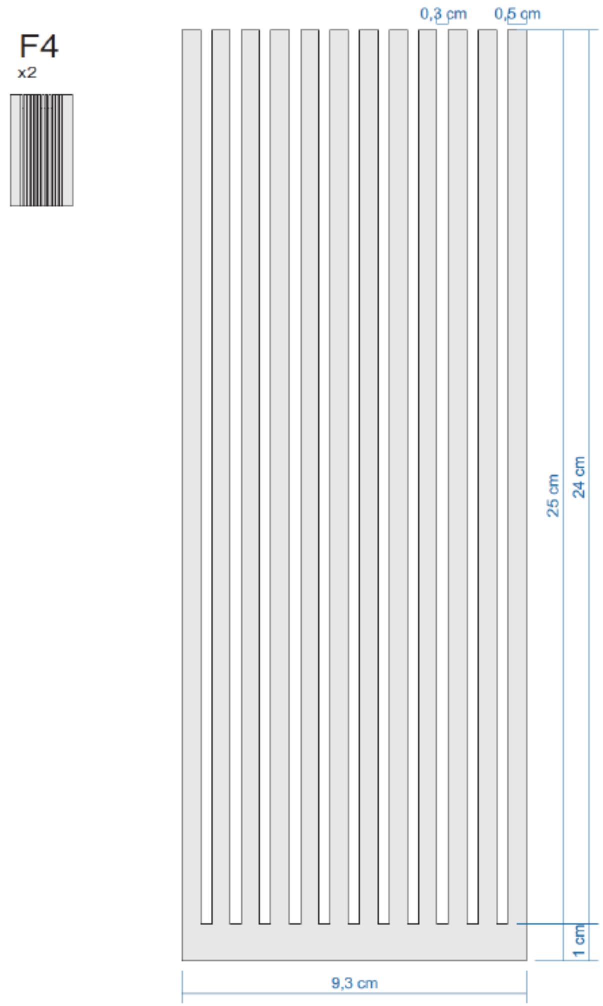
Appendix D. Sections of the equipment





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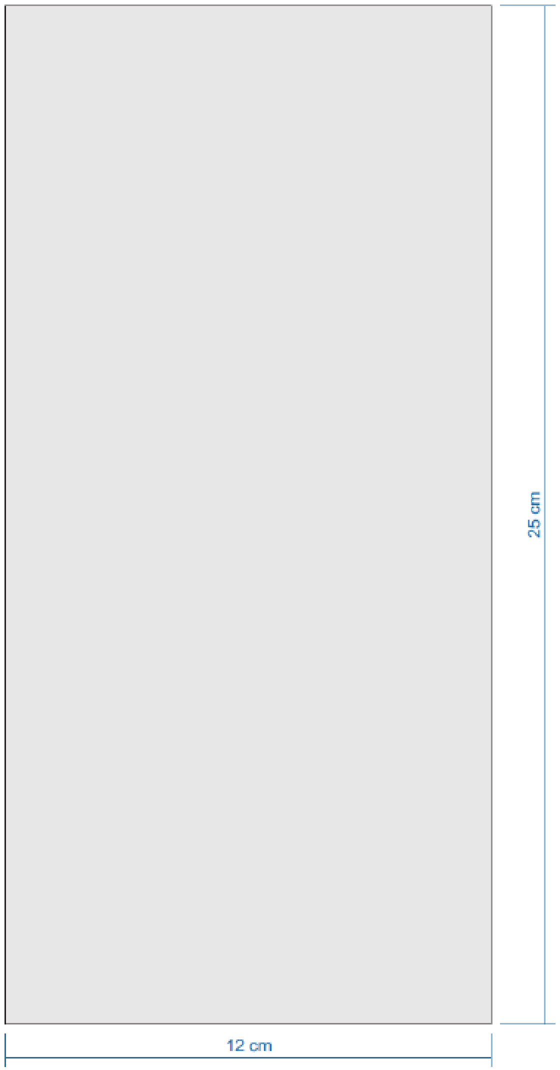
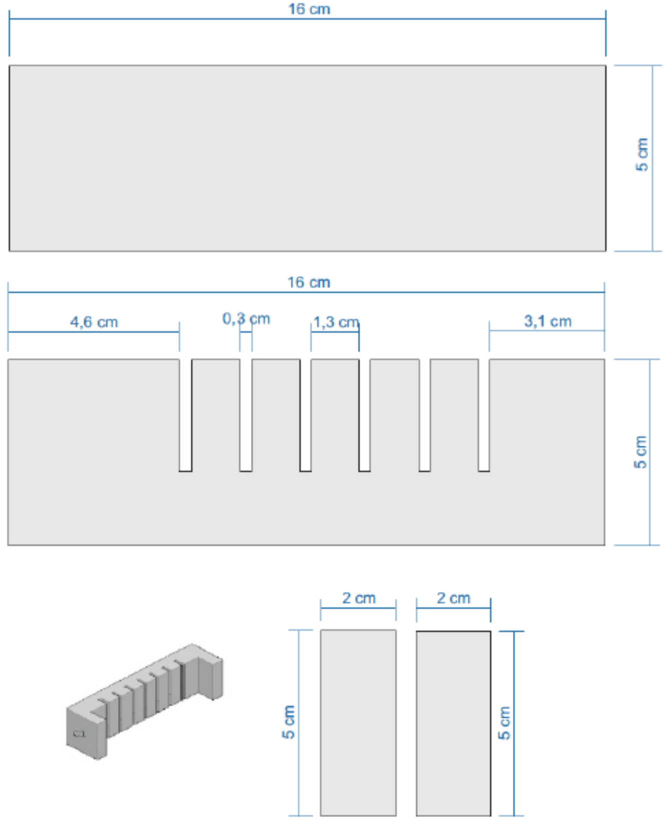
F5
x2



C1



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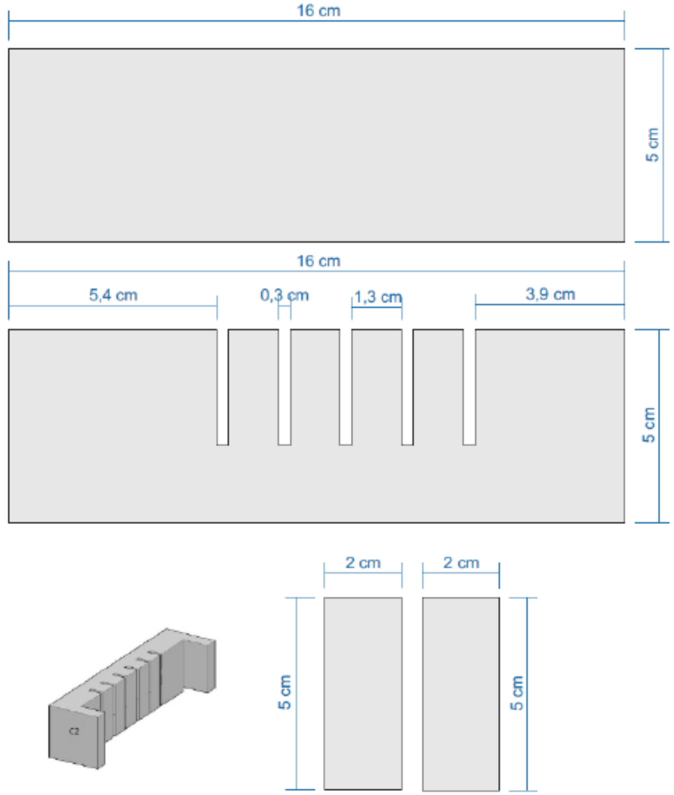
C2



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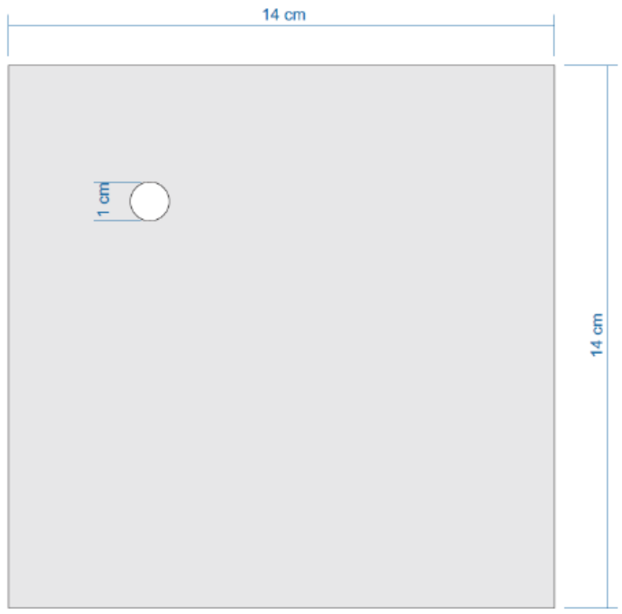

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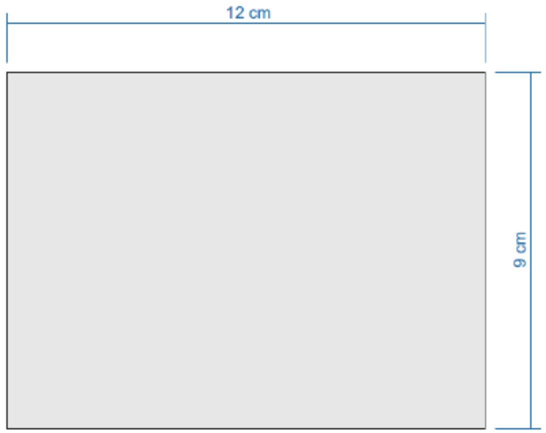
F2
x2



F3
x2

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Appendix D. Cost and source of materials for the construction of the equipment

Ref. description	Article	Quantity		Unit cost (USD)		Total price (USD)		Source of materials
Electroflotation	Acrylic	1.5	m²	55,84	m²		83,76	Local supplier
	Wire caliber18	2	m	1,01	m		2,02	Local supplier
	Connectors banana plug	2	ud	0,30	ud		0,60	Local supplier
	Cutting and assembly			34,72			34,72	Local supplier
						Subtotal	**121,10**	
mixing	Arduino® NANO	1	ud	3,47	ud		3,47	shorturl.at/hEU09
	LCD 16x2	1	ud	6,99	ud		6,99	shorturl.at/gyCYZ
	Neodymium magnet	2	ud	8,99	ud		8,99	shorturl.at/yzBLM
	L298N	1	ud	3,76	ud		3,76	shorturl.at/npRX9
	Potentiometer 10k	1	ud	8,99	ud		8,99	shorturl.at/afryO
	Motor Mh7 300 RPMs	1	ud	15,99	ud		15,99	shorturl.at/jvBJO
						Subtotal	**48,19**	
Accessories	Magnetic stir bar	1	ud	3,47	ud		3,47	Local supplier
	Aluminum sheets	0,3234	m²	33,27	m²		10,75	Local supplier
	Aluminum sheets cut	11	ud	0,10	ud		1,10	Local supplier
	0-50V Power Supply Stabilizer Module 15A 750W	1	ud	48,03	ud		75,00	shorturl.at/GOT27
						Subtotal	**90,32**	
						TOTAL	**259,61 USD**	

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