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Abstract

Many researchers consider efficient harvesting is the major bottleneck in cost efficient production of microalgae, contributing 20 – 30 % to total production cost.

This thesis is the conclusion of a two years research project to develop Salsnes Water to Algae Treatment (SWAT) harvesting technology. SWAT uses two main processes: flocculation and filtration. The SWAT objectives were achieved, 95 % algae removal and power consumption lower than 0,08 kWh/m^3.

To gain knowledge about harvesting algae, an overview of coagulation and flocculation principles, coagulation using metal ions, mixing procedures, microalgae species, microalgae flocculation and finally a general view of different harvesting technologies focusing on filtration was carried out.

PAX-18 and Chemifloc CM25 were selected for coagulation and flocculation respectively. Four different flocculator configurations were designed and tested, the best configuration (20 liters rapid mixing tank and 100 liters slow mixing tank) was chosen for further experimentations.

The PAX-18 concentration used was 114 mg/L as average and the Chemifloc CM25 concentration used was 4 mg/L.

Growth microalgae conditions (pH, temperature and dissolved oxygen concentration) were measured continuously during tests. Also key parameters for SWAT technology development were measured: power consumption kWh/m^3, water level set point (mm), algae flow rate (m^3/h) and cleaning procedure.

Different mesh pore sizes for filtration were investigated, resulting in an optimal mesh pore size for 210 and 250 µm.

Filter efficiency was determined using total suspended solids (TSS) and turbidity removal.

Finally, there is a need of lowering coagulant dosage, so several recommendations are given to improve SWAT performance and make it a marketable technology.

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Table of Contents

I. List of Figures

II. List of Tables

III. List of Acronyms

AOM	Algal Organic Matter
DO	Dissolved Oxygen
DOM	Dissolved Organic Matter
HRT	Hydraulic Retention Time
NTU	Nephelometric Turbidity Unit
p.m.	post merediem
rpm	Revolutions per minute
SF	Salsnes Filtration
Sp	Specie
SWAT	Salsnes Water to Algae Treatment
TSS	Total Suspendid Solids
TS	Total Solids
V	Volts

1. Introduction and Objectives

Microalgae are currently studied as a new renewable source of energy production. Increasing concerns about sustainability and the environment have led to a common practice to reduce carbon dioxide emissions and thus global warming (Uduman *et al*., 2010). Biofuels, produced from biomass (Demirbas, 2010), are one of the most feasible, renewable and alternate energy resources to deal with the above issues (Abou-Shanab, 2011).

Through various conversion processes, microalgae can be used to produce many different kinds of biofuels as vegetable oils, biodiesel, bio-ethanol, bio-syngas, bio-oil, and bio-hydrogen (Demirbas, 2010). However the most common research is focus on biodiesel production (Demirbas, 2009). Figure 1.1 summarizes biofuel production process.

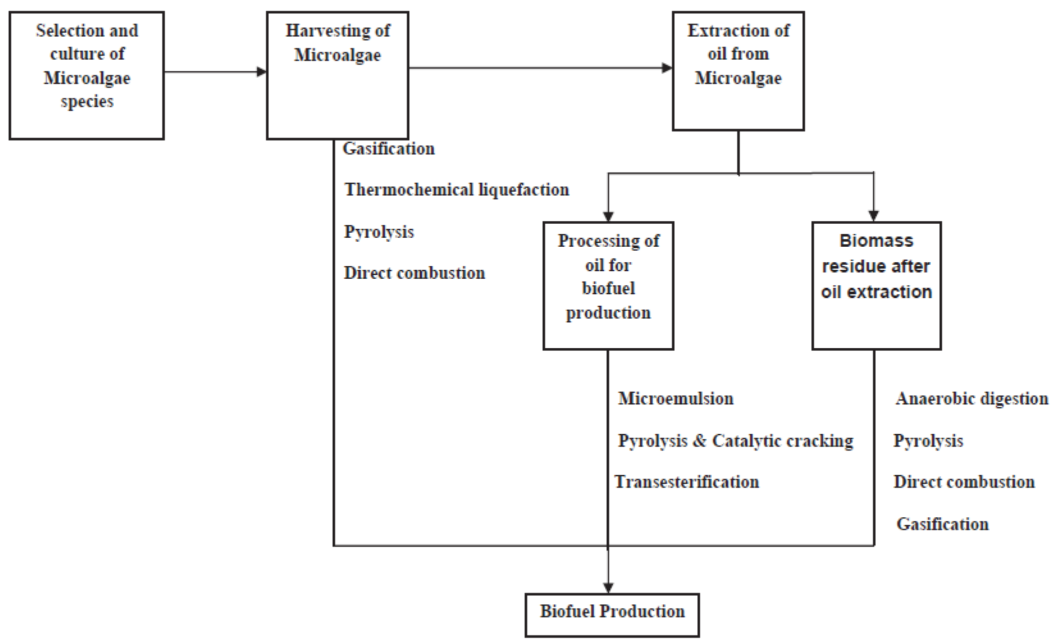

Figure 1.1: Different steps involved in producing energy from algae. (Pragya *et al.* / Renewable and Sustainable Energy Reviews 24 (2013) 159–171).

However, large scale production of microalgae biofuels, need to face a number of technical challenges to be a cost-efficient renewable energy source, the most important are efficient biomass harvesting, lipid extraction and biofuel production.

Harvesting alone, accounts for 20%–30% of the total production cost (Rawat *et al.*, 2011).An optimal harvesting method should be species independent, should use less chemicals and energy, and if possible, also release intracellular materials (Chen, 2011).

Microalgae harvesting can generally be divided into a three-step process (Kothandaraman and Evans, 1972). In that,

I. Bulk harvesting during which microalgae biomass is separated from the bulk culture. This step concentrates biomass to 2% - 7% dry weight.

II. Thickening, further concentrates the algal slurry. Thickening is more energy intensive than bulk harvesting, concentrates biomass to 8% - 20%.

III. Drying algae until concentration is 85% - 92%, obtaining an algae paste product.

On Figure 1.2 three different steps results can be seen.

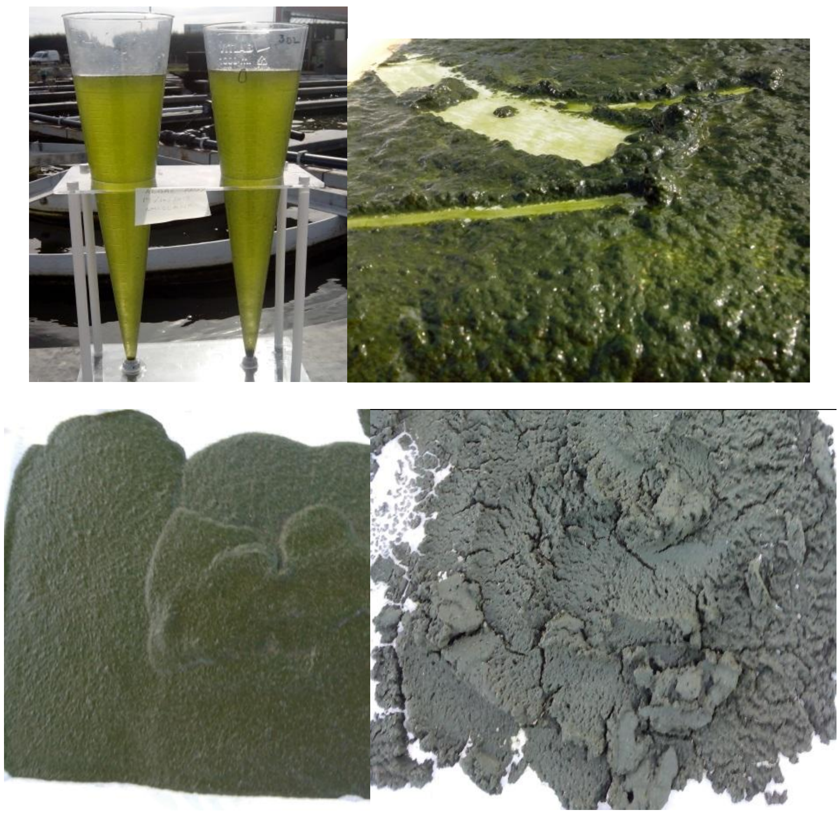

Figure 1.2: Up Left: Raw water microalgae 0,04-0,07% dry weight. Up Right: Microalgae 2-7% dry weight. Down Left: Microalgae 8-20%. Down Right: Microalgae 85-92% dry weight. (Aqualia I+D department).

Harvesting strategies that is equivalent to a solid-liquid separation processes can be classified into two kinds of separation (Svarovsky, 1979). In the first, the liquid is constrained in a vessel and particles can move freely within the liquid. Sedimentation and flotation fall into this category. In the second kind, the particles are constrained by a permeable medium through which the liquid can flow. Filtration, screening and centrifugation can fit this definition (Shelef *et al.*, 1984).
A brief description of mentioned methods:

- Gravity sedimentation: In this method particles in a suspension settle out of a fluid under gravity, and form concentrated slurry and clear liquid above. It is highly energy efficient method (Rawat *et al.*, 2011). However, it is a very slow process (Uduman *et al.*, 2010).

- Flotation: Flotation is a gravity separation process in which air or gas bubbles attach to solid particles, then carry them to the liquid surface, finally particles are skimmed off the top. Floatation has been found to be more effective and beneficial than sedimentation, in harvesting microalgae (Chen, 2011). However, a common problem associated with dissolved air flotation systems is that oversized bubbles break up the floc (Park *et al.*, 2011).

- Centrifugation: It is the harvesting method which involves centripetal acceleration to separate algal culture into regions of greater and less densities, there after the algae and water are separated by draining the excess medium (Harun *et al.*, 2010). However, high energy intensive nature of this method makes it economically unfeasible (Rawat *et al.*, 2011).

- Filtration: In this method algae culture runs through filters, which hold back algae and allow the water to pass through them. The process takes place continually until filters contain a thick paste of algae (Harun *et al.*, 2010).

Filtration method tends to avoid disadvantages from the other techniques as high energy intensive or process time. In this way a new microalgae filtration device is being developed by Salsnes Water to Algae Treatment (SWAT) technology. This thesis is the conclusion of mentioned SWAT, a two year project, which is aimed to develop a microalgae harvesting system which has a power consumption lower than 0,08 kWh/m^3 of microalgae and has a removal efficiency higher than 95%.

The patented Salsnes Filter system (Figure 1.3) is used for wastewater suspendid solids removal, thickening and sludge dewatering. It filters the wastewater retaining solids on a rotating endless wire mesh sieving cloth (1), producing filtrated and cleaner water (4). Once there is a thick cake-matter on top of mesh, a motor (2) moves the mesh transporting solids to a bin, where solids are removed from belt and deposited on the bin by an air or water knife. Where accumulated sludge is dewatered by compression using a extrusion screw (3).

Figure 1.3: Side view of Salsnes Filter Technology (www.salsnes-filter.com).

A high sensitivity pressure transmiter is used to provide information to control panel which decides according to preestablished parameters how to move filter mesh, (high velocity implies shorter filtration time, giving high hydraulic capacity but lower range of TSS removal, on the other hand, low velocity implies longer filtration time, giving low hydraulic capacity and higher range of TSS removal).

Modifications were made to make this technology suitable to filtrate flocculated microalgae instead of wastewater as installation of a scraper on mesh to collect filtrated microalgae, deflector and water knife to clean the mesh.

SWAT harvesting system consists on two stages (Figure 1.4):

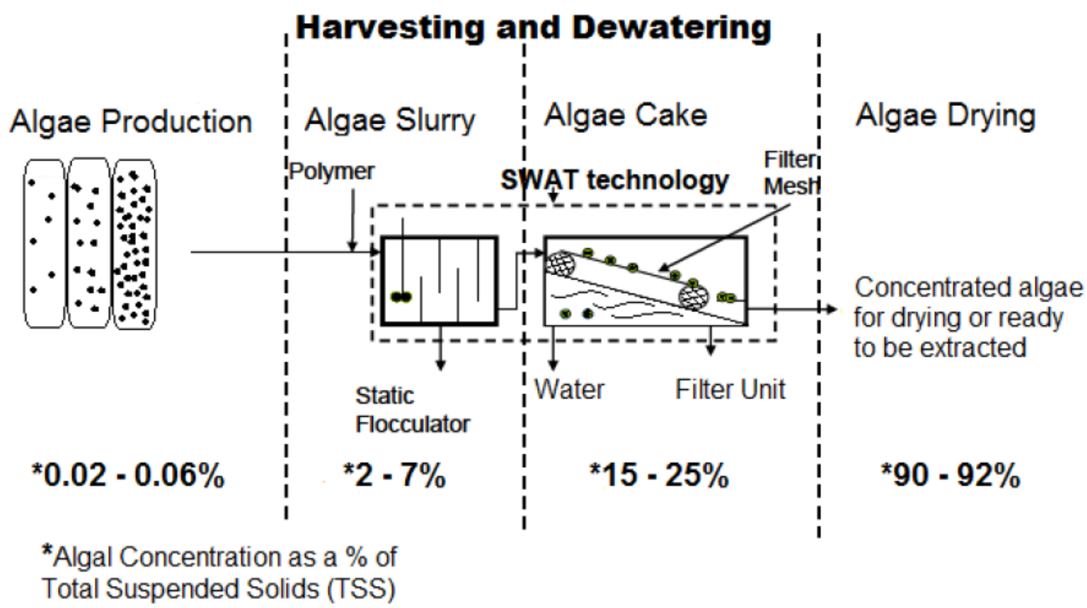

Figure 1.4: Stages of SWAT harvesting system. (Michael Nilan, 2013; Modified from Shelef *et al.,* 1984 to include SWAT technology).

1) Microalgae flocculation using an optimized dosage of polymer.
2) Salsnes Filter technology which filtrates flocculated *Coelastrum* algae specie.

Firstly, for microalgae flocculation, different flocculator designs were made and tested, then optimal polymer dosage was investigated. Microalgae flocs are extremely important for this technology due to the capacity to clog the filter, and the facility to be removed from mesh by a scraper, these microalgae flocs should be large in size and strong.

Secondly, for Salsnes Filter technology, designing parameter were studied and optimized, as mesh pore size, cleaning procedure and control panel setting were modified (water level, belt speed, cleaning procedure).

The pursued objectives of this SWAT project is the development and optimization of Salsnes Filter technology to harvest microalgae achieving two main requirements:

a) 95% removal efficiency of microalgae.
b) 0,08 kWh/m^3 power consumption per cubic meter of microalgae water treated.

In order to meet both requirements, this thesis completed the following specific objectives:

- Selection of the coagulant and flocculant which form best microalgae flocs.
- Optimising coagulant and flocculant dosage.
- Determining mixing speed for selected coagulant and flocculant.
- Designing different flocculators for microalgae flocculation.
- Designing modifications to adapt Salsnes Filter technology for harvesting microalgae.
- Optimizing control panel parameters for Salsnes Filter for harvesting microalgae.
- Determining microalgae removal efficiency from water phase.
- Determining power consumption to harvest microalgae.

2. Literature Review

A literature review was carried out to gain knowledge about concepts, processes and features related to the technology that are going to be used as part of SWAT project. Since microalgae are necessary to be flocculated for filtration process, an extensive research about coagulation and flocculation has been made, and a more detailed research about coagulation and flocculation for microalgae has been conducted. Since efficient used of energy is a goal for this project, a review of mixing energy requirements has been made. Also a review of filtration harvesting technologies was carried out.

2.1 Coagulation and Flocculation

Coagulation is the process of destabilizing colloidal particles so that particle growth can occur as a result of particle collisions (Metcalf and Eddy, 2003).

The term “chemical coagulation” includes all of the reactions and mechanisms involved in the chemical destabilization of particles and in the formation of larger particles through perikinetic flocculation (aggregation of particles in the size range from 0.01 to 1 μm) (Metcalf and Eddy, 2003).

In general, a coagulant is the chemical that is added to destabilize the colloidal particles in wastewater so that floc formation can result. A flocculant is a chemical, typically organic, added to enhance the flocculation process. Typical coagulants and flocculant include natural and synthetic organic polymers, metal salts such as alum or ferric sulfate (Metcalf and Eddy, 2003). As it can be seen lately, Alum was the option taken for this project.

The term “flocculation” is used to describe the process whereby the size of particles increases as result of particle collisions. There are two types of flocculation: (1) microflocculation (also known as perikinectic flocculation), in which particle aggregation is brought about by the random thermal motion of fluid molecules known as Brownian motion and (2) macroflocculation (also known as orthokinetic flocculation), in which particle aggregation is brought about by inducing velocity gradients and mixing in the fluid containing the particles to be flocculated (Metcalf and Eddy, 2003).

The purpose of flocculation is to produce particles, by means of aggregation, that can be removed by inexpensive particle-separation procedures such as gravity sedimentation and filtration (Metcalf and Eddy, 2003). In this thesis results of flocculation plus filtration are aimed.

Coagulation and flocculation are terms normally applied to colloidal particles found in wastewater that typically have a net negative surface charge, in this project microalgae also has negative charge (Uduman *et al.,* 2010).

2.1.1 Inorganic Coagulants

Microalgal cells are negatively charged, as a result of adsorption of ions originating from organic matter and dissociation or ionization of surface functional groups (Uduman *et al*., 2010). By disrupting the stability of the system, successful microalgal harvesting can be obtained. Addition of a coagulant, like iron-based or aluminum-based coagulants, will neutralize or reduce the surface charge (Grima *et al*., 2003). Alum was utilized for harvesting of *Scenedesmus* and *Chlorella* via charge neutralization (Grima *et al*., 2003). Microalgae can also be flocculated by inorganic flocculants at sufficiently low pH (Uduman *et al*., 2010). However, despite its advantages, coagulation using inorganic coagulants suffers from the following drawbacks:

1. A large concentration of inorganic flocculant is needed to cause solid–liquid separation of the microalgae, thereby producing a large quantity of sludge.
2. The process is highly sensitive to pH level.
3. Although some coagulants may work for some microalgal species, they do not work for others.
4. The end product is contaminated by the added aluminum or iron salts.

2.1.2 Organic Flocculants

Flocculation by aluminum sulfate followed by certain polyelectrolytes is effective in microalgal harvesting (Pushparaj *et al*., 1993).

Biodegradable organic flocculants, such as chitosan, are produced from natural sources that do not contaminate the microalgal biomass (Divakaran and Pillai, 2002). The most effective flocculants for the recovery of microalgae are cationic flocculants (Bilanovic *et al*., 1988). Anionic and nonionic polyelectrolytes have been shown to fail to flocculate microalgae, which is explained by the repulsion existing between charges or the insufficient distance to bridge particles. Polymer molecular weight, charge density of molecules, dosage, concentration of microalgal biomass, ionic strength and pH of the broth, and the extent of mixing in the fluid have all been found to affect flocculation efficiency (Grima *et al*., 2003). Bilanovic *et al*. (1988) noted that flocculation by cationic polymers can be inhibited by the high salinity of a marine environment. High molecular weight polyelectrolytes are generally better bridging agents. A high biomass concentration in the broth also helps flocculation due to the frequent cell–cell encounters. Mixing at a low level is thus useful, as it helps bring the cells together, but excessive shear forces can disrupt flocs.

2.2 Importance of Mixing

Because of the large number of particles found in wastewater, the mixing intensity must be sufficient to bring about the adsorption of the polymer onto the colloidal particles. With inadequate mixing, the polymer will eventually fold back on itself and its effectiveness in reducing the surface charge will be diminished. Further, if the number of colloidal particles is limited, it will be difficult to remove them with low polyelectrolyte dosages.

Mixing operations can be classified as continuous rapid mixing (less than 30 seconds) or continuous mixing (Metcalf and Eddy, 2003).

2.2.1 Continuous Rapid Mixing

Continuous rapid mixing is used where one substance is to be mixed with another. The principal application is the blending of chemicals with wastewater, as alum salts, prior to flocculation (Metcalf and Eddy, 2003). Typical mixers used in wastewater treatment for rapid mixing are Figure 2.1:

a) In-line static mixer with internal vanes
b) In-line static mixer with orifice for mixing dilute chemicals
c) In-line mixer
d) In-line mixer with internal mixer
e) High speed induction mixer
f) Pressurized water jet mixer with reactor tube

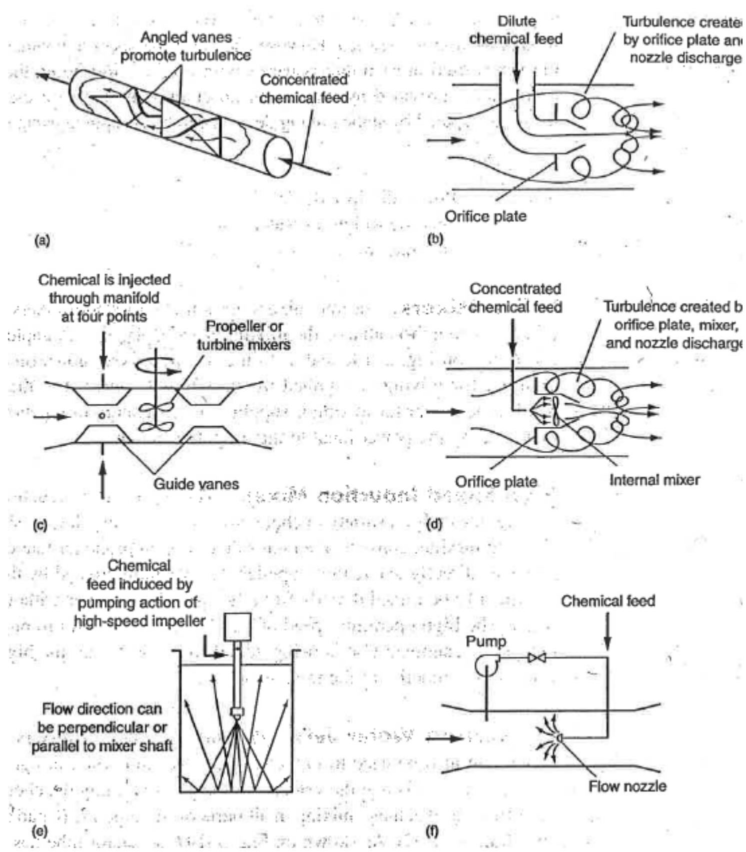

Figure 2.1: Typical mixers used in wastewater treatment for rapid mixing (Metcalf and Eddy, 2003).

2.2.2 Continuous Mixing

Continuous mixing is used where the contents of a reactor, holding tank or basin must be kept in suspension such as in equalization basing or flocculation basins. The principal types of mixers used for flocculation can be classified as:

1) Static mixers: the liquid to be treated is subjected to a series of flow reversals in which the direction of flow is changed. Static mixers can be comprised of over and under narrow flow channels, such as shown on Figure 2.2, or the narrow flow channels can be laid out horizontally (Metcalf and Eddy, 2003).
2) Paddle mixers: are used as flocculation devices when coagulants, such as aluminium or ferric sulfate, and coagulant aids, such as polyelectrolytes and lime, are added to wastewater. Paddle flocculator consists of a series of appropriately spaced paddles mounted on either a horizontal or vertical shaft. If the mixing is too vigorous, the increased shear forces will break up the floc into smaller particles. Agitation should be controlled carefully so that the floc particles will be of suitable size (Metcalf and Eddy, 2003).
3) Turbine and propeller mixers: The rotating element of turbine and propeller type flocculators consists of three or four blades attached to a vertical shaft. The flocculator is driven with an external gear reduction system powered by a variable speed drive. The blades of the propeller may be rectangular in shape or have the shape of a hydrofoil. Blades shaped as hydrofoils are used to limit the amount of floc shearing while at the same time providing the velocity gradients and pumping capacity needed for mixing (Metcalf and Eddy, 2003).

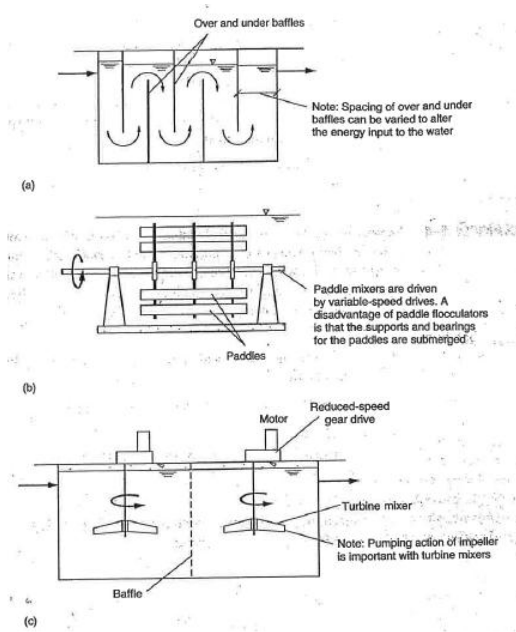

Figure 2.2: Typical mixers used for flocculation in wastewater treatment facilities (Metcalf and Eddy, 2003).

2.2.3 Energy Dissipation in Mixing and Flocculation

Mixing with an impeller in a reactor or mixing chamber causes two actions to occur: circulation and shearing of the fluid. The power input per unit volume of liquid can be used as a rough measure of mixing effectiveness, based on the reasoning that more input power creates greater turbulence, and greater turbulence leads to better mixing (Metcalf and Eddy, 2003).

The effect of velocity gradients in coagulation and flocculation tanks can be modeled by Equation 2.1 (Camp and Stein):

Equation 2.1

$$G = \sqrt{\frac{P}{\mu V}}$$

Where:

G = average velocity gradient, T^{-1} , $1/s$

P = power requirement, W

μ = dynamic viscosity, Ns/m^2

V = flocculator volume, m^3

Should be noted that velocity gradient G is a measure of the average velocity gradient in the fluid. High G values will be observed near the blades of the mechanical mixing device, while significantly lower values will be observed at some distance from the blades of the mixing device (Metcalf and Eddy, 2003). Typical values that have been used for G for various mixing operations are reported in Table 2.1:

Table 2.1: Typical detention time and velocity gradient G values for mixing and flocculation in wastewater (Metcalf and Eddy, 2003).

Process	Range of values	
	Detention Time	**G value, s^{-1}**
Mixing		
Typical rapid mixing operations in wastewater treatment	5 – 30 s	500 – 1500
Rapid mixing for effective initial contact and dispersion of chemicals	< 1 s	1500 – 6000
Rapid mixing of chemicals in contact filtration process	< 1 s	2500 – 7500
Flocculation		
Typical flocculation processes used in wastewater treatment	30 – 60 min	50 – 100
Flocculation in direct filtration processes	2 – 10 min	25 – 150
Flocculation in contact filtration processes	2 – 5 min	25 – 200

Since low energy consumption is a goal for SWAT technology, power consumption for mixing should be taken into account. It can be calculated by using Equation 2.2 (Metcalf and Eddy, 2003).

Equation 2.2

$$P = N_P \varrho n^3 D^5$$

Where:

P = power input, W

N_P = power number for impeller, unitless

ϱ = density, kg/m^3

n = revolutions per second, r/s

D = diameter of impeller, m

Power in a mechanical paddle system can be related to the drag force on the paddles as is described on Equation 2.3 (Metcalf and Eddy, 2003).

Equation 2.3

$$P = F_D v_p = \frac{C_D A \varrho {v_p}^2}{2}$$

Where:

P = power requirement, W

C_D = coefficient of drag of paddle moving perpendicular to fluid

A = cross-sectional area of paddles, m^2

ϱ = mass density of fluid, kg/m^3

v_p= relative velocity of paddles with respect to the fluid, m/s, usually assumed to be 0.6 to 0.75 times the paddle-tip speed.

2.3 Particle Destabilization and Aggregation with Polyelectrolytes

Polyelectrolytes may be divided into two categories: natural and synthetic. Important natural polyelectrolytes include polymers of biological origin and those derived from starch products such as cellulose derivatives and alginates (Metcalf and Eddy, 2003).

Depending on whether their charge, when placed in water, is negative, positive or neutral, these polyelectrolytes are classified as anionic, cationic, and nonionic, respectively (Metcalf and Eddy, 2003). In this thesis a cationic polyelectrolyte will be used because of its natural bonding tendency to negatively charged particles as microalgae.

2.3.1 Charge Neutralization

Polyelectrolytes act as coagulants that neutralize or lower the charge of the wastewater particles. This is the first mode of action of polyelectrolytes.

2.3.2 Polymer Bridge Formation

The second mode of action of polyelectrolytes is interparticle bridging. Figure 2.3:

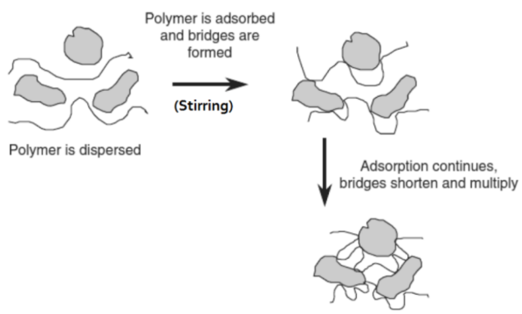

Figure 2.3: Floc formation by bridges (Metcalf and Eddy, 2003).

A bridge is formed when two or more particles become adsorbed along the length of the polymer. Bridged particle become intertwined with other bridged particles during the flocculation process. The size of the resulting three dimensional particles grows until they can be removed easily by sedimentation (Metcalf and Eddy, 2003). Using SWAT technology particles will be removed by filtration.

2.3.3 Charge Neutralization and Polymer Bridge Formation

The third type of polyelectrolyte action may be classified as a charge neutralization and bridging phenomenon, which results from using cationic polyelectrolytes of extremely high molecular weight (Metcalf and Eddy, 2003).

2.4 Particle Destabilization and Removal with Hydrolyzed Metal Ions.

Hydrolysis products formed from alum or ferric sulfate are the responsible for particle aggregation (Metcalf and Eddy, 2003).

2.4.1 Action of Hydrolyzed Metal Ions.

The action of hydrolyzed metal ions about the destabilization and removal of colloidal particles can be divided into three categories:

1. Absorption and charge neutralization: involves the adsorption of mononuclear and polynuclear metal hydrolysis species on the colloidal particles.
2. Adsorption and interparticle bridging: involves the adsorption of polynuclear metal hydrolysis species and polymer species which, in turn, will ultimately form particle-polymer bridges.
3. Enmeshment in sweep floc: if a sufficient concentration of metal salt is added, large amounts of metal hydroxide floc will form.Following macroflocculation, large floc particles will be formed that will settle readily. In turn, as these floc particles settle, they sweep through the water containing colloidal particles. The colloidal particles that become enmeshed in the floc will thus be removed (Metcalf and Eddy, 2003).

The sequence of reactions and events that occur in the coagulation and removal of particles can be illustrated as shown on Figure 2.4 (Metcalf and Eddy, 2003).

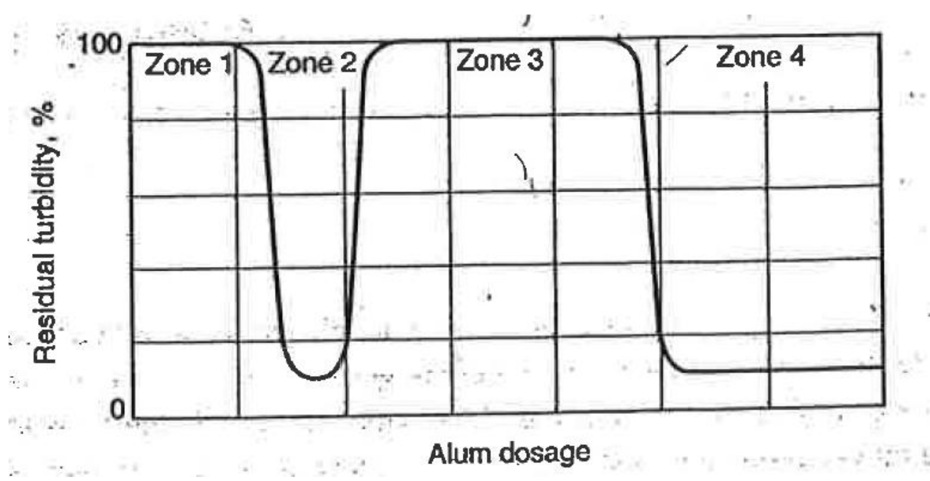

Figure 2.4: Effect of the continued addition of a coagulant on the destabilization and flocculation of colloidal particles (Metcalf and Eddy, 2003).

- Zone 1: sufficient coagulant has not been added to destabilize the colloidal particles, even though some reduction in surface charge may occur due to the presence of Al^{3+} and some mononuclear hydrolysis species.
- Zone 2: the colloidal particles have been destabilized by the adsorption of mono- and polynuclear hydrolysis species, and if allowed to flocculate and settle, the residual turbidity would be lowered as shown.
- Zone 3: as more coagulant is added, the surface charge of the particles has reversed due to the continued adsorption of mono- and polynuclear hydrolysis species. As the colloidal particles are now positively charged, they cannot be removed by perikinetic flocculation.
- Zone 4: as more coagulant is added, large amounts of hydroxide floc will form. As the floc particles settle, the colloidal particles will be removed by the sweep action of the settling

floc particles, and the residual turbidity will be lowered as shown (Metcalf and Eddy, 2003).

The coagulant dosage required to reach any of the zones will depend on the nature of the colloidal particles and the pH and temperature of the wastewater. Specific constituents will also have an effect on the coagulant dose (Metcalf and Eddy, 2003). Alum hydrolysis species are listed below, Table 2.2.

Table 2.2: Reactions and associated equilibrium constants for aluminum in equilibrium with amorphorous aluminum hydroxide (Metcalf and Eddy, 2013).

Reaction	Acid equilibrium constants	
	Equilibrium constant	Range
$Al(OH)_{3(s)} + 3H^+ = Al^{3+} + 3H_2O$	K_{s0}	9,0-10,8
$Al(OH)_{3(s)} + 2H^+ = AlOH^{2+} + 2H_2O$	K_{s1}	4,0-5,8
$Al(OH)_{3(s)} + H^+ = Al(OH)_2^+ + H_2O$	K_{s2}	1,5
$Al(OH)_{3(s)} = Al(OH)_3$	K_{s3}	-4.2
$Al(OH)_{3(s)} + H_2O = Al(OH)_4^- + H^+$	K_{s4}	-7,7-(-12,5)
Sp not considered: $\mathrm{Al_2(OH)_2^{4+}}$; $\mathrm{Al_8(OH)_{20}^{4+}}$; $\mathrm{Al_{13}O_4(OH)_{24}^{7+}}$; $\mathrm{Al_{14}(OH)_{32}^{10+}}$	-	-

2.4.2 Solubility of Metal Salts

To further appreciate the action of the hydrolyzed metal ions, it will be useful to consider the solubility of the metal salts. The solubility of the various alum species is illustrated on Figure 2.5, in which the log molar concentrations have been ploted versus pH. Only mononuclear species for alum have been plotted (Metcalf and Eddy, 2003).

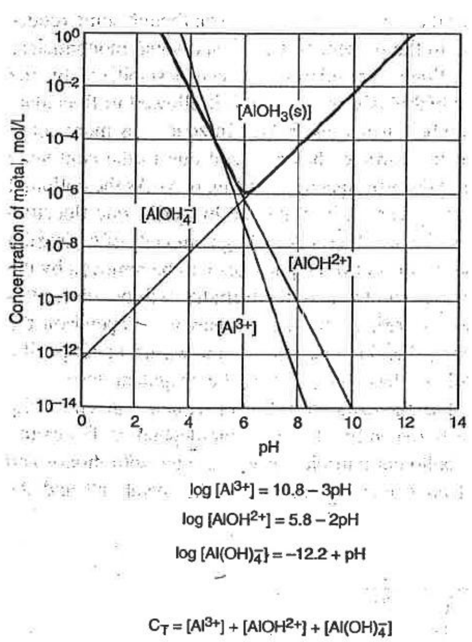

Figure 2.5: Solubility diagram for alum (Metcalf and Eddy, 2003).

As shown, the operating region for alum precipitation is from a pH range of 5 to about 7, with minimum solubility occurring at a pH 6.0.

2.4.3 Operating Regions for Action of Metal Salts.

Optimum particle removal by sweep floc occurs in the pH range of 7 to 8 with an alum dose of 20 to 60 mg/L. However this dose will vary for each wastewater. Anyway is common to all of them that with proper pH control it is possible to operate with extremely low alum dosages (Metcalf and Eddy, 2003).

2.4.4 Importance of Initial Chemical Mixing with Metal Salts.

The time required for the formation of mono- and polynuclear hydroxide species appears to be extremely short, on the order of 10^{-3} seconds. The time of formation for the polymer species was on the order of 10^{-2} seconds (Hahn and Stumm, 1968). So the instantaneous rapid and intense mixing of metal salts is of critical importance, especially where the metal salts are to be used as coagulants to lower the surface charge of the colloidal particles (Amirtharajah and Mills, 1982).

2.5 Microalgae

Microalgae can be classified in two broad categories, macro- and microalgae. There are diverse uses of microalgae, as animal food, pharmaceutics products or the one involved in this thesis, biofuel production.

Microalgae are suitable for biofuel production because under suitable culture conditions, some microalgal species are able to accumulate up to 50–70% of oil/lipid per dry weight (Chisti, 2007). The fatty acid profile of microalgal oil is suitable for the synthesis of biodiesel (Gouveia and Oliveira, 2009). The major attraction of using microalgal oil for biodiesel is the tremendous oil production capacity by microalgae, as they could produce up to 58,700 L oil per hectare, which is one or two magnitudes higher than that of any other energy crop. Microalgae have thus been widely recognized as the feedstock for third-generation of biofuels (Chisti, 2007). A table of different microalgae used for biofuel production, with their respective biomass and lipid data production is shown below Table 2.3.

The microalgae used in this study were a wild type of fresh water green algae *Coelastrum sp.* Their thalli (plant bodies) form 4, 8, 16, 32, or 64 celled coenobia that can be up to 100 µm diameter organized as spherical, pyramidal or cuboidal free-floating colonies (Guiry, 2013). *Coelastrum sp.* are planktonic and cosmopolitan in freshwater habitats ranging the arctic to the tropics (Guiry, 2013). They average 7-10µm in diameter, exhibit a generation time of 2 to 8 days, and are able to grow easily in stable water columns using photosynthesis (Sephton, 1980).

Table 2.3: Lipid content and productivities of different microalgae species. (Mata et al., 2010).

Marine and freshwater microalgae species	Lipid content (% dry weight biomass)	Lipid productivity (mg/L/day)	Volumetric productivity of biomass (g/L/day)	Areal productivity of biomass (g/m2/day)
Ankistrodesmus sp.	24.0–31.0	–	–	11.5–17.4
Botryococcus braunii	25.0–75.0	–	0.02	3.0
Chaetoceros muelleri	33.6	21.8	0.07	–
Chaetoceros calcitrans	14.6–16.4/39.8	17.6	0.04	–
Chlorella emersonii	25.0–63.0	10.3–50.0	0.036–0.041	0.91–0.97
Chlorella protothecoides	14.6–57.8	1214	2.00–7.70	–
Chlorella sorokiniana	19.0–22.0	44.7	0.23–1.47	–
Chlorella vulgaris	5.0–58.0	11.2–40.0	0.02–0.20	0.57–0.95
Chlorella sp.	10.0–48.0	42.1	0.02–2.5	1.61–16.47/25
Chlorella pyrenoidosa	2.0	–	2.90–3.64	72.5/130
Chlorella	18.0–57.0	18.7	–	3.50–13.90
Chlorococcum sp.	19.3	53.7	0.28	–
Crypthecodinium cohnii	20.0–51.1	–	10	–
Dunaliella salina	6.0–25.0	116.0	0.22–0.34	1.6–3.5/20–38
Dunaliella primolecta	23.1	–	0.09	14
Dunaliella tertiolecta	16.7–71.0	–	0.12	–
Dunaliella sp.	17.5–67.0	33.5	–	–
Ellipsoidion sp.	27.4	47.3	0.17	–
Euglena gracilis	14.0–20.0	–	7.70	–
Haematococcus pluvialis	25.0	–	0.05–0.06	10.2–36.4
Isochrysis galbana	7.0–40.0	–	0.32–1.60	–
Isochrysis sp.	7.1–33	37.8	0.08–0.17	–
Monodus subterraneus	16.0	30.4	0.19	–
Monallanthus salina	20.0–22.0	–	0.08	12
Nannochloris sp.	20.0–56.0	60.9–76.5	0.17–0.51	–
Nannochloropsis oculata.	22.7–29.7	84.0–142.0	0.37–0.48	–
Nannochloropsis sp.	12.0–53.0	37.6–90.0	0.17–1.43	1.9–5.3
Neochloris oleoabundans	29.0–65.0	90.0–134.0	–	–
Nitzschia sp.	16.0–47.0	8.8–21.6		
Oocystis pusilla	10.5	–	–	40.6–45.8
Pavlova salina	30.9	49.4	0.16	–
Pavlova lutheri	35.5	40.2	0.14	–
Phaeodactylum tricornutum	18.0–57.0	44.8	0.003–1.9	2.4–21

Marine and freshwater microalgae species	Lipid content (% dry weight biomass)	Lipid productivity (mg/L/day)	Volumetric productivity of biomass (g/L/day)	Areal productivity of biomass (g/m2/day)
Porphyridium cruentum	9.0–18.8/60.7	34.8	0.36–1.50	25
Scenedesmus obliquus	11.0–55.0	–	0.004–0.74	–
Scenedesmus quadricauda	1.9–18.4	35.1	0.19	–
Scenedesmus sp.	19.6–21.1	40.8–53.9	0.03–0.26	2.43–13.52
Skeletonema sp.	13.3–31.8	27.3	0.09	–
Skeletonema costatum	13.5–51.3	17.4	0.08	–
Spirulina platensis	4.0–16.6	–	0.06–4.3	1.5–14.5/24–51
Spirulina maxima	4.0–9.0	–	0.21–0.25	25
Thalassiosira pseudonana	20.6	17.4	0.08	–
Tetraselmis suecica	8.5–23.0	27.0–36.4	0.12–0.32	19
Tetraselmis sp.	12.6–14.7	43.4	0.30	–

2.5.1 Microalgae Flocculation

Flocculation can be induced by metal coagulants such as alum or ferric chloride or by polymeric flocculants such as polyacrylamides or chitosan. However, this requires addition of chemicals and thus results in contamination of either the microalgal biomass, the treated water or both. Flocculation of microalgae can also occur spontaneously without the need for chemicals, a phenomenon that is referred to as autoflocculation or bioflocculation. Auto- and bioflocculation are considered as promising approaches for harvesting microalgal biomass (Christenson *et al*., 2011; Salim *et al*., 2011). Bioflocculation describes flocculation caused by biopolymers produced by algae or by bacteria. Autoflocculation is the phenomenon where microalgae flocculate as a result of the pH increase of the medium due to photosynthetic consumption of carbon dioxide (Benemann *et al.*, 1980). This flocculation is the result of precipitation of Ca-phosphates. Ca-phosphate flocculation is a particularly attractive option when wastewater is used as a source of nutrients for production of biofuels, since wastewater often contains ample PO_4. Recent studies indicate that combination of microalgal biofuel production with wastewater treatment offers a sustainable and economically attractive approach to production of microalgae, as there is no need for synthetic fertilizers and additional income can be generated through treatment of wastewater (Fenton *et al*., 2012). (This is our case in Chiclana, cultivation of algae is made by using nutrients from secondary wastewater effluent). Sukenik and Shelef (1984) investigated the underlying mechanism of flocculation of microalgae by Ca-phosphate precipitates. They noted that flocculation can be induced within a pH range of 8.5 - 9 if the culture medium contains sufficient amounts of Ca (1500 - 2500 $\mu mol/L$) and PO_4 (100 - 200 $\mu mol/L$). They also demonstrated that Ca and PO_4 precipitate during flocculation and that these precipitates are involved in the flocculation of the algal cells. Sukenik *et al.* (1984) studied Ca-phosphate flocculation under laboratory conditions. In real systems, however, this flocculation is often unpredictable and the flocculation efficiency tends to be low, even when conditions appear to be favourable (Nurdogan *et al.,* 1995). It is not clear why flocculation by Ca-phosphate precipitates fails even though Ca and

PO_4 concentrations and pH are sufficiently high for the mechanism to occur. A possible explanation may be the interference with dissolved organic matter (DOM) in the medium. The DOM may be present in the wastewater (e.g. humic substances) or be produced as extracellular organic matter by the microalgae (algal organic matter or AOM). It is known that several organic compounds may interfere with Ca-phosphate precipitates by complexation of Ca^{2+} or by reducing crystal growth, thus preventing the formation of the Ca-phosphate precipitates required to induce flocculation (Inskeep *et al*., 1988; Song *et al*., 2006). Alternatively, organic matter present in the medium may also compete with microalgal cells for positive charges of the flocculant and thus increase the required flocculant dose (Bernhardt *et al*., 1989; Vandamme *et al*., 2012). A better understanding of the influence of organic matter on flocculation by Ca-phosphate precipitates may lead to a more reliable use of this potentially cost-efficient harvesting method. Despite the fact that autoflocculation by Ca-phosphate precipitation was considered a promising harvesting method in the 1980's, this flocculation method has not received much attention in recent years.

2.5.2 Microalgae Harvesting Technologies

Efficient harvesting of biomass from cultivation froth is essential for mass production of biodiesel from microalgae. The major techniques presently applied in the harvesting of microalgae include centrifugation, flocculation, filtration and screening, gravity sedimentation, flotation, and electrophoresis techniques (Uduman et al., 2010).

An optimal harvest method of microalgae for biofuel production should be species independent, use minimal chemicals and energy, and, if possible, preferentially release intracellular materials for collection. The different existing harvesting technologies are classified on Figure 2.6:

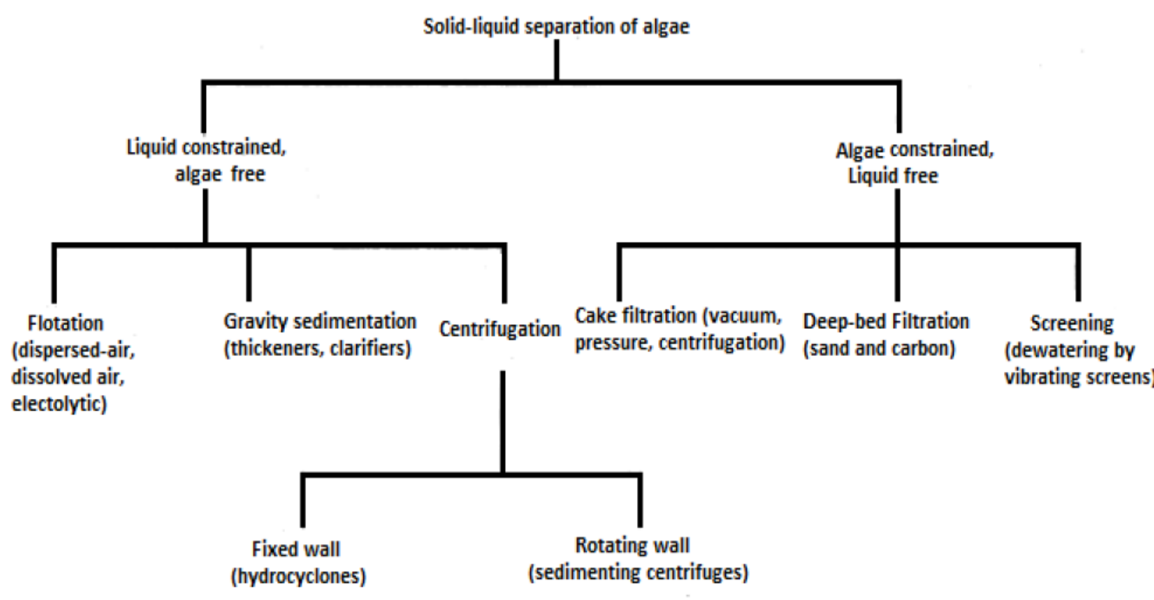

Figure 2.6: Classification of common industrial solid-liquid separation techniques. (Adapted from Shelef et al., 1984).

2.5.2.1 Filtration and Screening

Grima *et al*. (2003) reviewed harvesting process options to recover biomass and the related it to economic costs. Screening involves introducing the suspension through a screen with a particular pore size. Microstrainer and vibrating screen filters are two of the primary screening devices in microalgae harvesting. Microstrainers can be realized as rotating filters with fine mesh screens with frequent backwash. A high microalgal concentration can result in blocking the screen, whereas a low microalgal concentration can result in inefficient capture (Wilde *et al*., 1991). Microstrainers have several advantages, such as simplicity in function and construction, easy operation, low investment, negligible abrasion as a result of absence of quickly moving parts, being energy-intensive and having high filtration ratios.

There is a wide a variety of filter designs, membrane filters can be simply classified by the pore or membrane size; macro filtration > 10 µm, micro-filtration 0.1–10 µm, ultrafiltration 0.02–0.2 µm and reverse osmosis <0.001 µm. The pressure to force fluid through a membrane, and therefore the operational energy required, generally increases with reducing membrane pore size. As the size range of microalgae is typically between 2 and 30 µm (Brennan and Owende, 2010; Molina Grima *et al*., 2003) this would suggest that micro-filtration has the most appropriate pore size for the majority of common species such as *Chlorella* and *Cyclotella* at 5–6 µm in diameter (Edzwald, 1993); while and macro filtration is the most appropriate for flocculated cells and larger cells. Filtration of *Isochrysis Galbana* has shown that a pore size of less than 1.5 µm is required to remove 'most' marine microalgal cells from suspension, but on flocculation a pore size of 25 µm was found to be effective (Shelef *et al*., 1984). Micro-filtration has been used for the recovery of microalgal cells for aquaculture, but membrane filtration has not been widely used for producing microalgal biomass on a large scale and could be less economic than centrifugation at commercial scale (Molina Grima *et al*., 2003). Ultrafiltration is a possible alternative for recovery, in particular of very fragile cells, but has not been generally used for microalgae (Mata *et al*., 2010; Molina Grima *et al*., 2003), and operating costs are high and maintenance costs very high (Mata *et al*., 2010; Purchas, 1981). It has been suggested that ultrafiltration of microalgae will develop in a similar way to desalination of sea water by reverse osmosis, and that the energy input of an optimised microalgal ultrafiltration plant could be 3 kWh/m^3, equivalent to the lowest current energy usage in reverse osmosis desalination (Gouveia, 2011). Extracellular organic matter has been reported to lead to rapid clogging of ultrafiltration membranes in the filtration of *Spirulina* (Rossi *et al*., 2004). An ultrafiltration membrane with 0.03 µm pore size has been used to harvest microalgae grown on carbon dioxide emissions from a semiconductor manufacturing plant (Avanti Membrane Technology, Inc. private communication 2012). Average permeate flux was 70 l/m^2h, but although 95 % of the microalgae were recovered the concentration factor was only 20 and additional means of concentration are required for further processing. Energy consumption is believed to be range between 1 and 3 kWh/m^3 (Avanti Membrane Technology, Inc. private communication 2012). A wide range of macro-filtration units are available and have been used for water treatment. Vibrating screens were able to separate *Coelastrum* and *Spirulina*, although not considered to be the optimum method for *Spirulina* (Mohn, 1988). The energy cost to produce 6 % dry weight of microalgae has been estimated to be 0.4 kWh/m^3 (Van den Hende *et al*., 2011).

Although the equipment is relatively cheap, labor costs can be high and cake washing is not always effective (Brennan *et al*., 1969; Richardson *et al*., 2002). A modified filter press with plastic diaphragms that inflate to remove the microalgae from the filter membrane has been found to be effective in the filtration of *Scenedesmus*, but capital cost are approximately one third higher than conventional filter presses and pre-coating of membrane with starch was required to prevent clogging (Mohn, 1988). Rotary vacuum filters are a common filter design (Brennan *et al*., 1969; Richardson *et al*., 2002) and have been used to dewater organic sludge from anaerobic digestion (Bailey and Ollis, 1977; Srinivas, 2008). *Coelastrum*, a microalga that forms small colonies, can be filtered to a cake containing 18 % dry weight solids without a filter pre-coat, but filtration rates fall rapidly and high energy inputs are required making this not recommended for microalgal recovery (Mohn, 1988). Filter aids have also been required for filtration of *Penicillium* and *Streptomyces mycelia* by rotary vacuum filter presses (Bailey and Ollis, 1977). Vacuum belt filters can filter larger or colonial microalgae, but investment and energy costs are very high (Mohn, 1988). Larger species of microalgae such as *Spirulina* and *Micractinium* have been found to filter on a rotary vacuum filter with a 12 μm pore diameter yielding a 1–3 % dry weight microalgal slurry, but smaller species of microalgae such as *Chlorella* did not filter effectively even if the pore size was reduced to 5 μm (Goh, 1984).

Belt filters are widely used in the water treatment industry and have been suggested as suitable for separation of *Spirulina* (Mohn, 1988). Large microalgae have been reported as readily filtered to a concentration of 18 % dry weight if the belt filter press is feed with pre-concentrated algae at 4 %, with an energy consumption of 0.5 kWh/m^3 (Molina Grima *et al*., 2003). A three-belt filter is used by Thames Water, UK to remove sludge from an activated sludge wastewater treatment plant. The sludge suspension is first settled in a large conical settler to 0.6 % dry solids and then fed to the belt filter press together with a low dose of polyelectrolyte flocculant, and first gravity filtered to over 6 % dry solids and then further dewatered in the rotary belt filter to up to 25 % (Thames Water private communication, 2012). Such a process could be envisioned for harvesting microalgae. The price of a three belt ''Klampress'' is approximately £360,000 to process 80 m^3/h with estimated power consumption of 17–21 kW (Ashbrook Simon Hartley private communications, 2009 and 2012), equivalent to an energy input about 0.25 kWh/m^3. Two extensive reviews of the filtration of microalgae have concluded that filtration methods are suitable for microalgae with larger cells, but inadequate to recover microalgal species with diameters of less than 10 μm (Molina Grima *et al*., 2003; Uduman *et al*., 2010). Filter aids and flocculants would both appear to assist filtration and reduce equipment operational energy requirements, but at additional materials increase costs and they may need to be removed from the microalgal biomass and the spent microalgal growth medium.

Ultrafiltration is capable of the removal of small microalgae, but its use is limited by high energy input and low output microalgal suspension concentrations. Flocculation and belt filtration has been successfully used in the water treatment industry as an effective low-cost separation method for microbial biomass and could be a viable method for the large scale separation of microalgae, but requires further investigation.

3. Materials and Methods

This chapter describes materials and methods used for this project. It is divided into sections that describe the work site, SF 500 description, equipment set up, flocculators design, parameters investigated, polymer preparation and use, list of experiments done and how the experiments were conducted.

3.1 Field Site Description

The experiments took place at the same place where the algae production plant is, at the municipal wastewater treatment plant in Chiclana de la Frontera (Cádiz, Andalucía), Spain. The plant had six raceways ponds to grow algae. Each pond is labeled with a number from 301 to 306, from left to right. Each one was ovular with a capacity of 9.6 m^3, with a depth of 30 cm. Each pond had two deflectors at each side to route flow inside the raceway (Figure 3.1). Also paddles kept the algae in suspension and constant movement for faster algae growth and mixing the nutrients to feed the algae (nitrogen and phosphorus that were obtained from the secondary reactor at the wastewater treatment plant).

Figure 3.1: Left: Three algae raceway ponds in a row. Right: Algae raceway pond nº302.

The ponds contained wild type specie of *Coelastrum*. The algae characteristics, concentration, suspension and size depended on weather variation and day time.

3.2 Algae Collection

Algae were collected directly from the raceways ponds. A sump pump was submerged into the pond and operated with a bypass valve to ensure a flow range of 0.3-0.6 m^3/h.

In this case the valve used to regulate flow was a 32mm metallic ball valve which fitted into the plastic feeding tube.

The flow measurements were made by the use of a 3 liter bucket and a stopwatch. Dividing the 3 liter volume by the time taken to collect them, a flow of liters per second is obtained.

Equation 3.1

$$\text{Flow } \left({}^{m^3}/_{h}\right) = \frac{[Volume\ of\ water\ collected\ (l)]}{[Time\ taken\ (s)]} \times \frac{1\ m^3}{1000\ l} \times \frac{3600\ s}{1\ h}$$

3.3 Parameters Investigated

The necessary parameters that affect microalgae harvesting process were collected using the following equipment: Temperature and Dissolved Oxygen (DO) multimeter, turbidity meter, TSS and TS-by-weight measurements and an electronic control panel for energy consumption and belt speed, also water level sensor for water level.

3.3.1 Total Suspendid Solids (TSS) and Total Solids (TS)

TSS and TS were measured according to Standard Methods, 2540.

3.3.2 Turbidity

A Turbidimeter 2100P was used to measure turbidity. The 2100P Portable Turbidimeter (Figure 3.2) gives lab quality results in a portable unit. It has a selectable signal averaging mode compensates for fluctuations in readings caused by movement of large particles in the light path. Its features include:

- Range: 0 to 1000 NTU.
- Pre-programmed calibration procedure, with microprocessor-controlled adjustment of calibration curve. This includes three calibration ranges: 0-10, 0-100 and 0-1000 NTU.
- Electronic zeroing: compensates for electronic and optical offsets. No manual adjustments are required.
- Direct digital readout in NTU.

Figure 3.2: The HACH 2100P portable turbidity meter.

A small glass vial was filled up with different algae water sample when and then the vial was shaken and placed immediately into the turbidity meter, so the turbidity meter had a homogenous sample to read, therefore a more accurate measure was given by the turbidity meter.

3.3.3 Turbidity Removal Efficiency

Turbidity removal is a resulting important parameter as it gives an indication about the clarity of the liquid. In this case an indication about microalgae and suspended solids remaining in the effluent. It was calculated using Equation 3.2.

Equation 3.2

$$\%\, Turbidity\ Removal = \frac{([NTU\ of\ raw\ algae\ at\ inlet] -\ [NTU\ of\ raw\ algae\ at\ effluent])}{NTU\ raw\ algae\ at\ inlet} \times 100$$

3.3.4 Temperature, pH and DO

Temperature, pH and DO values of microalgae cultivation ponds were given by Aqualia.

3.4 Polymer Preparation

Both, coagulant (PAX-18) and flocculant (Chemifloc CM25) that were used to form the flocs were recommended by Dr. Arbib Zouhayr (Aqualia I+D research engineer).

3.4.1 Coagulant Preparation

PAX-18 was added directly, without dilution as data sheet for PAX-18 indicates. Appendix I.

PAX18 description:

- Active material: Aluminium oxide (Al_2O_3).
- Concentration of active material: 17 %.
- Specific gravity (25ºC): 1,37 $\pm$ 0,03.
- Substance form: Yellowish liquid.
- pH: 0.9 $\pm$ 0.3
- Common applications: Clarification in either potable or wastewater.
- Supplier: Kemira Ibérica.
- References: Kemira.

3.4.2 Flocculant Preparation

A 12 liters container was filled with 10 liters of tap water, then a stirrer longer than the container was attached to a drill. Once the drill was working at a high speed, 10 g of polymer were weighed and added to the container gradually to ensure a good polymer distribution. The drill was kept working on mixing the solution until solution was homogeneus and no polymer lump could be seen. Mixing time duration was one hour, and the result was a clear and viscous solution.

This polymer solution had a lifetime of 1 day, so polymer preparation was made daily.

Flocculant used was Chemifloc CM25, characteristics:

- Substance form: Dry powder
- Common applications: Increase of sedimentation, clarification and dehydration.
- Suppliers: Chemipol
- Reference: Chemipol catalogue

3.5 Jar Test Flocculator

A bench scale Jar Test Flocculator used in this study was a 6 positions SBS – Floc Tester (Figure 3.3). Each position had a paddle which allowed slow and rapid mixing. Time of mixing and rpm values were set at the same values for all positions. Range: 10 – 250 rpm.

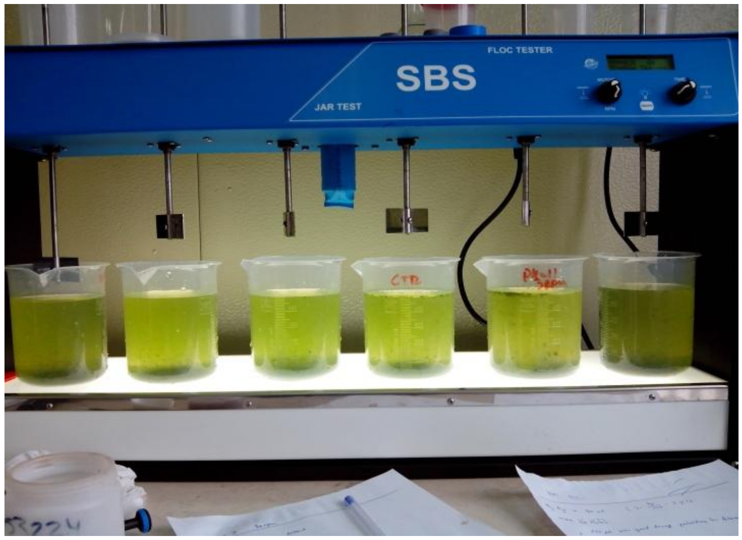

Figure 3.3: Positions SBS – Floc Tester flocculator.

3.5.1 Dosage Optimization Using Jar Testing

The coagulant and flocculant dosage was based on jar test experimentation. Turbidity removal was measured as deciding parameter. The dosages tested were a combination of coagulant and flocculant (Figure 3.4):

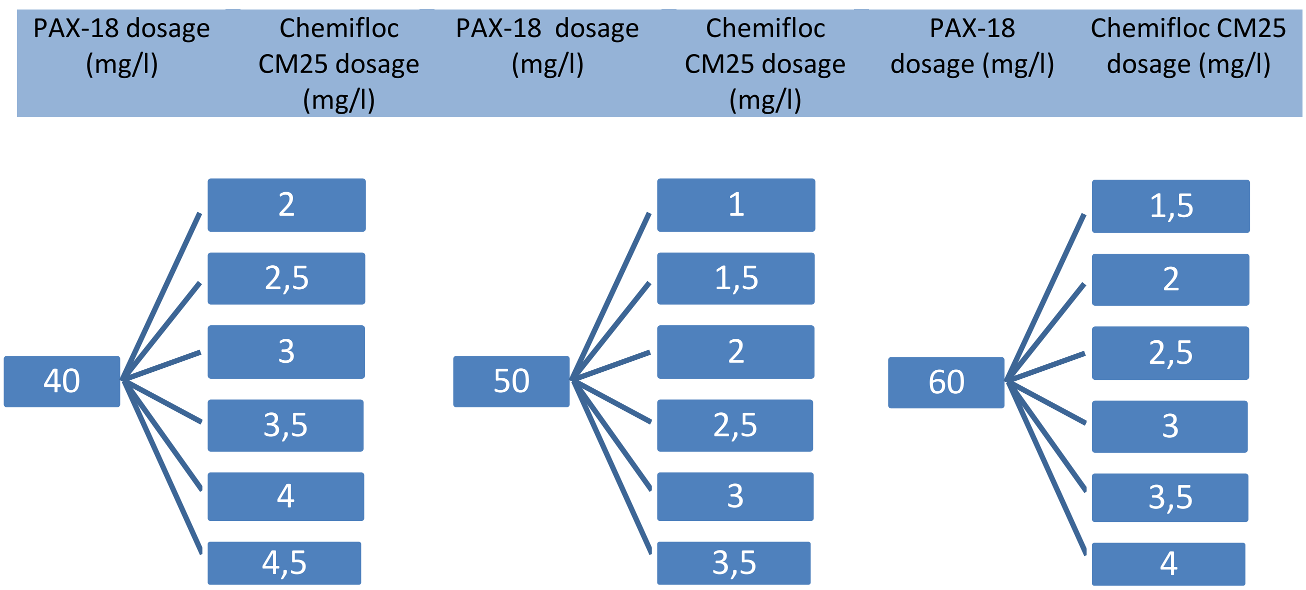

Figure 3.4: Protocol schemes for coagulant and flocculant optimization.

3.5.2 Speed Optimization Using Jar Testing

The speed selected was 250 rpm for rapid mixing (coagulant mixing), and 50 rpm for slow mixing (flocculant mixing). Because of the need to obtain small and strong flocs those rpm were chosen.

3.6 Pilot Scale Flocculators

Four different flocculator configurations were tested during this study, all of them were tank flocculators.

To obtain low energy consumption per cubic meter of algae water filtered, a higher flow of flocculated algae was needed. In order to do so, maintaining HRT, bigger flocculators were designed gradually.

The four configurations were:

1) Two 20 liters tank flocculators were used in series.
2) A 20 liters tank in combination with a 50 liters tank flocculator.
3) Two 50 liters tank flocculators used in series.
4) A 20 liters tank in combination with a 100 liters tank flocculator.

Hydraulic retention times (HRT) for the four flocculator configurations were calculated using Equation 3.3:

Equation 3.3

$$HRT\ (minutes) = \frac{Volume\ of\ reactor\ (liters)}{Flow\ (liters/minutes)}$$

Every hose connections to the flocculators were made by using brass connectors, clamps and teflon wrapped around the connection to ensure water tight conditions.

3.6.1 Configuration 1 – Pilot Scale Tank Flocculator

The pilot-scale tank flocculators provided by Asio® consisted of two 20 L tank in series. The first tank that received the algae was used as a rapid mixing tank and the second one was used as a slow mixing tank (Figure 3.5). Coagulant was added to the rapid mixing tank and flocculant to the slow mixing tank. Both of them were mixed in by the paddles fixed at the top of each tank.

Figure 3.5:Pilot scale tank flocculator configuration provided by Asio®.

3.6.2 Configuration 2 – Pilot Scale Tank Flocculator

The 50 L tank was made from a 50 L water tank, dimensions were 38 cm diameter and 45 cm height. The top part was cut off and the original paddles from a 20 L tank were screw into the new tank. A 32 mm diameter hole was made and brass connectors were installed at the top part in order to receive algae from the smaller tank, another hole was made and brass connectors were installed at the bottom in order to feed the SF500. A knob dial for regulating the speed of the mixing paddles was installed at the upper part (Figure 3.6).

Figure 3.6: Left: 50 liters tank flocculator perspective with connections at the inlet and effluent. Right: 50 liters tank flocculator inside view with paddle, motor and knob dial attached.

The 20 L tank was used as a rapid mixing tank, and the 50 L one was used as a slow mixing tank.

The 20 L tank was placed at a high level than the 50 L tank in order to feed by gravity to the second one (Figure 3.7).

As previous tank configuration, coagulant was added to the rapid mixing tank and flocculant to the slow mixing tank. Both of them were mixed in by the paddles.

Figure 3.7: 20 Liter tank in combination with a 50 Liter Pilot Scale Tank Flocculator configuration 2.

3.6.3 Configuration 3 – Pilot Scale Tank Flocculator

Two 50 liter plastic tanks designed like the one previously described on Section 3.6.2 were connected in series (Figure 3.8).

Coagulant was added directly into the algae feeding hose, two meters distance from tank. Flocculant was added directly into the first tank. SF500 was fed from the second tank bottom. Both tanks were used as slow mixing tanks. (It was considered that coagulant was well mixed inside the hose). Tanks were connected by a 50 mm diameter tube, installed at the upper part.

Figure 3.8: Up: Two 50 Liters Pilot-scale Tank Flocculator configuration. Left: 50 liters tank cupper connection. Right: 50 mm diameter connection between both tanks.

3.6.4 Configuration 4 – Pilot Scale Tank Flocculator

A 100 liter flocculator was constructed using a 100 liter water tank. 32 mm diameter holes were made and brass connectors were installed at the top and bottom part in order to be fed and feed the SF500 (Figure 3.9).

A 20 L tank was used as rapid mixing tank, prior to the 100 L tank. Original paddles, motor and knob dial from a 20 L Asio® tank were screwed using a wooden plank as an upper support.

The tanks were placed at different levels and connected by a fixed hose. Algae were pumped directly from the ponds to the rapid mixing tank. The slow mixing tank was gravity fed from the rapid mixing tank and the SF500 after that.

Figure 3.9: Left: Side view 100 Liters Pilot-scale Tank Flocculator Configuration. Right: aerial view.

Two modifications were made during experimentation. A plastic deflector was installed next to the outlet tank, so shear forces were converted into turbulence before the outlet. Two more outlets were made at the upper part during this study to decrease the flow velocity when feeding SF500 (Figure 3.10).

Figure 3.10 Up: 100 liters tank with 3 outlets, wooden support for stirrer and knob dial for regulating speed. Left: Deflector installed right before outlet. Right: Deflector from upper view.

3.7 Mixing Paddles for Flocculators

The paddles used in this study were the same for all flocculators. Since all flocculators were circular tanks, the paddles needed to be flat to ensure a good mixing. The description of the paddles is: a 35 cm long with three 20 cm length and 5 cm width metal plates welded. These paddles were connected to a 12 V motor (Figure 3.11). This motor was controlled by a knob dial to regulate the speed of the paddles.

Figure 3.11 Paddle with motor attached on top and knob dial speed regulation on upper left.

3.8 Coagulant and Flocculant Pumps

The coagulant and flocculant pump used for running the experiments were peristaltic pumps. Pumps had and analogic regulator.

These pumps used had a flow capacity of 4,5 $liters/hour$ and a maximum pressure of 2,5 bar (Figure 3.12).

Figure 3.12 Left: Peristaltic pump. Right: Peristaltic pump specifications

To measure polymer flow, a 50 ml test tube and a stopwatch were used, measuring how much polymer could be collected on one minute. Pump flow rate was calculated using Equation 3.3:

Equation 3.3

$$Polymer\ flow\ \left({ml}/{min}\right) = \frac{Polymer\ volume\ (ml)}{Time\ taken\ to\ collect\ polymer\ (min)}$$

To calculate polymer dosage on mg/l Equation 3.4:

Equation 3.4

$$Polymer\ dosage\ \left({mg}/{l}\right) = \frac{Polymer\ concentration\ \left({g}/{l}\right) * Polymer\ flow\ \left({ml}/{min}\right) * \frac{1000\ mg}{1\ g} * \frac{1\ l}{1000\ ml}}{Algae\ water\ flow\ \left({l}/{min}\right)}$$

To calculate chemical dosage on mg/g of algae Equation 3.5 was used:

Equation 3.5

$$Polymer\ dosage\ \left(\frac{mg}{g\ TSS\ of\ algae}\right) = \frac{Polymer\ flow\ \left(\frac{ml}{min}\right) * Polymer\ concentration\ \left(\frac{g}{l}\right) * 1000\ \frac{mg}{g} * \frac{1\ l}{1000\ ml}}{Algae\ water\ flow\ \left(\frac{l}{min}\right) * Algae\ TSS\ concentration\ \left(\frac{mg}{l}\right) * \frac{1\ g}{1000\ mg}}$$

To calculate PAX-18 dosage mg/g of algae Equation 3.6 was used:

Equation 3.6

$$PAX-18\ dosage\ \left(\frac{mg}{g\ TSS\ of\ algae}\right) = \frac{PAX{-}18\ flow\ \left(\frac{ml}{min}\right) * PAX{-}18\ specific\ gravity\ \left(\frac{Kg}{l}\right) * 10^6\ \frac{mg}{Kg} * \frac{1\ l}{1000\ ml}}{Algae\ water\ flow\ \left(\frac{l}{min}\right) * Algae\ TSS\ concentration\ \left(\frac{mg}{l}\right) * \frac{1\ g}{1000\ mg}}$$

To calculate PAX-18 active material (Al_2O_3) dose mg/g Equation 3.7 was used:

Equation 3.7

$$Al_2O_3 dose\ \left(\frac{mg}{g\ TSS\ of\ algae}\right) = \frac{Active\ Material\ Concentration\ (\%) * PAX{-}18\ flow\ \left(\frac{ml}{min}\right) * PAX{-}18\ specific\ gravity\ \left(\frac{Kg}{l}\right) * 10^6\ \frac{mg}{Kg} * \frac{1\ l}{1000\ ml}}{Algae\ water\ flow\ \left(\frac{l}{min}\right) * Algae\ TSS\ concentration\ \left(\frac{mg}{l}\right) * \frac{1\ g}{1000\ mg}}$$

To calculate Alum dose mg/g Equation 3.8 was used:

Equation 3.8

$$Alum\ dose\ \left(\frac{mg}{g\ TSS\ of\ algae}\right) = \frac{Active\ Material\ Concentration\ (\%) * \frac{27\ mg\ of\ Al}{51\ mg\ of\ Al_2O_3} * PAX\!-\!18\ flow\ \left(\frac{ml}{min}\right) * PAX\!-\!18\ specific\ gravity\ \left(\frac{Kg}{l}\right) * 10^6\ \frac{mg}{Kg} * \frac{1\ l}{1000\ ml}}{Algae\ water\ flow\ \left(\frac{l}{min}\right) * Algae\ TSS\ concentration\ \left(\frac{mg}{l}\right) * \frac{1\ g}{1000\ mg}}$$

3.9 Fine Mesh to Dry Microalgae Using Solar Radiation

A fine mesh was used to spread on the algae solids produced by SF500 system. Laying on this mesh for 24 hours, the algae was dried (Figure 3.13) and Aqualia used it as a biomass for further proceeding.

Figure 3.13 Fine mesh to dry algae

3.10 Salsnes Filter 500

The Salsnes Filter™ 500 is based on a currently patented Salsnes Filter model that is used for wastewater, it has been modified to accommodate the needs for algae harvesting. It works by capturing algae with a rotating wire mesh sieving cloth. Belt angle, belt speed, mesh size, and cleaning procedures are the most important parameters.

A sketch of the eventual Salsnes Filter system is shown below (Figure 3.14):

Figure 3.14: Side view of SF500.

The most important parts:

- (1) Inlet
- (2) Effluent compartment
- (3) Water wash compartment
- (4) Sludge collecting bin

This filter technology underwent several modifications during the experimentation period.

A more detailed description of devices that are part of SF500 is given below.

3.10.1 Mesh

A wide variety of meshes with different pore sizes were provided by Salsnes Filter, (11 µm, 17 µm, 33 µm, 55 µm, 90 µm, 158 µm, 210 µm, 250 µm and 350 µm).

Mesh dimensions are 32 cm wide and 140 cm length. Every mesh has a rubber line in each side that works as guidance for the mesh to move through the stainless frame (Figure 3.15):

Figure 3.15 Left: Unpacked Salsnes Filter meshes. Right: Mesh set on SF500 frame.

3.10.2 Motor

Motor is designed to move a roller which smoothly moves the filter mesh. In this case the motor used was a three phase motor, 0,09 kW power capacity and 1320 rpm as maximum speed (Figure 3.16):

Figure 3.16 Left: Side view of motor attached to SF500, connected to a ruler to move the mesh. Right: Motor specification.

3.10.3 Water Knife

Water knife is a water spray made of stainless steel with 9 nozzles uniformly distribute along frame width. The longer distance the filter mesh is set from the water knife, more area a single nozzle can wash (Figure 3.17):

Figure 3.17 Left: Water knife set on frame. Right: Water knife working.

3.10.4 Scraper

Scraper is made of plastic and is situated on the edge of filter mesh, its functionality is to remove the solids from the mesh. Scraper has a soft but sharp edge, which is design to be introduced right into the water layer between the mesh and microalgae flocs (Figure 3.18):

Figure 3.18 Plastic scraper set on filter.

3.10.5 Water Knife Valve

A solenoid valve was used for regulation of water knife use. Two way direct acting solenoid valve with spring return, normally closed, suitable for gaseous and liquid media. It's made of a forged brass body and brass guide tube with stainless steel internal parts and stainless steel springs. This valve can be rotated 360° and it will operate in any position (Figure 3.19):

Figure 3.19 Side view of solenoid valve with specifications.

3.10.6 Flow Meter

A commercial flow meter was used to measure water consumption during mesh cleaning procedure. The minimum measurement unit is a liter. It was set on right before solenoid valve (Figure 3.20).

Figure 3.20 Up: Flow meter. Down: Flow meter and solenoid valve connected to each other.

3.10.7 Water Level Sensor

Water level parameter is represented on Figure 3.21:

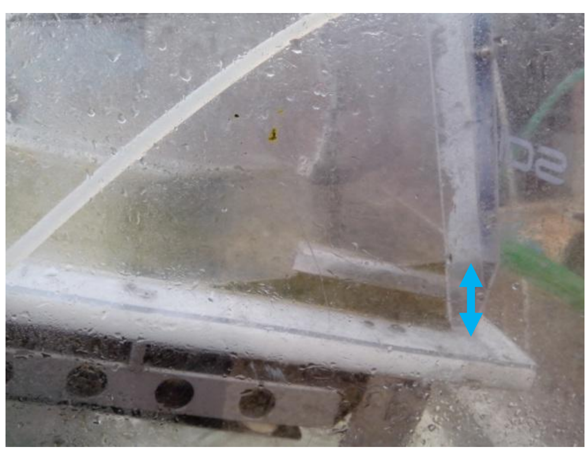

Figure 3.21: Water level on SF500 frame represented by blue arrow.

Two different water level sensors were used during experimentation period. First one which was the original one which came with SF500 which was based on a capacitive ceramic sensor. It can measure from 0 to 40 mbar (Figure 3.22).

A second water level sensor was used when the first one broke down. This one was a VEGAWELL52 (Figure 3.22).

Both water level sensors needed to be calibrated.

Figure 3.22: Left: Original SF500 water level sensor. Right: VEGAWELL52 water level sensor.

3.10.8 SF500 Inlet and Deflector

The original inlet for SF500 frame was a 32mm brass connector situated at the bottom of the frame in order to avoid any turbulence or splashing water and consequently breaking flocs. A deflector was situated 5 cm from inlet in order to equally distribute the algae water around the mesh. Two more inlets were made during experimentation period with the objective to handle higher flowrate avoiding higher turbulence (Figure 3.23).

Figure 3.23: Left: 1 inlet SF500 (inside view). Middle: SF500 3 inlets (inside view). Right: SF500 3 inlets (outside view).

A deflector was improvised on site, however a good deflector should be design considering flow patterns which does not break floc, avoiding turbulences and high velocity speed zones. A computer design of two deflectors have been drawn using Catia drawing program. For each one, a study of the flow around them has been made using Fluent Ansys 14.0 software. Real dimensions were used for computer design deflectors.

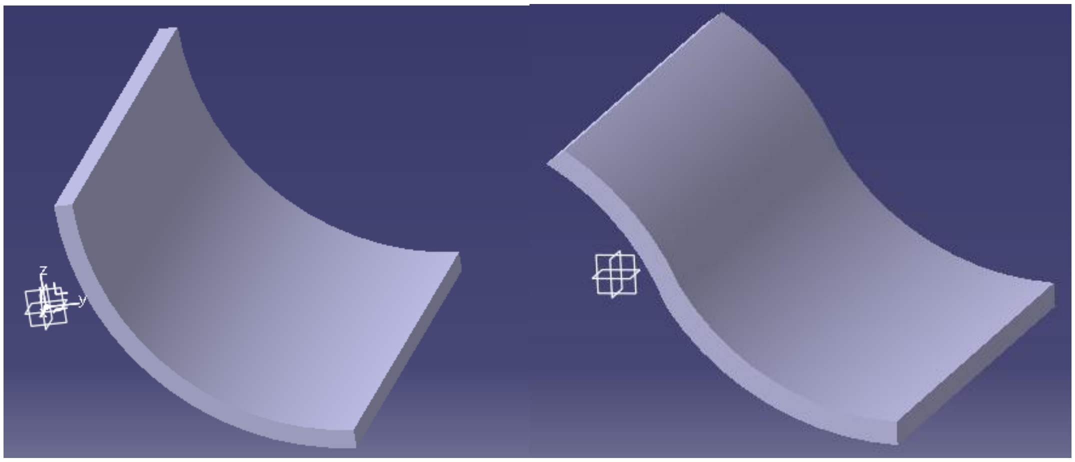

Figure 3.24: Left: Deflector Design 1. Right: Deflector Design 2.

3.10.9 SF500 Outlet

A 15 meter sewage pipe was installed to evacuate filtered water from SF500 effluent compartment to sewer (Figure 3.25)

Figure 3.25 Left: SF500 outlet. Right: SF500 outlet connected to sewage pipe.

3.11 SF500 Control Panel Settings Parameters

The control panel unit for the SF500 houses all of the sensor controllers, motor control, and stores information on the different running parameters. A touch-screen program on the panel face is used to operate the machinery, and it can be run automatically with the sensors controlling belt speed, and can also control its wash water. Many other logical parameters are able to be changed through the panel's controls touch screen which controls the behavior of the filter in automatic mode.

In manual operation, the motor is set to a particular belt speed and run continuously at that speed. It will run independent of influent flow and water level inside of the filter tank.

In automode operation, the motor moves the belt as much as it is needed to maintain a certain water level that has been set up previously on control panel. A constant water level measure is given to the control panel by the water level sensor. When water level is higher than the one set, motor moves the filter, so new and clean mesh surface comes out, and consequently algae is filtered, water level falls down and when the new mesh surface is clogged again, water level starts to rise. This operation is kept doing during several mesh rotations until the whole mesh surface is clogged. During this attempt to reduce the increase in water level, motor moves faster and when it achieves a certain speed (belt speed threshold) cleaning procedure starts working by using a water wash.

The control panel on the SF500 was equipped with one individual Danfoss frequency inverters for the filter belt speed motor. The inverter reports speed in hertz (Hz), rpms, and power consumption of the motor.

The control panel has different options to regulate water level sensor calibration, filter movement depending on water level and cleaning procedure.

3.11.1 Water Level Sensor Calibration Setting Parameters

To calibrate any water level sensor, there are two main parameters that should be configured, one is sensor range and the second one is sensor offset, this is the initial value which sensor should show. When sensor is not situated right at the bottom level, offset is a key parameter.

When Vegawell52 sensor was used, a sensor calibration was needed. It was done simply, with the use of a jar and a meter (Figure 3.26). The calibration settings were 950 mm for sensor range and 10 mm as offset.

Figure 3.26: Water level sensor and meter partially submerged into water in order to calibrate it.

3.11.2 Filter Movement Depending on Water Level

Three different parameters should be set up in order to decide how filter should behave considering water level data that sensor provides.

I. Water level setpoint in filter: this parameter shows the water level reference value at which SF500 should work. Range: 0-1000 mm.
II. Water level start filter cloth: this parameter is set to program the SF500 to start moving the filter cloth when the water level sensor shows a higher level than the one set. Range: 0-1000 mm.
III. Water level stop filter cloth: this parameter is set to program the SF500 to stop moving the filter cloth when water level sensor shows a lower level than the one set. Range: 0-1000 mm.

3.11.3 Cleaning Procedure Setting Parameters

Deciding when the automode cleaning procedure should work is a matter of reducing energy and water consumption. Four parameters should be programmed on the control panel for the machine to decide when cleaning procedure should start and finish.

I. Belt speed threshold to begin cleaning: this parameter is set to program SF500 to start cleaning procedure when a belt speed higher than the one set is achieved. Range: 0-100 %.
II. Rotations of cloth to be cleaned: this parameter is set to program SF500 to move cloth as many rotations have been set up. Range: 0-100 %.
III. Cloth travel time per revolution at 50 % : this parameter gives the information necessary to the control panel to know how long it takes to the cloth to do a complete revolution at 50 % speed. So control panel knows when a complete revolution has been made. Range: 0-1000 s.
IV. Belt speed during cleaning: this parameter is set to decide at which belt speed the cleaning procedure should be made.

3.12 Integration of Flocculator and SF500

Each tank outlet is connected to a SF500 inlet through a 32 mm diameter pipe and using brass connections. Inlets at SF500 were made at 2 cm distance from filter mesh surface.

Three effluent ports were made on 100 liters tank during experimentation period. This was made to ensure smooth and slow moving of flocs without breaking onto the deflector and filter mesh. Two different deflectors were used during experimentation, when there was only one inlet to SF500, a curved small deflector was used, and when there were three inlets a wider deflector was used, so no algae was spread directly onto the mesh (Figure 3.27).

Figure 3.27 Left: First deflector made, designed for one single inlet. Right: Second deflector made, designed for 3 inlets.

A good deflector should be designed considering flow patterns and be made of methacrylate or stainless metal, however in this project a provisional plastic deflector was fabricated.

3.13 Control Panel

With the objective to operate the machine with the lowest power consumption, an optimize setting of parameters described in Sections 3.9.10.1, 3.9.10.2 and 3.9.10.3 should be set up on control panel.

Table 3.1 List of control panel parameters.

Parameter	Unit
Nivel Set Point in Filter	mm
Start Level Filter Cloth	mm
Stop Level Filter Cloth	mm
Water level sensor range	mm
Water level sensor offset	mm
Belt speed threshold to begin cleaning	percentage
Rotations of cloth to be cleaned	Unitless
Cloth travel time per revolution at 50%	Seconds
Belt speed during cleaning	percentage

A figure of main screen on control panel is shown on Figure 3.28:

Figure 3.28 Control panel principal screen.

Control panel gives total power consumption in Watts unit (this value will be named average power consumption) and from that calculation power consumption per cubic meter of microalgae harvested can be calculated using Equation 3.6:

Equation 3.6

$$Total\ Power\ Consumption\ \left({}^{kWh}/_{m^3}\right) = \frac{Power\ (W) * \frac{1\ kWh}{1000\ W}}{Flow\ (m^3)}$$

3.14 SF500 Harvesting Procedure

A brief explanation of how SF500 works is made on this section. Water inlet is spread onto mesh surface by deflector. The mesh is capable of filtering water and retaining algae flocs. Those flocs retained starts to form a "cake" which behaves as a filtering layer, which helps to get a higher filtration efficacy. Once accumulation of microalgae on mesh reaches a value which collapse filtration capacity, water level starts to rise up Figure 3.29:

Figure 3.29: Algae cake on mesh.

In auto mode, when water level achieves a value set on “water level set point in filter and water level start filter cloth” control panel parameters, motor is switched on and moves filter cloth at a velocity in the range of 1 – 6% velocity. Moving the mesh provokes that new clean mesh surface comes up, filtering water and procedure of algae being retained by mesh forming a cake starts over.

Once the filter mesh has been moving for several rotations, this mesh is clogged by algae particles and polymer is stuck on it, so mesh does not have filtration capacity, independently is mesh is moved or not.

However mesh keeps rotating increasing its velocity, to bring new clean mesh. If this velocity goes higher than 6%, this is the input value which establishes that cleaning procedure should start.

I should be remarked that threshold parameter to start cleaning procedure is belt speed, not water level (nevertheless both of them are dependent).

Cleaning procedure is carried out by the water knife, which spread water behind the mesh, dislodging the particles from the filter mesh cloth. This cleaning procedure last for one belt rotation and takes 34 seconds.

Once the cleaning procedure stops, filter procedure described above starts over.

3.15 List of Experiments

Experiments were conducted to determine filtration and removal efficiency of algae using turbidity and SS by flocculation of algae and filtration. One coagulant (PAX-18) and one flocculant (Chemifloc CM25) were investigated in order to decide the optimum dosage and mixing speed. Following this, jar test and pilot-scale flocculation were conducted from which flocs were produced and used to perform filtration using SF500.

3.15.1 Jar Test Flocculation

Jar testing experiments were performed in order to find out the optimum coagulant and flocculant dosage to produce the right algae floc size to be filtered without an excesive filter clogging. Raw algae samples were collected from open pond 302 using a 7 liters bucket. Initial pH and water temperature were measured for each new raw algae sample collection. A 250 ml bottle was filled from each sample collection to measure TSS. And then each 500 ml flocculation jar was filled up.

PAX-18 was the coagulant used, mixing it for 30 seconds at 250 rpm, followed by Chemifloc CM25 as flocculant, mixing it for 10 minutes at 50 rpm.

Once slow mixing had finished, forming the right flocs, flocs were let to settle at the jar bottom for 10 minutes, and then using a syringe a sample was taken 1 cm below the surface.

For each jar, turbidity was measured before and after flocculation process.

3.15.2 Testing Different Flocculator Configurations

The first step to do in order to determine which flocculator design is the best for highest algae removal is to analyze which flocculator forms the best flocs, handling the highest algae flow and consuming the lowest energy. To achieve mentioned objectives, 95% algae removal and 0,08 kWh/m^3 the flocculators described in Sections 3.6.1, 3.6.2 and 3.6.3 were investigated. Their operation was made as describe in Section 3.11.3, but no data collection was made because the decision to use them or not, was taken on site, empirically, just by observation of flocs formed. This way of proceeding saved time and resources, so a more detailed experimentation could be made using 100 liters pilot-scale tank flocculator which provided the best results.

Flocculation of algae using fourth consiguration, 100 liter tank, was done continuously. Then, the flocculated algae from the effluent were filtered by using SF500 machine.

Despite the fact that control panel setting can be fixed from the beginning of experiment until the end, some setting variations were made while experiments were running.

This flocculator gave the best results, so it was the only used for further experiments.

The general procedure for operating this flocculator was to ensure that:

1) All hoses were connected in their proper places with appropriate fluids (i.e. coagulant to coagulant peristaltic pump, flocculant to flocculant peristaltic pump or water knife connected to fresh water supply hose).
2) Control panel had the right parameters set up as described at Section 3.9 (i.e. automode was on).
3) A hose was connected from flocculator to algae pond, the sump pump was first submerged into a pond and then it was turned on (if accidentally a sump pump starts working while is not submerge into fluid, it can result into a pump seizure).
4) A ball valve was used to regulate the algae flow using a by-pass.
5) After measuring algae flow using a 3 liter bucket and a stopwatch, coagulant and flocculant pumps were set to their respective flows needed for each experiment. Paddle motor was turn on.
6) Coagulant outlet pump tube was introduced into the feeding algae hose, and flocculant outlet pump tube was submerged to bottom tank.
7) After 30 minutes had passed, so tank was filled up producing a continuous and homogenous amount of algae flocs, 100 liters tank outlet tube was connected to the SF500 inlet. (Before that outlet tube was connected directly to drainage).
   This is the time when starting experiment time was recorded.
8) After step number 7, SF500 system was running in automode during the period of time necessary for each experiment, since it was running in automode there was no need for an operator working with the system.
9) For each experiment, samples were taken from raw algae inlet and SF500 effluent for measuring TSS and turbidity. A solids produced sample was taken to measure TS by weight.

10) After each run, ending time was recorded and the system was turned off and a complete cleaning of flocculators and SF500 machine was made.
11) Algae solids produced were spread on a fine mesh in order to be dried using solar radiation.

Table 3.2 Specifications of experiments using flocculator configuration 4.

Experiment Number:	1	2	3	4	5	6	7	8
Mesh pore size (µm):	90	158	158	210	210	250	250	350
Algae Flow rate(m^3/h):	0.514	0.36	0.47	0.54	0.54	0.54	0.54	0.54
HRT coagulant (seconds):	42	60	46	40	40	40	40	40
HRT flocculator (min):	11.67	16.67	12.78	11.11	11.11	11.11	11.11	11.11
Stock PAX-18 active material (Al2O3) solution (g/l):	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
Stock Chemifloc solution (g/l):	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 3.3 List of control setting parameters for each experiment.

Experiment Number:		1	2	3	4	5	6	7	8
Filter parameters	**Water Level set point in filter (mm):**	33	55	36	45	45	45	45	45
	Water level start filter cloth (mm):	33	55	36	45	45	45	45	45
	Water level stop filter cloth (mm):	33	55	36	45	45	45	45	45
Belt parameters	**Belt speed during cleaning (%):**	50	50	50	50	50	50	50	50
	Belt speed threshold to begin cleaning (%):	6	6	6	6	6	6	6	6
Water level sensor parameters	**LT1 Offset (mm):**	10	10	10	15	10	10	10	10

In order to know SF500 performance depending on water level set point in filter and belt speed during cleaning, these parameters were changed during mentioned experiments:

- Experiment number 1:
  - I. From time 12:55:07 til 13:12:31 filter parameters (water level set point in filter, water level start filter cloth and water level stop filter cloth) were set at 31 mm.
  - II. From time 13:12:33 til 13:40:05 filter parameters were set at 21 mm.
  - III. From time 13:35:03 til 13:37:51 filter parameters were set at 33 mm.
  - IV. From time 13:37:53 til 13:44:13 filter parameters were set at 23 mm.
  - V. From time 13:44:15 til 15:11:47 filter parameters were set at 33 mm.
  - VI. From time 15:11:49 til 15:35:59 filter parameters were set at 28 mm.

  - VII. From time 12:55:07 til 13:37:17 belt speed during cleaning is set at 25%.

- Experiment number 2:
  - I. From time 11:05:03 til 11:13:01 filter parameters were set at 30 mm.
  - II. From time 11:13:03 til 11:18:59 filter parameters were set at 40 mm.
  - III. From time 11:19:01 til 12:44:25 filter parameters were set at 55 mm.

- Experiment number 3:
    I. From time 16:34:01 til 16:44:07 filter parameters were set at 24 mm.
    II. From time 16:44:09 til 17:56:23 filter parameters were set at 36 mm.

- Experiment number 4:
    I. From time 11:49:50 til 12:02:24 filter parameters were set at 36 mm.
    II. From time 12:02:26 til 14:30:00 filter parameters were set at 45 mm.

- Experiment number 5: all parameter values were kept as indicated in Table 3.3.

- Experiment number 6: all parameter values were kept as indicated in Table 3.3.

- Experiment number 7:
    I. From time 11:49:02 til 12:01:12 filter parameters were set at 45 mm.

- Experiment number 8:
    I. From time 16:15:26 til 16:26:40 filter parameters were set at 31 mm.

4. Results and Discussion

In this chapter results from the list of experiments described in Section 3.13 are presented and discussed in the same order. First, dosage optimization of coagulant and flocculant by Jar Test Flocculation. Then four different flocculator configurations were tested to find the one that performed the best, and once a flocculator configuration was selected, a detailed analysis of SF500 performance with that flocculator was made.

4.1 Polymer Dosage Optimization

In order to find the optimal chemical dosage of coagulant and flocculant, the resulting synergy of both chemicals working together was analyzed.

The algae provided at WWTP in Chiclana were a wild type of *Coelastrum sp*. which had a certain degree of auto-coagulation, this supported the coagulant and flocculant efficiency.

Weather variation can affect algae, however weather during the project phase was sunny and algae water temperature was nearly the same during sampling, average of 16ºC.

TSS measurements were made for each sample before chemical additions and algae concentrations were in a range between 227-241 mg/l during all samplings.

Floc size and floc strength are key parameters for this project. In case there was not a good flocculation, small algae flocs will simply pass through the mesh either clog the mesh filter. On the other hand an overdose of flocculant will clog the mesh because flocculant will stick to mesh surface, behaving like glue, not allowing water to pass through mesh pores. To sum up, strong flocs were aimed to obtain. In order to get strong flocs a rapid mixing speed of 50 rpm was chosen empirically to mix flocculant.

Three main criteria are considered to decide the optimal dosage (in order of importance):

I. Floc quality.
II. Turbidity removal higher than 95%: this is one of project goals.
III. Lower dosage of chemicals: in order to make a cost-efficient project.
IV. Lower dosage of PAX-18: in order to reduce TS value.

Results of turbidity removal depending on chemical dosages established on Section 3.5.1 are presented on Figures 4.1, 4.2 and 4.3:

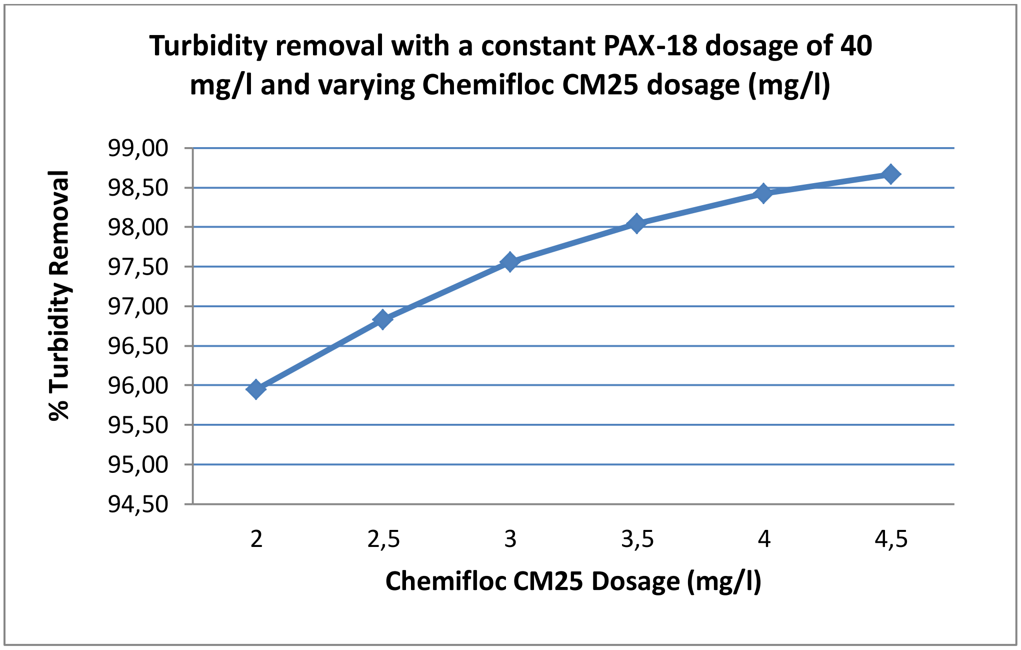

Figure 4.1: Dosage optimization using a fixed PAX-18 coagulant dosage (40 mg/l) and a varying Chemifloc CM25 flocculant dosage for *Coelastrum sp*.

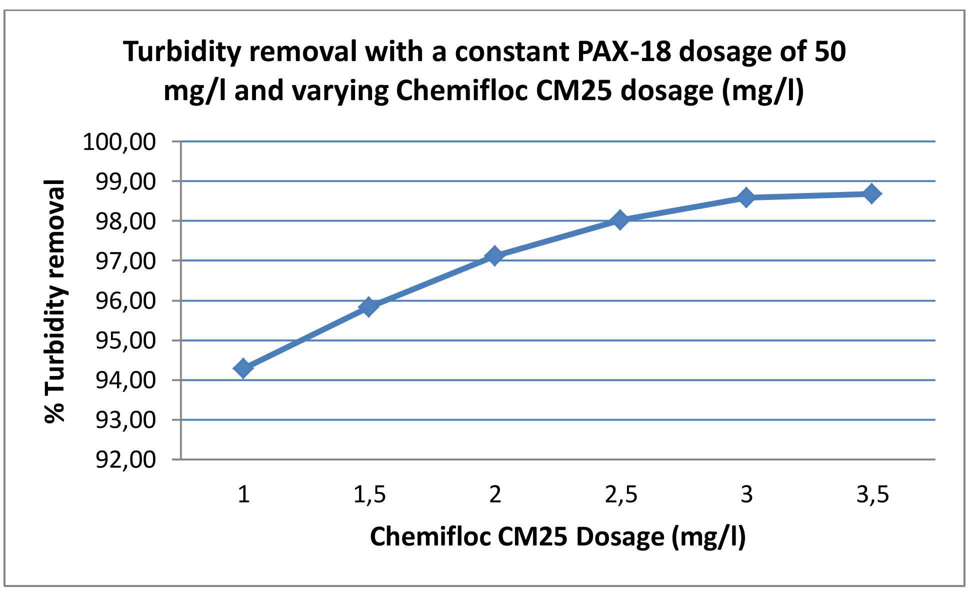

Figure 4.2: Dosage optimization using a fixed PAX-18 coagulant dosage (50 mg/l) and a varying Chemifloc CM25 flocculant dosage for *Coelastrum sp*.

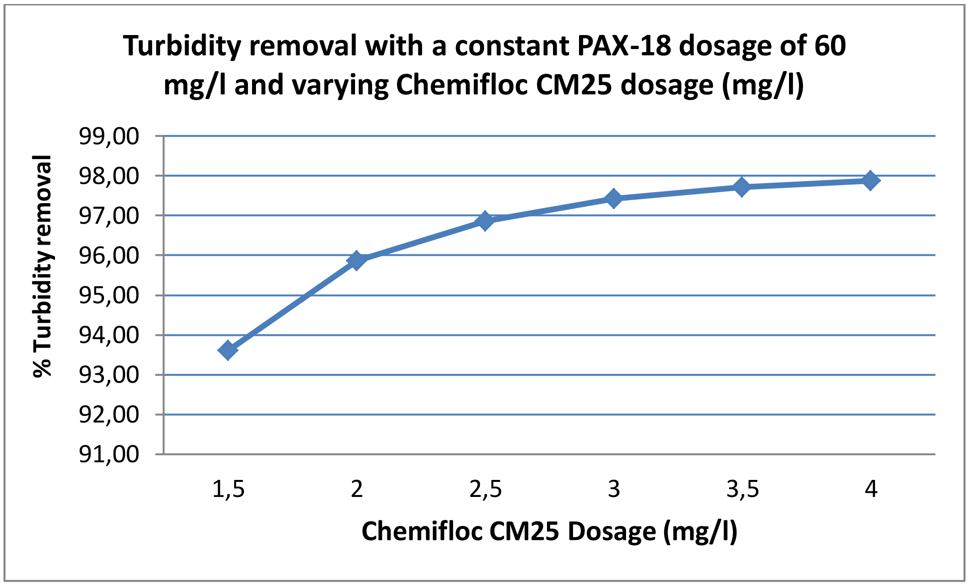

Figure 4.3: Dosage optimization using a fixed PAX-18 coagulant dosage (60 mg/l) and a varying Chemifloc CM25 flocculant dosage for *Coelastrum sp*.

In each experiment a higher value than 95% turbidity removal was achieved.

Figure 4.3 shows the flocculant dosage needed to obtain the same turbidity removal as in Figure 4.1 and Figure 4.2 is higher, this means that a very high addition of coagulant has a negative influence on floc formation. This is due to the repulsion between particles which was provoked by an overdose of coagulant (Metcalf and Eddy, 2003).

Analyzing Figures 4.1 and 4.2, with the objective to obtain the same turbidity removal, a higher dosage of flocculant is needed when adding 40 mg/l PAX-18. For instance, if 98% turbidity removal is taken as a reference, with 40 mg/l PAX-18 dosage a Chemifloc CM25 dosage of 3,5 mg/l is needed, on the other hand with 50 mg/l PAX-18 dosage a Chemifloc CM25 dosage of 2,5 mg/l is needed, this represent 15% less dosage of Chemifloc CM 25. So a 50 mg/l PAX-18 coagulant dosage was chosen as optimum.

To decide the best Chemifloc CM 25 flocculant dosage in combination with a 50 mg/l PAX-18 dosage, a flocculant dosage corresponding to a high representative turbidity removal was chosen, in this case, 98% was chosen since reaching a higher turbidity removal (99%) represents a much higher dosage and not so cost-efficient use of flocculant. This can be seen on Figure 4.2 the curve becomes more asymptotic from 98% to 99% value. Samples to measure turbidity removal were taken after 10 minutes of settling time, and they were taken 1 cm below jar test water level. In conclusion a 50 mg/l PAX-18 and 2,5 mg/l Chemifloc CM 25 dosage combination were chosen.

pH value of water samples were in a range between 7,6 and 8,2 which are acceptable values for a good Alum based coagulant performance. The pH of the water plays an important role when alum is used for coagulation because the solubility of the aluminum species in water is pH dependent.

For example, optimum particle removal by sweep flocs occurs in the pH range of 7 – 8 (Metcalf and Eddy,2003). However since algae water is a mix of algae and wastewater this pH range can be altered.

4.2 Pilot Scale Tank Flocculators Performances

Once the most effective combination of coagulant (50 mg/l) and flocculant dosage (2,5 mg/l) had been determined, this concentration was used for subsequent flocculation experiments.

The objectives aimed for during flocculator configuration testing performances are listed below (in order of importance):

I. Floc quality, (it was judge empirically).
II. High hydraulic capacity: With the objective of designing a SF500 cost-efficient system, a low power consumption per m^3 of water treated is need to be reached, this means that a minimum hydraulic capacity should be 0.5 m^3/h.
III. Low deviation from theoretical coagulant and flocculant consumption.
IV. Simplicity: a simple flocculator configuration implies small footprint.

The resulting performance for each flocculation configuration was judge as a combination of previously mentioned criteria and results are presented on following sections.

4.2.1 Configuration 1- Pilot Scale Tank Flocculator Performance

The original tank flocculator provided by Asio® consisited on two 20 liters tanks connected in series, first tank for coagulation/rapid mixing and the second one for flocculation/slow mixing. Considering that coagulation tank needs 30 seconds at rapid mixing and flocculation tank more than 10 minutes for good floc formation, and both tanks have the same volume, it was easy to realize that this flocculator configuration will not work. Best efforts were made to convert the first tank receiving algae into a rapid mixing tank, and the following one into a slow mixing tank.

In order to reduce the retention time of rapid mixing tank, the physical height at which rapid mixing tank was situated, was risen up to 15 cm with respect to the slow mixing tank. As a direct consequence of this modification, the pressure difference between both tanks was increased significantly. Therefore outlet flow from first tank flowed easily to second tank and retention time was reduced.

Figure 4.4: Configuration 1 - Pilot Scale Tank-Flocculator.

A flow of 300 l/h was set, considering this flow a rapid mixing retention time of 48 seconds and a slow mixing retention time of 4 minutes were obtained.

Another issue faced, was the fact that rapid mixer was not able to reach the necessary rpm to provoke rapid mixing, the maximum speed reached was 100 rpm. A more powerful motor was desirable to buy, but for logistic reasons it could not be bought, so it was considered that the increment of time during rapid mixing (48 seconds in total) provoked a good coagulant mixture, compensating the fact that mixing speed was not high enough.

With the objective to get a floc quality according to SF500 needs to be operated in good terms, a mixing velocity of 70 rpm was set for slow mixing tank, this velocity resulted in a good floc quality, strong flocs, and polymer consumption was triple than theoretical values, reaching 150 mg/l of PAX-18 and 7,5 mg/l of Chemifloc.

In addition hydraulic capacity was clearly insufficient to meet power consumption requirements. When hydraulic capacity was tried to be increased from 300 l/h to 500 l/h, retention time at slow mixing tank was unacceptably low, about 2,5 minutes, provoking small flocs.

For this reason this flocculator was decided unsuccessful, and a bigger tank flocculator able to handle higher flows was aimed to be built.

4.2.2 Configuration 2 - Pilot Scale Tank Flocculator Performance

The first solution that came up to solve previous flocculator configuration limitations, was to increase hydraulic retentation time on slow mixing tank by changing it for a 50 liters tank instead.

The difference water level between 20 liters and 50 liters tank was kept at approximately 15 cm in order to reduce hydraulic retention time on rapid mixing tank as previous flocculator configuration.

With 50 liters tank, HRT was increased so flocculator was able to handle a flow of 400 l/h, this means that HRT was equal to 7,5 minutes (Equation 3.3), this is a significant increment but still a little bit far from the goal of 10 minutes.

In addition, the inlet flow from rapid mixing tank was coming out to the slow tank at a high speed due to the fact that the inlet opening had a diameter of 32 mm, using Equation 4.1 the flow speed can be calculated:

Equation 4.1

$$Water\ Inlet\ Opening\ Flow\ Velocity\ \left({}^{m}/_{s}\right) = \frac{Flow\ \left({}^{m^3}/_{s}\right)}{Opening\ Area\ (m^2)}$$

Assuming a constant flow of 400 l/hour a flow velocity of 0.138 m/s is resulted.

This high water speed coming into a slow flocculator mixing tank had a non-desirable effect, breaking flocs.

Regarding to mentioned criteria on Section 4.2, this flocculator made good floc quality, chemicals consumption was still too high from theoretical values and the determining parameter which did not meet was hydraulic capacity, lower than 500 l/h. For that reason a third flocculator configuration was designed.

4.2.3 Configuration 3 - Pilot Scale Tank Flocculator Performance

In this flocculator configuration the 20 liters tank was kept as rapid mixing tank, then two 50 liters tanks were configured in series, so total capacity of 100 liters was obtained. Also the water level difference between this tank and the following two 50 liters tank were as previous configurations, about 15 cm.

To connect both flocculators avoiding any turbulence which could break the flocs, a 120 mm diameter pipe was connected between them, brass connections were used. For this tank configuration algae water flow could be increased up to 500 $l/hour$ obtaining a 12 minutes HRT, meeting our requirements.

However a new challenge came up: floating algae tendency. This was a minor problem on previous flocculators because they had a better mixing rate (paddle were specifically designed for them), however in this flocculator tank floating algae tendency is more noticeable. Mainly during mid-day hours, when algae produce more oxygen, so oxygen dissolved concentration values can go up to 18 mg/l (as it will lately described on Section 4.3.1).

When algae flocs are floating over the tanks two main consequences occurred, firstly flocculated algae from the first tank did not flow into second tank, it was being accumulated on the top, because pipe connection between them was not installed at the very top part of the tanks, so majority of algae was stopped at the first tank, not flowing to second one. And secondly, the random algae floc which flowed into second tank was floating over in this second one, so no flocculated algae was flowing through bottom outlet to SF500. An attempt to solve this problem was made by increasing rpm of paddles, but it was unsuccessful.

For this reason this flocculator configuration was dismissed.

4.2.4 Configuration 4 - Pilot Scale Tank Flocculator Performance

An Asio® 20 liters tank plus a 100 liters tank were set as final flocculator configuration.

A 100 L tank flocculator was made in substitution of 50 liters slow mixing tank, and rapid mixing water level was situated as previously, approximately 15 cm higher than slow mixing tank.

PAX-18 addition was done directly into algae feeding tube, two meters ahead of 20 liters rapid mixing tank. This way of feeding coagulant, gave a better mixing rate, since coagulant is being mixed by high flow inertia on tube. In addition coagulant was kept mixing on 20 liters tank for approximately a retention time of 40 seconds.

Flocculant addition was done directly into the tube which fed the slow mixing tank from the rapid mixing tank. This was a positive aspect for a better flocculant mixture.

Two openings were made on tank, one at the bottom which was used as inlet and one at the upper part which was used as outlet. This inlet and outlet configuration is a completely opposite design from previous configurations.

The reason for situating the outlet at the upper part was to oblige the floating algae to flow through outlet to reach SF500 avoiding previous floating problems.

Figure 4.5: 20 Liters tank in combination with 100 Liters Pilot-scale Tank Flocculator.

However a consequent problem appeared when performing this flocculator: paddles designed for a 20 liters tank flocculator did not work out accurately for a 100 liters flocculator.

100 liters tank was 20 cm higher and 20cm wider than paddles available to use. This had a direct consequence: mixing quality went down.

The fact that paddles were 20cm shorter than tank high provoked that paddles could not mix water at tank bottom, there was only indirect mixing provoked by water flow inercia. Consequently real HRT was lower than 12 minutes theoretical HRT.

In order to mix water at tank bottom paddles speed was increased up to 70 rpm.

As a result, maximum hydraulic capacity flocculator was able to handle was 540 $l/hour$ (forming flocs with the necessary quality).

As previously written before in this present Section, at the beginning only one outlet to feed SF500 was drilled, but after a try it was clearly noticed that flow speed was too high when going into SF500, consequently when this flow splashed onto the deflector installed on SF500 flocs were easily breaking. Therefore it was decided to drill two more outlets (so in total three outlets were at the same height, so there was no pressure difference between them). Drilling these two extra outlets, flow velocity to SF500 decreased from 0.18 m/s to 0.062 m/s so no flocs were broken. These velocities were calculated using Equation 4.1.

Attending to criteria established on Section 4.2:

I. Floc quality was acceptable.
II. Hydraulic capacity was 540 l/h, higher than 500 l/h needed.
III. Chemical consumption was higher than theoretical values, but acceptable.
IV. Flocculator configuration simplicity was kept, as only two tanks were used.

So this flocculator combination was selected as the right one to be used for the full SF500 experiments.

4.3 Deflector Designs

Figures 4.6 and 4.7 that are results based on Fluent Ansys 14.0 flow modeling software are presented below, red color indicates zones with highest flow velocity and blue with lowest.

Model is based on a SF500 frame with real dimensions, and inlet flow of 0.5 m^3/h, water density equal to 1 Kg/L, water viscosity = 0.001002 Pa·s, environment pressure = 1 bar.

Should be noted that this is a 2D representative model, which does not take into account all SF500 3D design detail, an accurate study should be made on site.

4.3.1 Design 1

Units on left are E-01 mm/s.

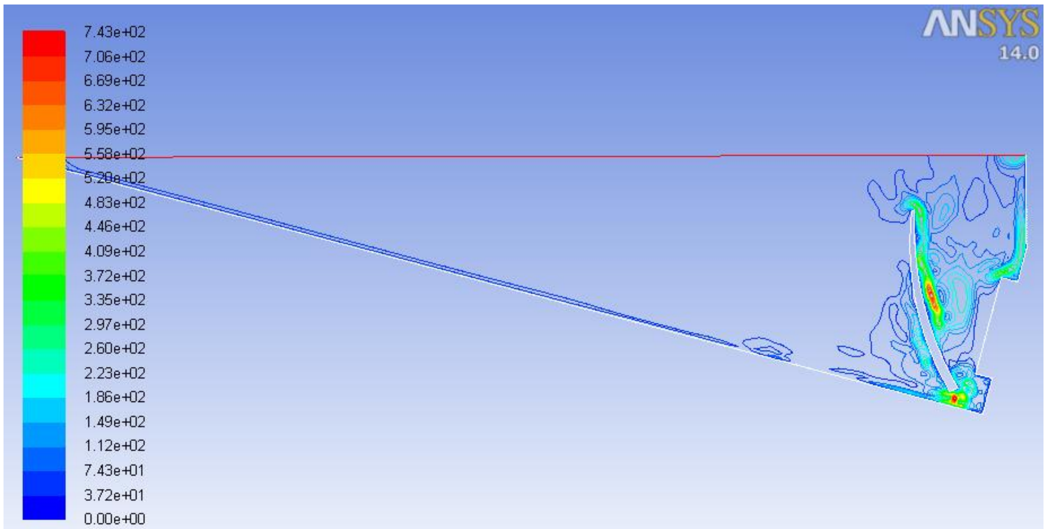

Figure 4.6: Deflector design 1 - flow pattern.

High speed velocities are localized in front of deflector, where flow impacts with deflector, and bottom part where the flow has to flow through.

4.3.2 Design 2

Units on left are E-01 mm/s.

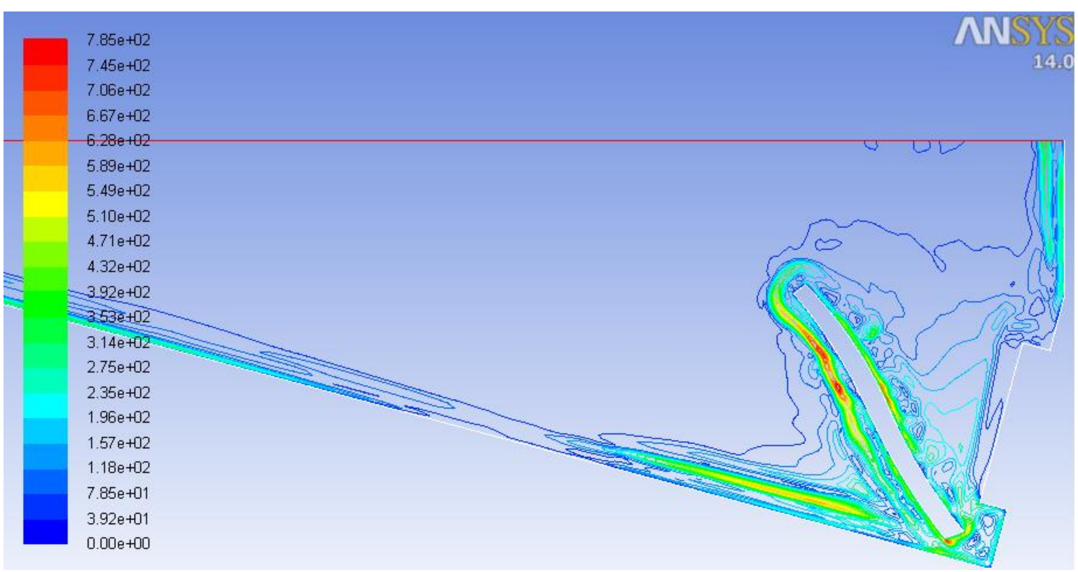

Figure 4.7: Deflector design 2 flow pattern.

In this design high speed velocities are produce behind deflector and at the bottom after deflector, this is an undesirable effect because it would prevent flocs from settling down.

4.4 SWAT Technology Performance

Once flocculator configuration tank has been selected, (20 liters tank in combination with 100 liters tank), 8 experiments were performed using SF500 technology, with the objective to find SF500 configuration parameters which suited the best to achieve the primary objectives of 95% TSS removal and power consumption lower than 0.08 kW/m^3 of water treated. These configuration parameters were: mesh pore size, belt speed, cleaning protocol and control panel parameters. All experiments were conducted in a continuous mode run.

It was possible to test a wide variety of different pore size meshes. Pore size mesh has an important effect on water flux through mesh, since a small pore size will obstruct water flux due to water superficial tension, this was more noticeable when using a meshes pore size in the range of 90 – 158 μm. However, the resulting maximum flow handled by SF500 (540 $l/hour$) was limited not by meshes characteristics, but due to flocculator limitations. On every test, it was noticed that was imperative the use of deflector at SF500 inlet, and deflector used was working properly.

There are two main reasons why a deflector must be installed:

1) To form an algae cake: algae cake behaves as a "filter mat", which helps to achieve more than 95% removal even when using wider meshes than 210 μm.
2) The only mechanism to harvest algae from the mesh is using mentioned scraper in Section 3.9.4. The thicker the algae mat was, the easier and more effective to harvest flocculated algae was.

The deflectors channelized the inlet turbulent flow into a laminar flow, breaking as less as possible algae flocs. When water is flowing in a laminar way, flocs are able to settle down onto the mesh forming a cake.

To help deflector work, turbulent flow was reduced at SF500 entrance by drilling two more inlets (in total there were three inlets at SF500). So flow velocity was reduced to one third reducing turbulences.

Data recording procedure was eased by SF500 control panel software program, which recorded every two seconds values of: water level sensor (mm), belt speed (%) and power consumption (W).

Dissolved oxygen concentration (%), temperature (ºC) and pH values were recorded at real time by Aqualia SCADA program directly from ponds in use. pH and temperature values fluctuated in a small range of values, so an average calculations was made and noted out as experimental condition value.

During these experiments it was discovered that water knife did not clean 100% of mesh surface, only about 65 – 70% (Figure 4.8). This was due to the fact that nozzles were too closed to mesh surface, so nozzles could not spread water all over the mesh surface (it was noticed that nozzles needed to be pointing out to mesh at a 90º angle to be effective).

As a direct consequence of this lack of cleaning ability, algae particle striped were visible on mesh. That provoked that on those stripes not water was filtered, so no cake could be formed on them.

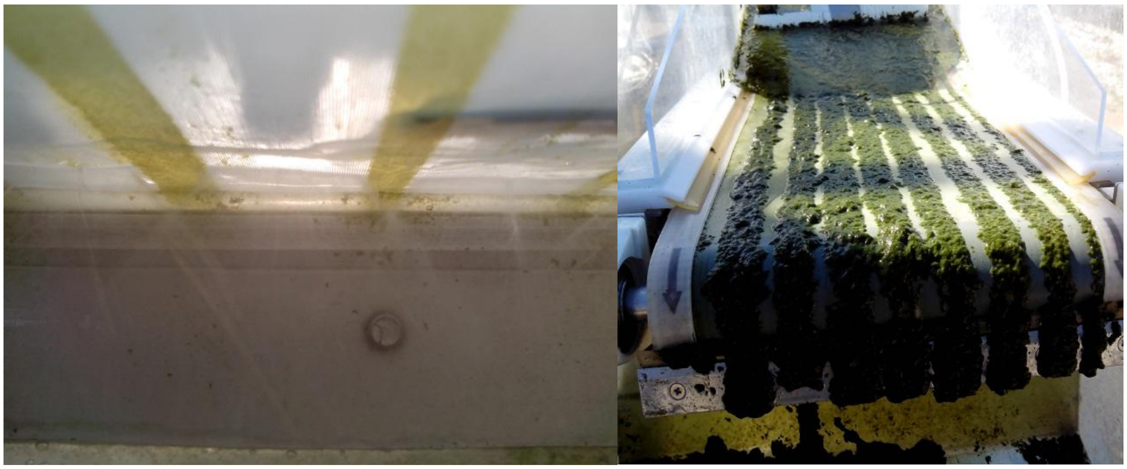

Figure 4.8: Left: Water knife cleaning partially mesh surface (350µm mesh pore size). Right: Algae cake stripes on mesh due to inefficacy of water wash.

This had an important consequence, lower filtration capacity, provoking a more filter cloth movement, more frequency of cleaning procedure and consequently higher power consumption.

A complete detailed analysis of data and results provided is described for every experiment, also the relationships between parameters values and SF500 performance.

4.3.1 Experiment 1 (90 µm)

Experimental conditions and data overview are presented in following Chapters. Figure 4.9 is a combination of power consumption, filter level and filter cloth speed. On following Chapters a detailed analysis of parameter with influence on SF500 performance is made, those parameters are DO, pH, temperature, water level, filter cloth speed and power consumption.

Results obtained during this experiment met the established objectives of 95% algae removal and power consumption lower than 0,08 kWh/m^3.

In this case, harvesting efficacy reached was 96,95% TSS removal. TSS value for raw water algae was 233,82 mg/L and effluent TSS was 7,14 mg/L.

Looking from a turbidity removal point of view, turbidity of raw algae was 136 NTU and effluent turbidity had a value of 2,97 NTU, using Equation 3.2 a turbidity removal value of 97,82% was obtained.

Total Solids (TS) for this experiment was 27,5 g/Kg.

Higher coagulant and flocculant dose than theoretical values were added to form good quality flocs, this overdose is due to the inaccurate flocculator design. PAX-18 dose (168 mg/L) was 3,3 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (5,4 mg/L) was twice than theoretical value (2,5 mg/L).

Average power consumption was 70,58 W, considering flow treated during experiment (0,514 m^3/h), power consumption is equal to 0,137 kWh/m^3 (using Equation 3.6) . In addition, considering that control panel has a power consumption of 33 W by itself, the net power consumption is 37,58 W, doing previous calculations a power consumption of 0,074 kWh/m^3 is resulted, a fairly lower value than objective set (0,08 kWh/m^3). Pictures related to Experiment 1 can be seen in Appendix C.

4.3.1.1 Experimental Conditions for Experiment 1

Table 4.1 Experimental conditions for Experiment 1 using SWAT technology.

Description	Specification
Mesh pore size	90 µm
Experiment time	
Experiment date	28/11/2013
Start Time	12:55:07
End Time	15:35:59
Total Test Time	2 h 40 min 52 seconds
PAX-18 dosage	
PAX-18 dosage (mg/L algae)	168
PAX-18 dosage (mg/g algae)	718
Active material (Al_2O_3) (mg/g algae)	122
Alum (III) (mg/g algae)	65
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae water)	5,4
Chemifloc CM25 dose (mg/g algae)	23
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	33
Water level start filter cloth (mm)	33
Water level stop filter cloth (mm)	33
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	301
pH Algae water average	7,52

Influent Characteristics	
Water temperature average (ºC)	13,57
TSS of raw algae (mg/L)	233,82
Turbidity of raw algae (NTU)	136
Dissolved oxygen average (mg/L)	16,87
Operating Conditions	
Algae flow rate (m^3/h)	0,514
HRT of coagulation (seconds)	45
HRT of flocculator tank (minutes)	11,67

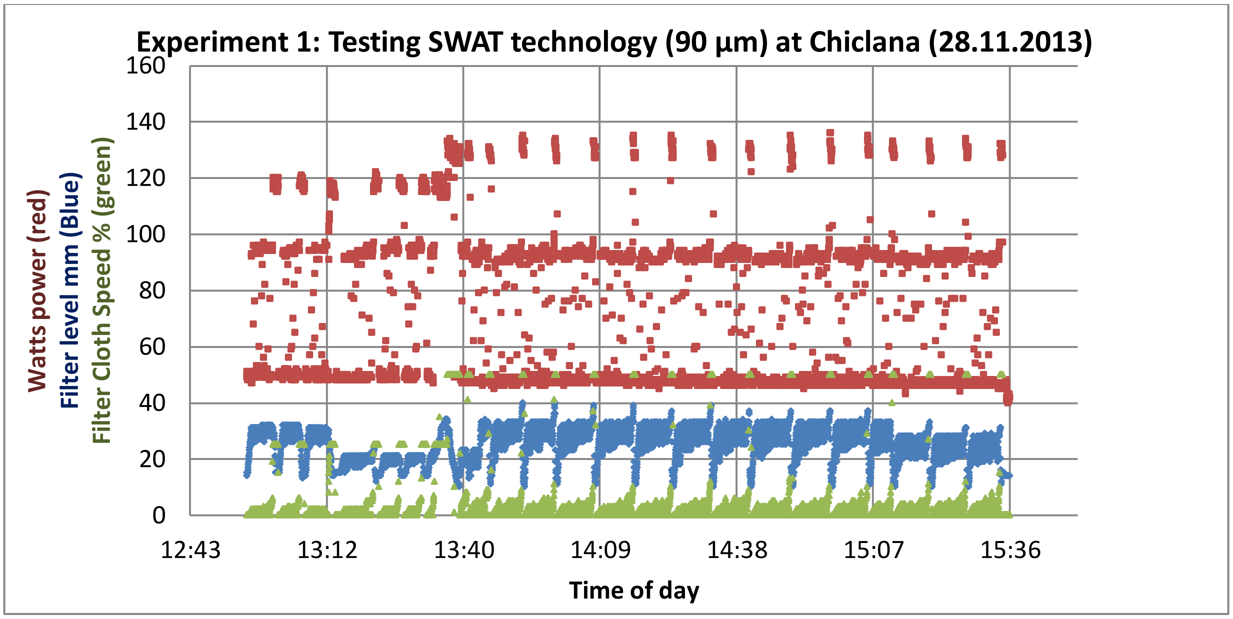

Figure 4.9: Overview results for Experiment 1.

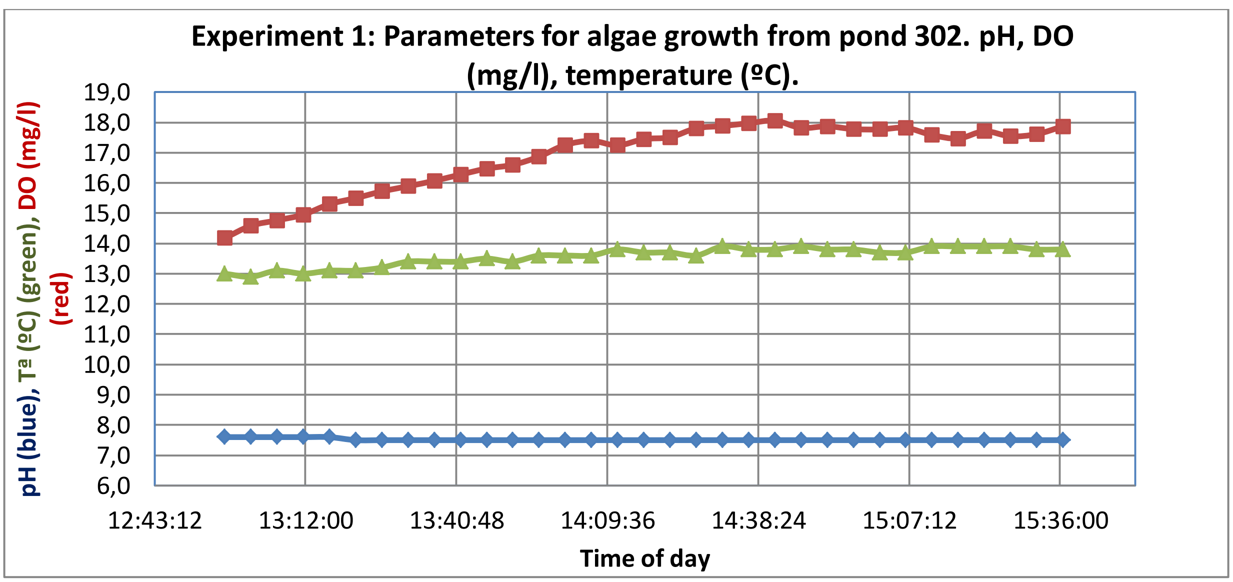

Figure 4.10: Experiment 1: Parameters for algae growth from pond 302 (pH, temperature and DO).

As it can be seen in Figure 4.10, pH values kept nearly constant during experiment at an average value of 7.5.

Regarding algae water pond temperature values, they fell in a range between 12,9ºC and 13,9ºC with an average value of 13,57ºC. Since algae ponds are opened to ambient, water Temperature increases with higher solar radiation which happens around 15 – 16 p.m. (www.aemet.es, Agencia estatal de meteorología).

As it is represented on Figure 4.10, DO concentration fell in a range between 14,2 mg/l and 18,1 mg/l with and average value of 16,87 mg/l. Also DO concentration increases during experimentation time, due to the increase of solar radiation on algae pond, reaching maximum DO concentration at 14:41:35 hours. This is because solar radiation stimulates algae O_2 production. To understand DO values which are higher that possible maximum DO at a certain temperature, there is a consideration that should be taken into account, there is a not a steady state, algae is producing more oxygen that water pond liberates to the ambient.

From start experiment time till 16:25:35 DO concentration increases almost linearly, with a rate of 1,2 mg/l O_2 per 30 minutes, then it keeps nearly constant with minor fluctuations till experiment time ends.

4.3.1.2 Water Level Analysis for Experiment 1

In order to do a more detailed analysis of SF500 performance, Figure 4.11 with only water level measurements represented is shown below. Circles to explain different concepts have been drawn on graph:

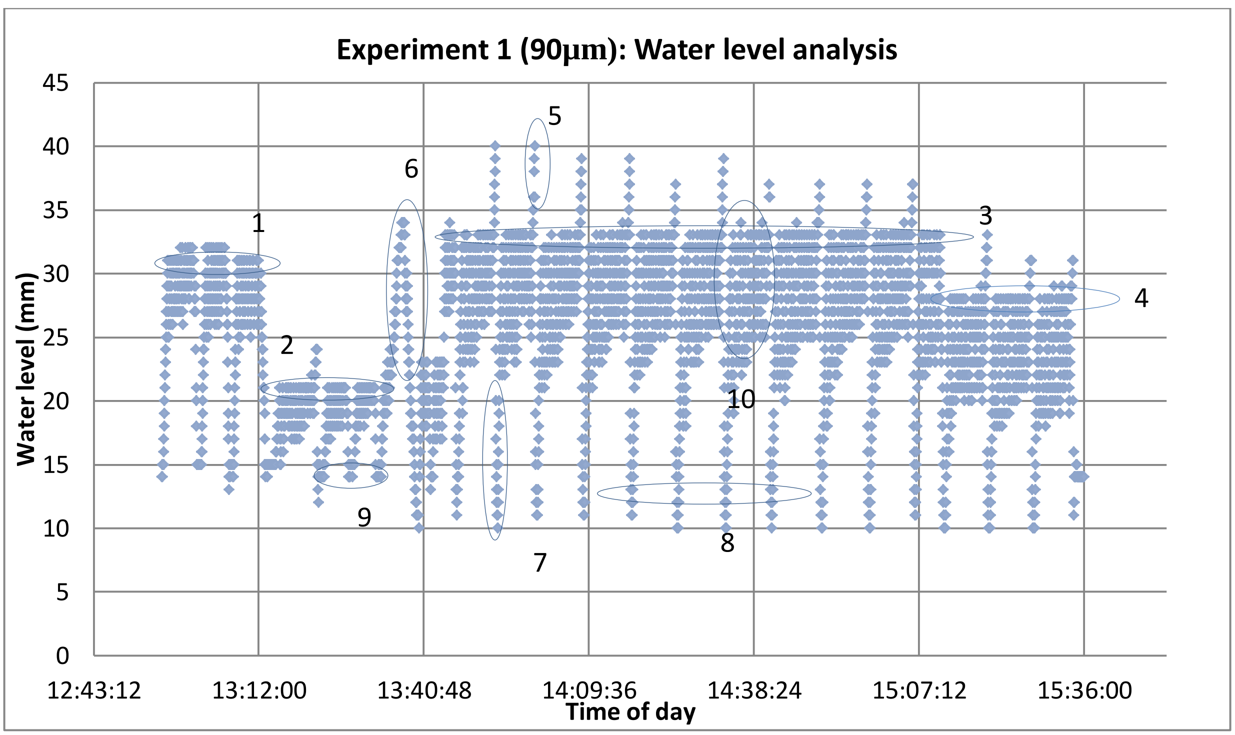

Figure 4.11: Experiment 1: Water level analysis.

1. During experiment time, different values of "water level set point and start level filter cloth" were set. At the beginning was set at 31 mm as it is circled as number 1 on graph.
2. Water level set point and water level start filter cloth were set at 21 mm.
3. Water level set point and water level start filter cloth were set at 33 mm.
4. Water level set point and water level start filter cloth were set at 28 mm.
5. When filter is clogged and moving the mesh does not bring any cleaned mesh surface to filter water, then motor moves faster and faster the mesh to bring that cleaned mesh until it reaches 6% motor velocity, (this is the threshold value when cleaning procedure starts), meanwhile water has being accumulated on SF500, consequently increasing water level, as it is reflected on circle 5.
6. This tiny "mountain" of water level values is provoked by the effect of changing the "water level set point and water level start filter cloth" to 34 mm during a couple of minutes and then set it back to 23 mm. This was made to see the time response of SF500 to parameter changing.
7. Once cleaning procedure is on, its effect results in a drop of water level because cleaned mesh is filtering water. This drop reaches the minimum water level value which is equivalent to water level sensor offset, in this case 10 mm.
8. Looking at this water level drops, a frequency of cleaning procedures can be obtained, in this case is one every 8 minutes approximately (should be taken into account that water level set point has a direct influence on this frequency, in this case was 33 mm).
9. When water level set point and water level start filter cloth were set at 21 mm, cleaning frequency was 5 minutes approximately. This is reasonable more frequent than when mentioned parameters were set at 33 mm. This difference is due to the fact that lower water level implies a more frequent belt movement to keep that low level, consequently mesh will be cover by algae faster and will be clogged faster.
10. What is represented on Circle 10 is that after cleaning procedure mesh is fully cleaned, so its capacity to filter water is highest therefore filter moves at minimum speed (1%). This minimum velocity is meant to keep water level as close as possible to the reference "water level set point". If a zoom in is made on Figure 4.11 during the time circled as number 10, this is the figure can be obtained (Figure 4.12): Where water level moves in a small range between 22 – 31 mm, during 8 minutes until the time cleaning procedure starts again.

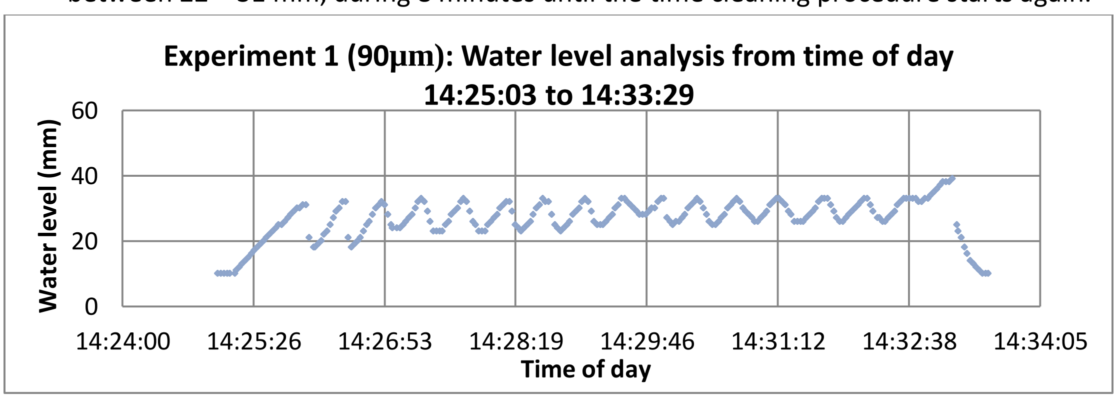

Figure 4.12: Experiment 1: Water level analysis from time of day 14:25:03 to 14:33:29.

4.3.1.3 Filter Cloth Speed Analysis for Experiment 1

Regarding to filter cloth speed, Figure 4.13 was obtained, which represents filter cloth speed value every two seconds.

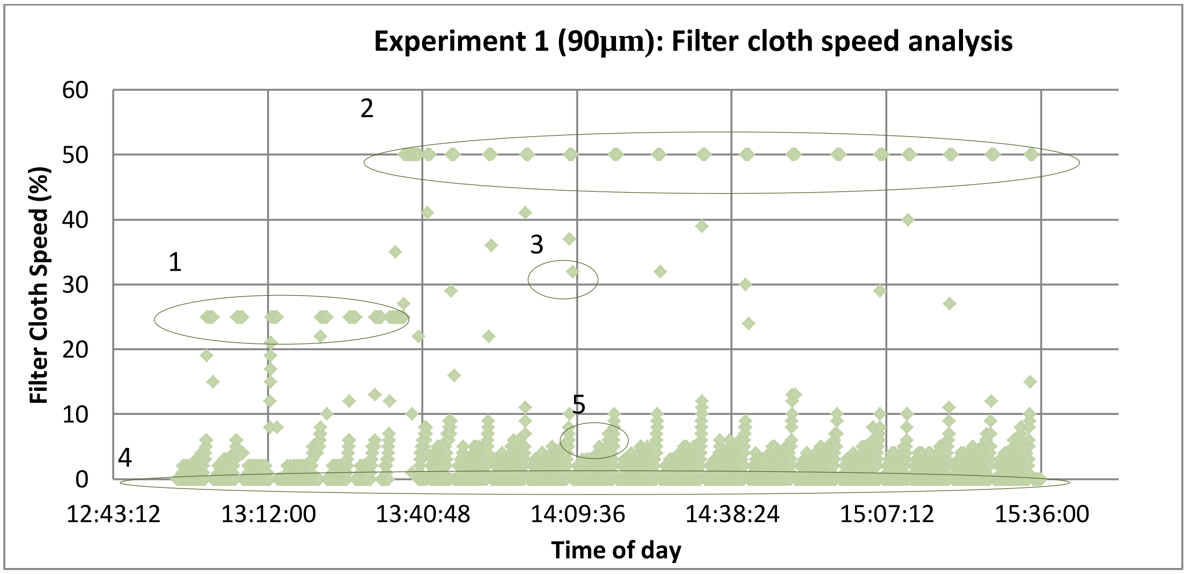

Figure 4.13: Experiment 1: Filter cloth speed analysis.

1. As it can be seen on Circle 1, the maximum filter cloth speed is achieved during cleaning procedure, at the beginning it was set at 25 %, this value can be set on control panel on "belt speed during cleaning" parameter.
2. During major experiment time, "belt speed during cleaning" was set at 50%, and cleaning procedure went on at that speed with a frequency of 8 minutes. It should be remarked that belt speed and time during belt speed is working at highest velocity produces a significant increment of power consumption, therefore both speeds were compared to their cleaning performances, it turned out to be the same, so higher speed but less time working was chosen.
3. Points in the middle of graph, represents filter speed when filter is accelerating to get maximum speed.
4. There is an accumulation of points at 0 %, because that was the time when filter is not moving, just filtering water, and water level is below water level set point. And it should be noted that there are an accumulation of points around 1 – 5 % value.
5. Every column represents when belt speed went above threshold belt speed 6 % and therefore cleaning procedure started and maximum filter speed was reached. This can be easier notice on Figure 4.14, below:

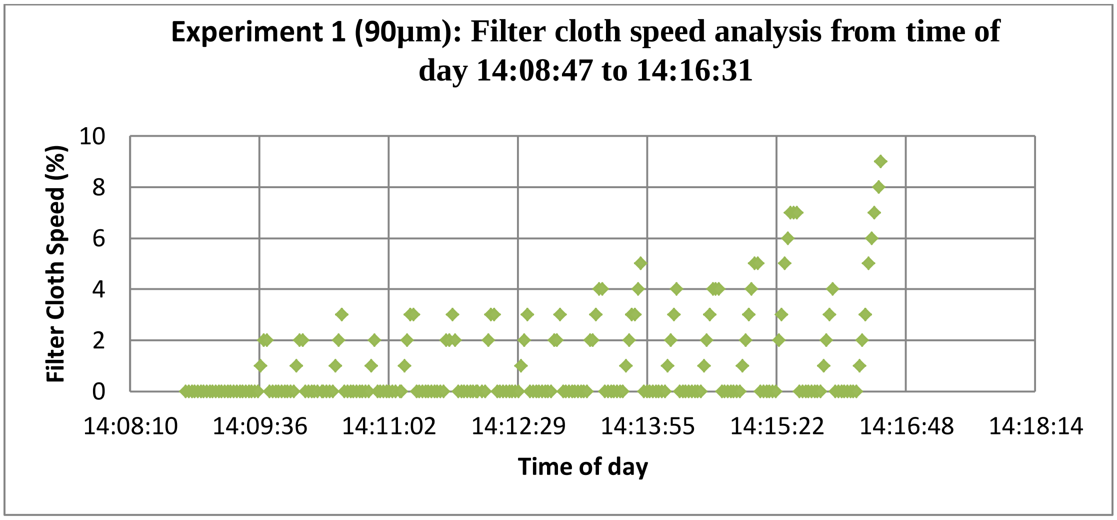

Figure 4.14: Experiment 1 (90µm): Filter cloth speed analysis from time of day 14:08:47 to 14:16:31.

4.3.1.4 Power Consumption Analysis for Experiment 1

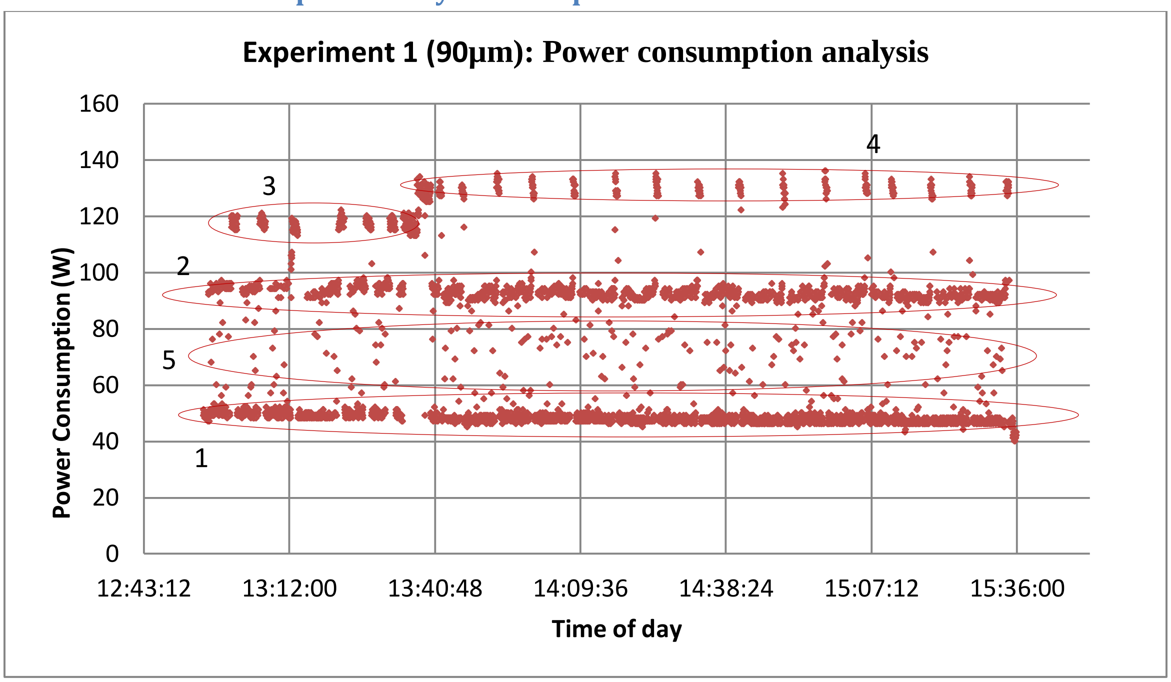

Figure 4.15: Experiment 1: Power consumption analysis.

As it can be seen on Figure 4.15:

1. Power consumption is steady between 46 and 48 Watts, this is power consumption resulted by dosage pumps, 12 volts motor which moves flocculator paddles and control panel consumption (control panel consumption by itself is 36 W).
2. On circle number 2 is represented power consumption when motor is working to move the filter in a range of 1 – 6 % velocity. This power consumption is about 90 – 94 W.

3. On circle number 3 is represented power consumption when motor is running at 25% speed that is when cleaning procedure is on. This power consumption is about 115 – 118 W.
4. On circle number 4 belt speed during cleaning procedure was set at 50 %, so higher power consumption that at 25% was noticed. Values are in a range of 131 – 135 W.
5. All points are power consumption values recorded while motor was accelerating.

4.3.2 Experiment 2 (158 µm)

For this experiment a wider mesh pore size was used, which has a higher filtration capacity.

Results obtained during this experiment also met the established objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3.

For this experiment, harvesting efficacy reached was 96,15% TSS removal. TSS value for raw algae water was 230 mg/L and effluent TSS was 8,85 mg/L.

Looking from a turbidity removal point of view, turbidity of raw algae was 144 NTU and effluent turbidity had a value of 2,97 NTU, using Equation 3.2 a turbidity removal value of 97,94% was obtained.

Total Solids (TS) for this experiment was 56,01 g/Kg.

Higher coagulant and flocculant dose than theoretical values were added to form good quality flocs, this overdose is due to the inaccurate flocculator design. PAX-18 dose (205 mg/L) was 4 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (6,5 mg/L) was 2,5 times the theoretical value (2,5 mg/L).

Average power consumption was 53,87 W, considering flow treated during experiment (0,36 m^3/h), power consumption is equal to 0,15 kWh/m^3 (using Equation 3.6) . In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 20,87 W, doing previous calculations a power consumption of 0,058 kWh/m^3 is resulted, a lower value than Experiment 1 and lower than objective set (0,08 kWh/m^3).

Pictures related to Experiment 2 can be seen on Appendix D.

4.3.2.1 Experimental Conditions for Experiment 2

Table 4.2 Experimental conditions for Experiment 2 using SWAT technology.

Description	Specification
Mesh pore size	158 µm
Experiment time	
Experiment date	26/11/2013
Start Time	11:05:03
End Time	12:44:25
Total Test Time	1 h 39 min 22 seconds

PAX-18 dosage	
PAX-18 dosage (mg/L algae)	205
PAX-18 dosage (mg/g algae)	893
Active material (Al_2O_3) (mg/g algae)	152
Alum (III) (mg/g algae)	80
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	6,5
Chemifloc CM25 dosage (mg/g algae)	28
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	55
Water level start filter cloth (mm)	55
Water level stop filter cloth (mm)	55
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Cloudy
Pond number	301
pH Algae water average	7,6
Water temperature average (ºC)	12,35
TSS of raw algae (mg/L)	230,16
Turbidity of raw algae (NTU)	144
Dissolved oxygen average (mg/l)	7,02
Operating Conditions	
Algae flow rate (m^3/h)	0,36
HRT of coagulation (seconds)	64
HRT of flocculator tank (minutes)	16,67

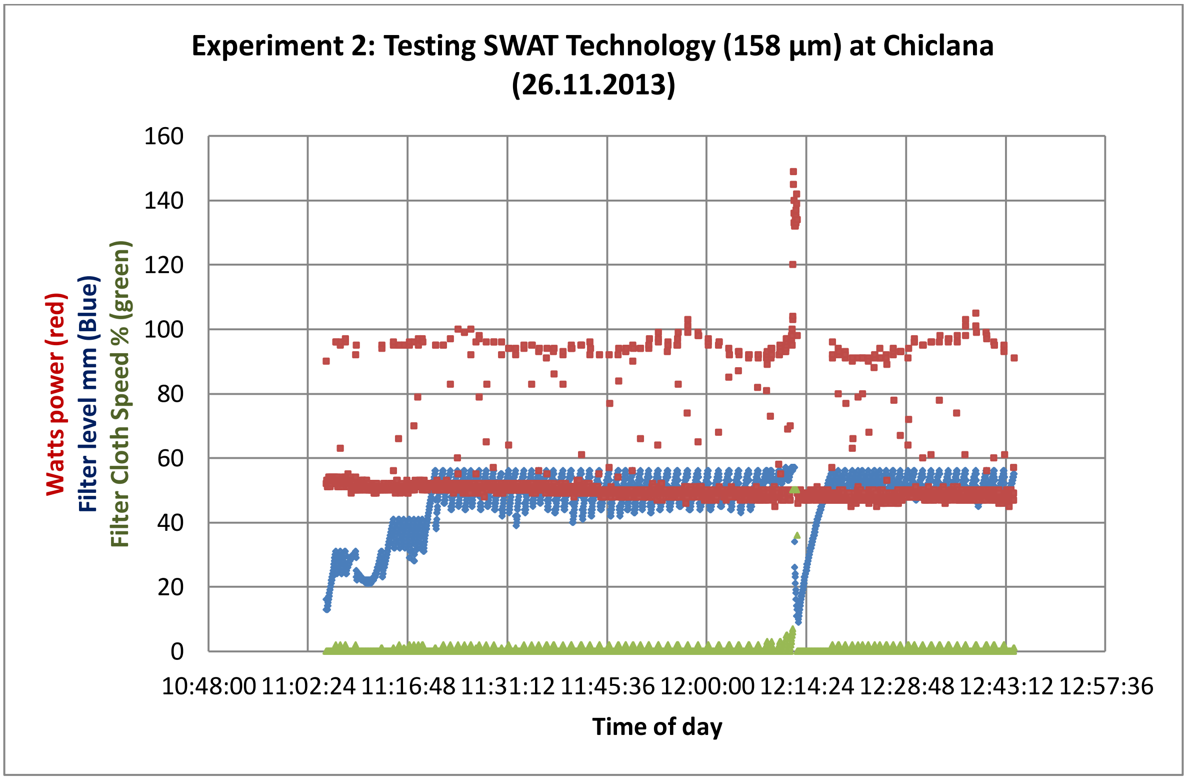

Figure 4.16: Overview results for Experiment 2.

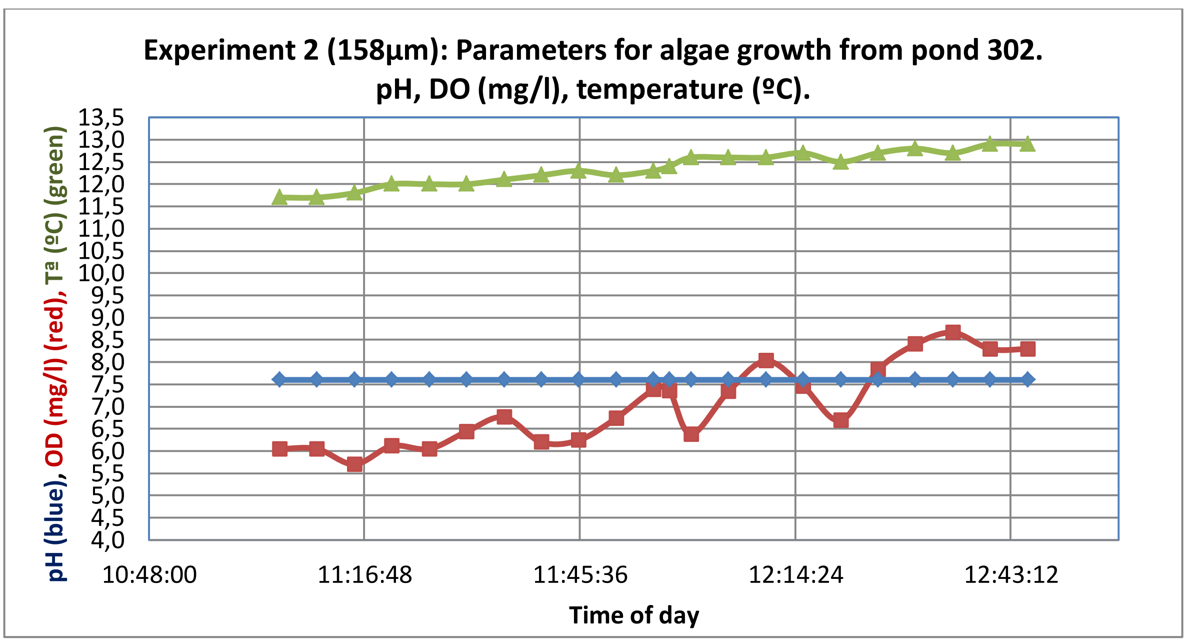

Figure 4.17: Experiment 2: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH kept constant at a 7,6 value.

Water temperature fell in a range between 11,7ºC and 12,9ºC, with an average value of 12,35ºC.

DO concentration fell in a range between 5,7 and 8,7 mg/L, with an average value of 7,02 mg/L. It has been noticed that DO remarkably fluctuated during this experiment, so it has been hypothesized that was due to cloudy weather. When clouds obstructed solar radiation, DO values went down, and when solar radiation hit the pond, DO went up.

DO values are significantly lower than DO values for Experiment 1, considering that TSS values are nearly the same for both experiment, it was reasoned this is because Experiment 2 was carried out at earlier hour than Experiment 1, consequently lower solar radiation was hitting the pond.

4.3.2.2 Water Level Analysis for Experiment 2

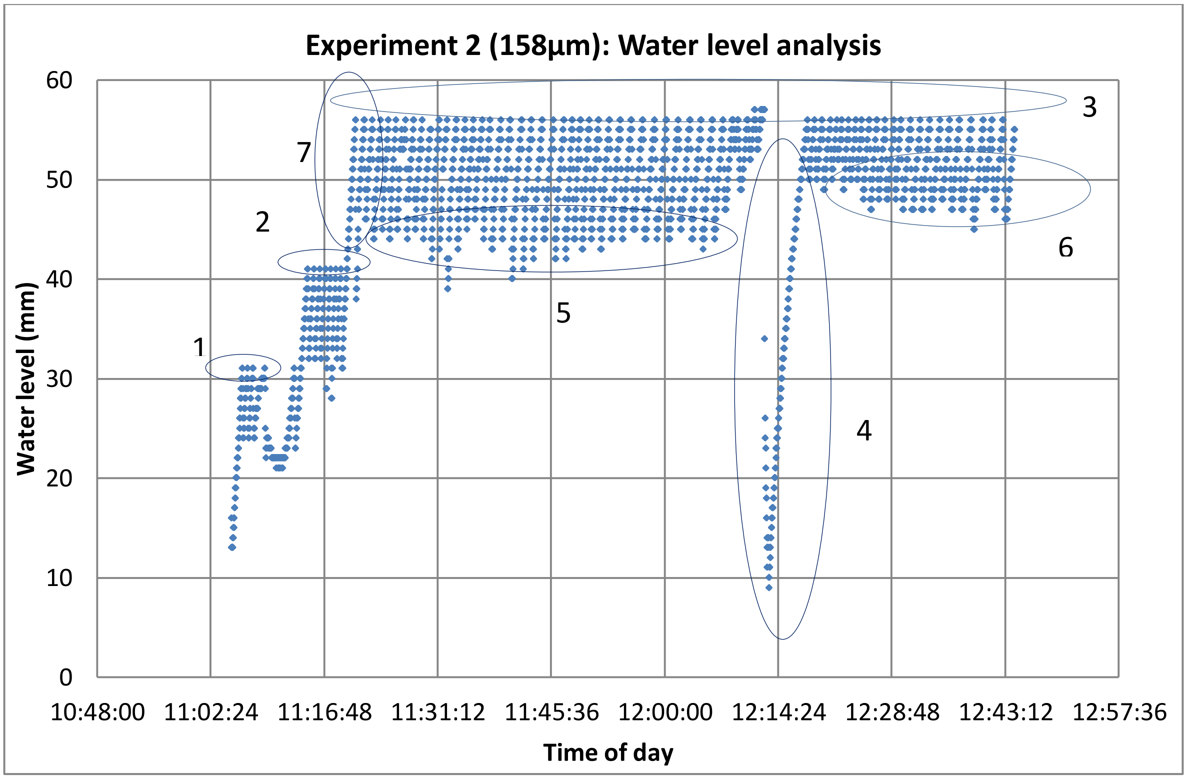

Figure 4.18: Experiment 2: Water level analysis.

1. Different values for "water level set point" were set during experiment time. During period circled it was set at 31 mm.
2. Water level set point was set at 41 mm.
3. Water level set point was set at 56 mm during major time of this experiment.
4. During this experiment water knife went on only one time, this is due to the low flow treated (360 L/h) and test time was short: 1 hour 39 minutes and 22 seconds.
5. When filter moves and cleaned mesh comes up, water is filtered lowering water level, therefore lectures about 44 mm were made.
6. In this case the situation is the same as pointed out in Circle 5, but the reason why water decreases until 49 mm instead of 44 mm as previously, is because when filter moves, it

does not bring a completely cleaned mesh because water knife was not able to clean 100% mesh surface, leaving the mentioned stripes on Section 4.4.

7. One option to vary the water level decrement when moving the filter mesh, is by the use of "water level stop filter cloth" parameter on control panel. By setting a low value the filter will not stop moving until it reaches that low value preset.

4.3.2.3 Filter Cloth Speed Analysis for Experiment 2

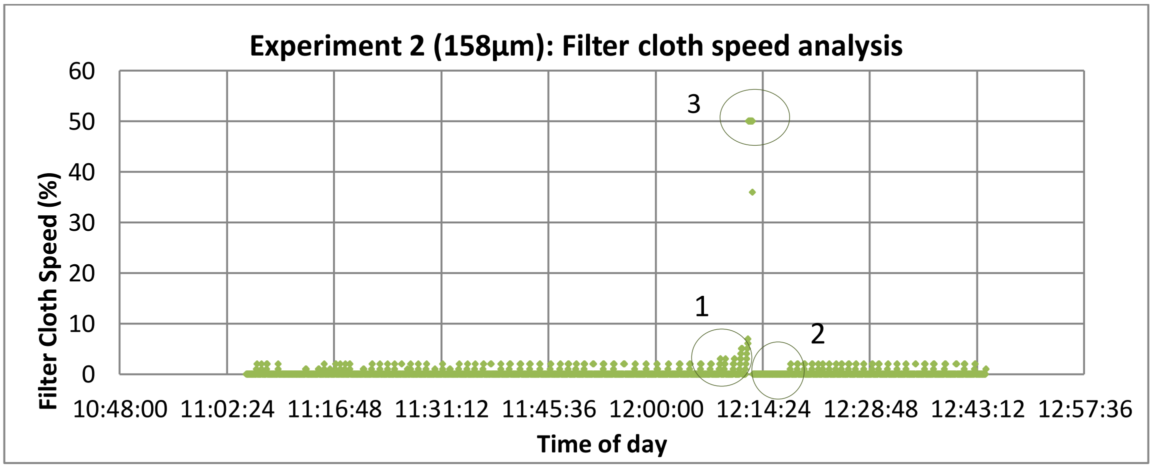

Figure 4.19: Experiment 2: Filter cloth speed analysis.

1. It can be clearly seen that belt speed has a tendency to increase when the filter is close to be completely clogged and therefore cleaning procedure is about to start.
2. After cleaning procedure, mesh is completely clean, so it has a high capacity to filter, therefore there is no need of moving the filter for a relatively long period of time, this is represented on Figure 4.19 as a continuous value of 0 % filter cloth speed.
3. Cleaning procedure went on, only one time, so there is only one value for 50%.

4.3.2.4 Power Consumption Analysis for Experiment 2

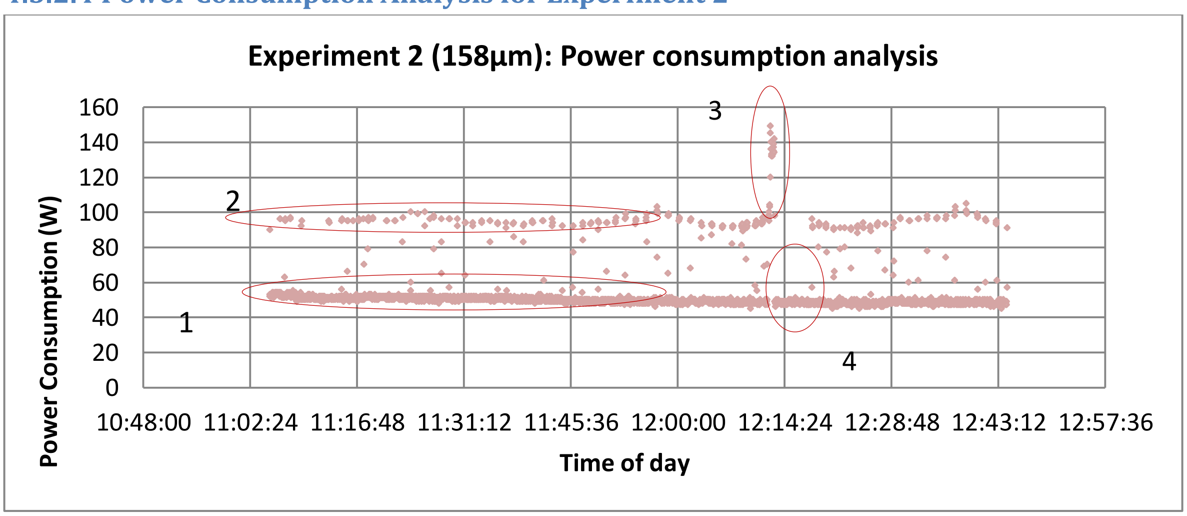

Figure 4.20: Experiment 2: Power consumption analysis.

1. Power consumption without belt moving is in the range of 50 – 52 W.
2. Power consumption when belt is moving in a range between 1 – 6 % velocity, is about 93 – 96 W.
3. Cleaning procedure went on only one time, so a maximum power consumption of 149 W was reached only once.
4. After cleaning procedure and taking into account the small water flow that was being treated 360 l/h, there was no need of moving the filter, so no increment on power consumption was made because of motor work.

4.3.3 Experiment 3 (158 µm)

A second experiment with the same mesh pore size 158 µm was carried out.

Objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3 were met.

Harvesting efficacy reached was 97,03% TSS removal. TSS value for raw water algae was 230 mg/L and effluent TSS was 6,84 mg/L.

Turbidity of raw algae was 124 NTU and effluent turbidity had a value of 2,35 NTU, using Equation 3.2 a turbidity removal value of 98,10% was obtained.

Total Solids (TS) for this experiment was 56,21 g/Kg.

PAX-18 dose (221 mg/L) was 4,4 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (5,9 mg/L) was 2,6 times the theoretical value (2,5 mg/L).

Average power consumption was 55,84 W, considering flow treated during experiment (0,47 m^3/h), power consumption is equal to 0,119 kWh/m^3. In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 22,84 W, doing previous calculations a power consumption of 0,049 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3).

Pictures related to Experiment 3 can be seen on Appendix D.

4.3.3.1 Experimental Conditions for Experiment 3

Table 4.3 Experimental conditions for Experiment 3 using SWAT technology.

Description	Specification
Mesh pore size	158 µm
Experiment time	
Experiment date	26/11/2013
Start Time	16:35:03
End Time	17:56:23
Total Test Time	1 h 22 min 22 seconds

PAX-18 settings	
PAX-18 dosage (mg/L algae)	221
PAX-18 dosage (mg/g algae)	959
Active material (Al_2O_3) (mg/g algae)	163
Alum (III) (mg/g algae)	86
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 settings	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	5,9
Chemifloc CM25 dosage (mg/g algae)	25,6
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	36
Water level start filter cloth (mm)	36
Water level stop filter cloth (mm)	36
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	301
pH Algae water average	7,6
Water temperature average (ºC)	14,54
TSS of raw algae (mg/L)	230
Turbidity of raw algae (NTU)	124
Dissolved oxygen average (mg/l)	10,93
Operating Conditions	
Algae flow rate (m^3/h)	0,47
HRT of coagulation (seconds)	49
HRT of flocculator tank (minutes)	12,78

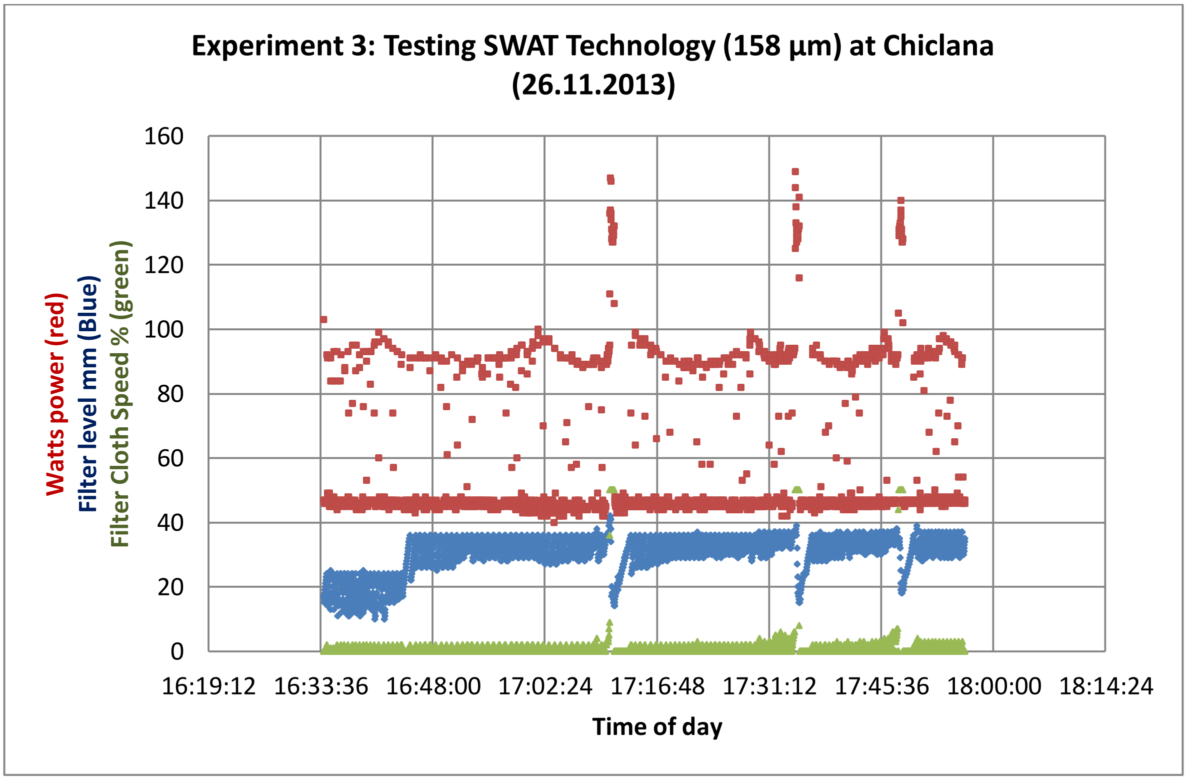

Figure 4.21: Overview results for Experiment 3.

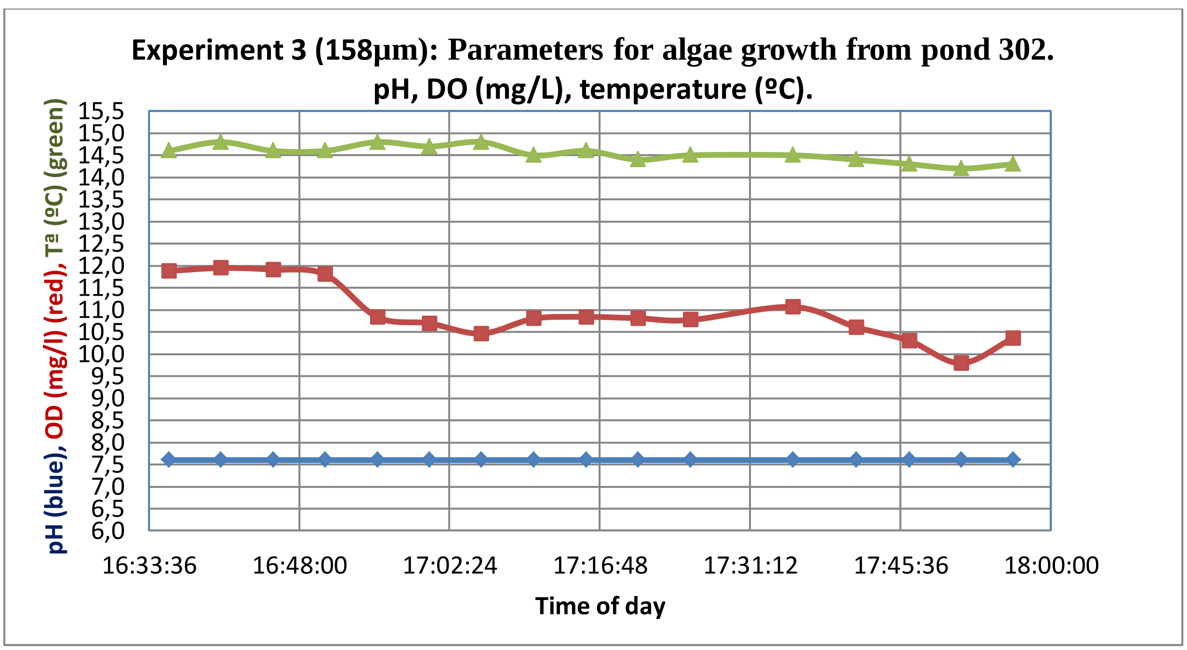

Figure 4.22: Experiment 3: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH kept constant at a 7,6 value.

Water temperature fell in a range between 14,8ºC and 14,2ºC, with an average value of 14,54ºC. In this experiment water temperature did not vary notably due to the hour time when experiment was conducted.

DO concentration fell in a range between 11,9 and 9,8 mg/l, in this case it was noticed that water temperature and DO had a decreasing tendency due to the fact that experiment was conducted after highest solar radiation hours.

4.3.3.2 Water Level Analysis for Experiment 3

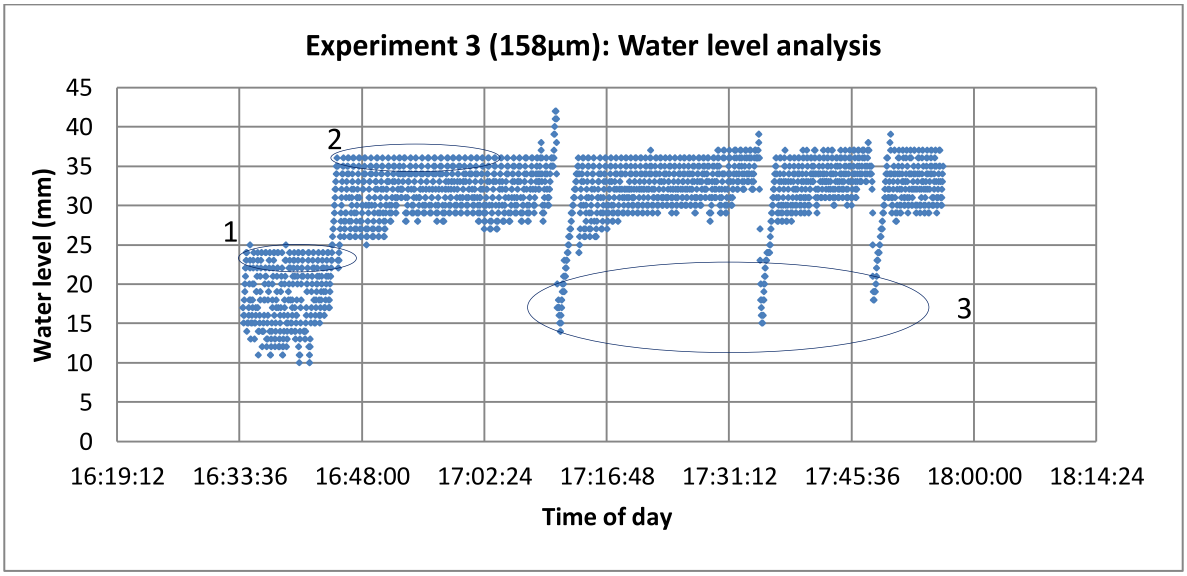

Figure 4.23: Experiment 3: Water level analysis.

1. Water level set point in filter was set at 24 mm.
2. Water level set point in filter was set at 36 mm.
3. As it can be seen on Figure 4.23, the frequency of cleaning procedure is increasing due to the fact that a not completely mesh cleaning could be done.

4.3.3.3 Filter Cloth Speed Analysis for Experiment 3

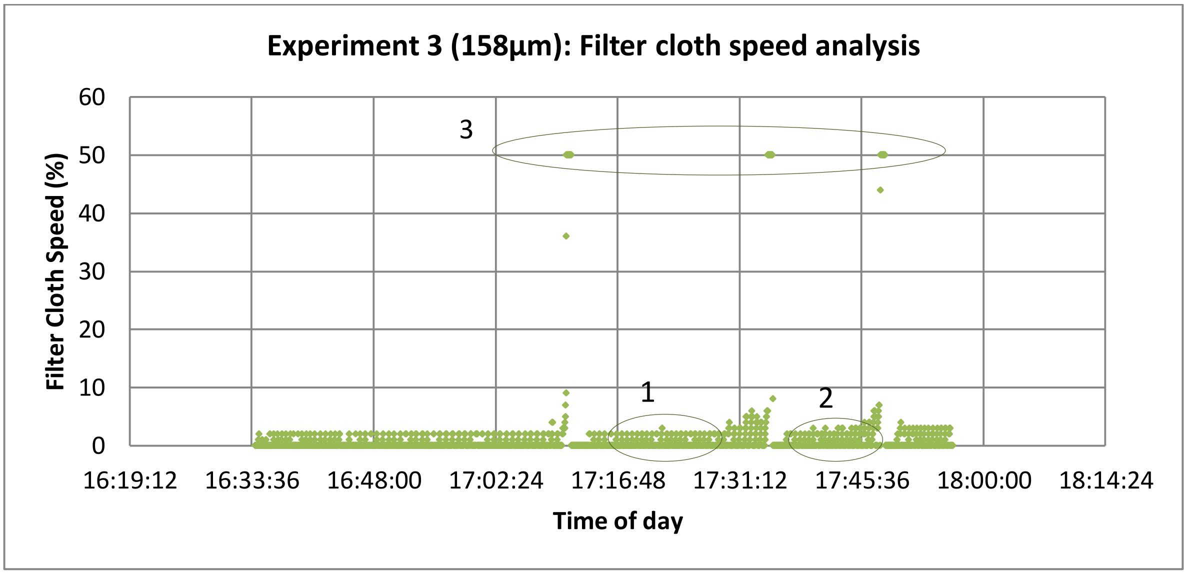

Figure 4.24: Experiment 3: Filter cloth speed analysis.

1. There is and increment on number of point about 1 – 4 % in circle number 2 compare with circle number 1, this is because of the mesh which was not fully cleaned, provoking a more movement on mesh to filter water.
3. Cleaning procedure went on three times during experiment, the first one with a frequency of 24 minutes and then 13 minutes.

4.3.3.4 Power Consumption Analysis for Experiment 3

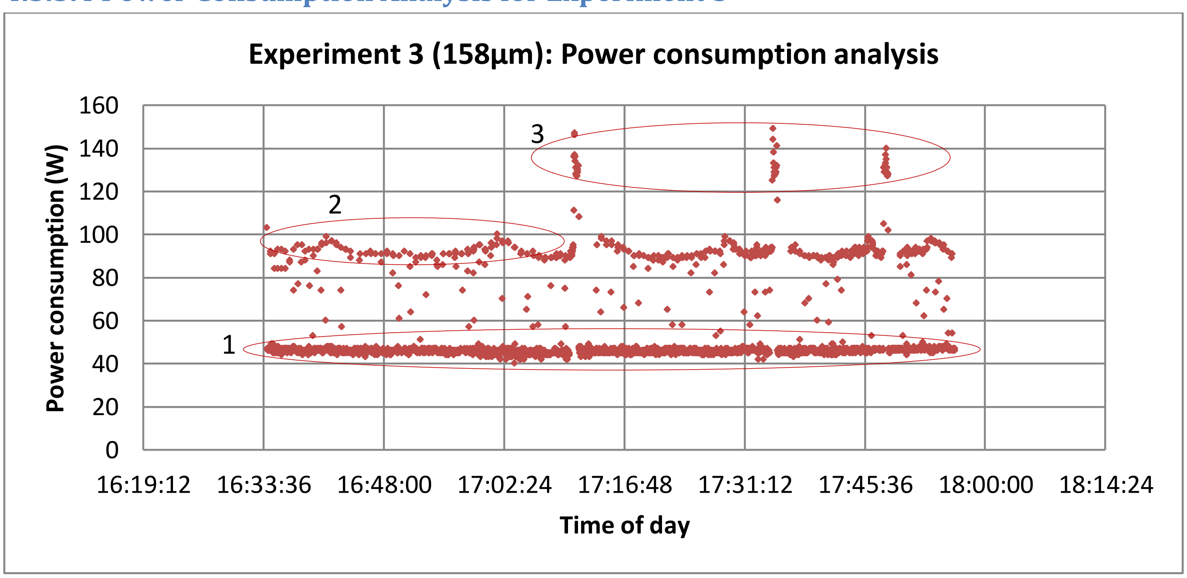

Figure 4.25: Experiment 3: Power consumption analysis.

1. Power consumption when filter cloth is not moving is in a range between 44 – 47 W.

2. Power consumption when filter cloth speed is about 1 – 6% is in a range between 91 – 95 W.
3. Power consumption when filter cloth speed is maximum (50%) is in a range between 146 – 149 W.

4.3.4 Experiment 4 (210 µm)

For this experiment a new pore mesh size was used, 210 µm.

Objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3 were met.

Harvesting efficacy reached was 96,95% TSS removal. TSS value for raw water algae was 255 mg/L and effluent TSS was 7,78 mg/L.

Turbidity of raw algae was 135 NTU and effluent turbidity had a value of 2,61 NTU, using Equation 3.2 a turbidity removal value of 98,07% was obtained.

Total Solids (TS) for this experiment was 58,79 g/Kg.

PAX-18 dose (142 mg/L) was 2,8 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (5,2 mg/L) was twice than theoretical value (2,5 mg/L).

Average power consumption was 59,24 W, considering flow treated during experiment (0,54 m^3/h), power consumption is equal to 0,110 kWh/m^3. In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 26,24 W, doing previous calculations a power consumption of 0,049 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3).

Pictures related to Experiment 4 can be seen on Appendix E.

4.3.4.1 Experimental Conditions for Experiment 4

Table 4.4 Experimental conditions for Experiment 4 using SWAT technology.

Description	Specification
Mesh pore size	210 µm
Experiment time	
Experiment date	2/12/2013
Start Time	11:49:50
End Time	14:30:00
Total Test Time	2 h 40 min 10 seconds
PAX-18 dosage	
PAX-18 dosage (mg/L algae)	142
PAX-18 dosage (mg/g algae)	555
Active material (Al_2O_3) (mg/g algae)	94
Alum (III) (mg/g algae)	50
PAX-18 theoretical dose (mg/L algae)	50

Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae water)	5,2
Chemifloc CM25 dosage (mg/g algae)	20,5
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	45
Water level start filter cloth (mm)	45
Water level stop filter cloth (mm)	45
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	301
pH Algae water average	8,09
Water temperature average (ºC)	11,52
TSS of raw algae (mg/L)	255
Turbidity of raw algae (NTU)	135
Dissolved oxygen average (mg/l)	9,73
Operating Conditions	
Algae flow rate (m^3/h)	0,54
HRT of coagulation (seconds)	43
HRT of flocculator tank (minutes)	11,11

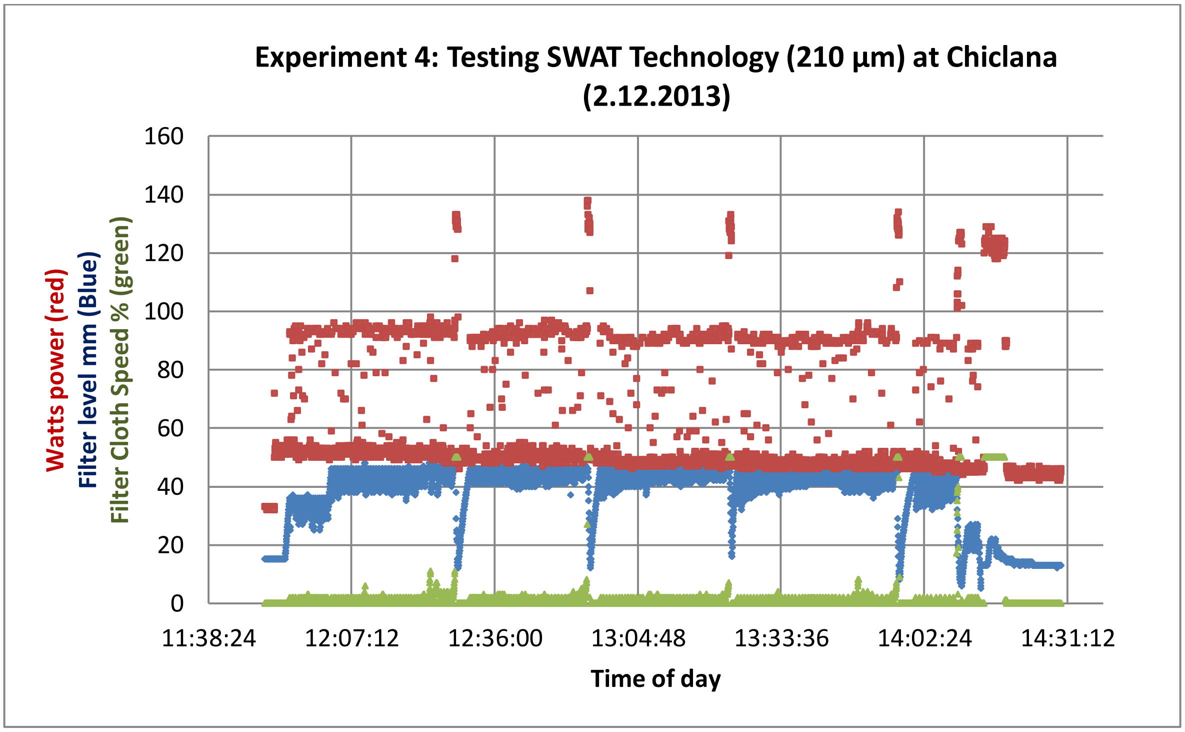

Figure 4.26: Overview results for Experiment 4.

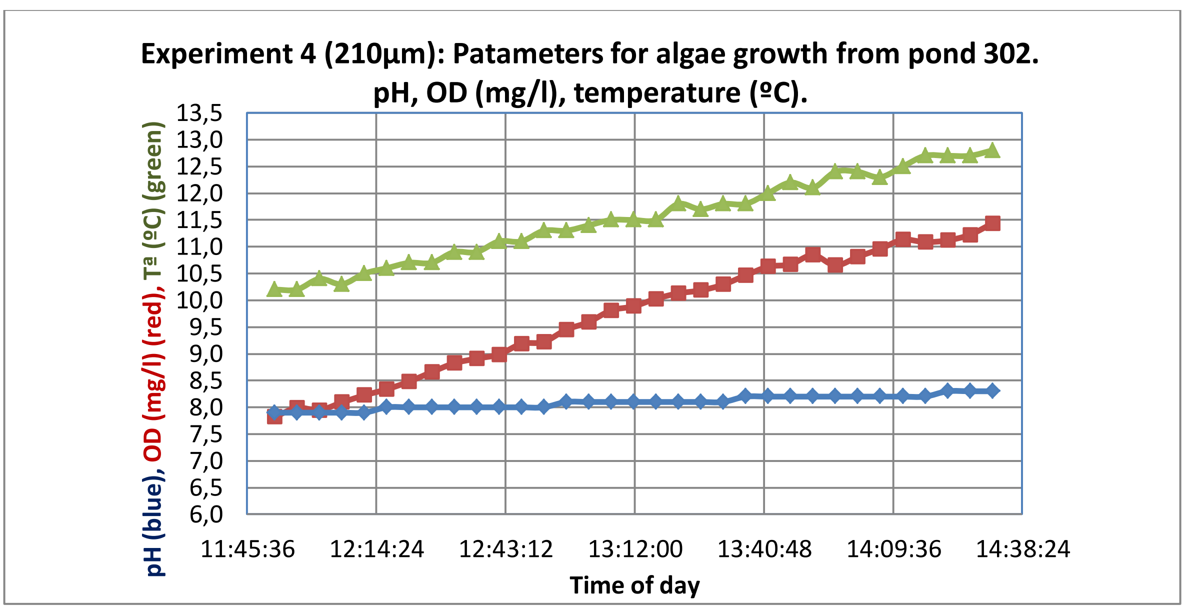

Figure 4.27: Experiment 4: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH varied in a range between 7,9 and 8,3.

Water temperature fell in a range between 10,2ºC and 12,8ºC, with an average value of 11,52ºC.

DO concentration fell in a range between 7,9 and 11,4 mg/L. Looking at Figure 4.27 it is clear to see the correlation between increasing water temperature and increasing DO value, both of them due to solar radiation. DO has a higher increasing rate, 0,656 mg/l per 30 minutes, than water temperature was 0,4875 ºC per 30 minutes.

4.3.4.2 Water Level Analysis for Experiment 4

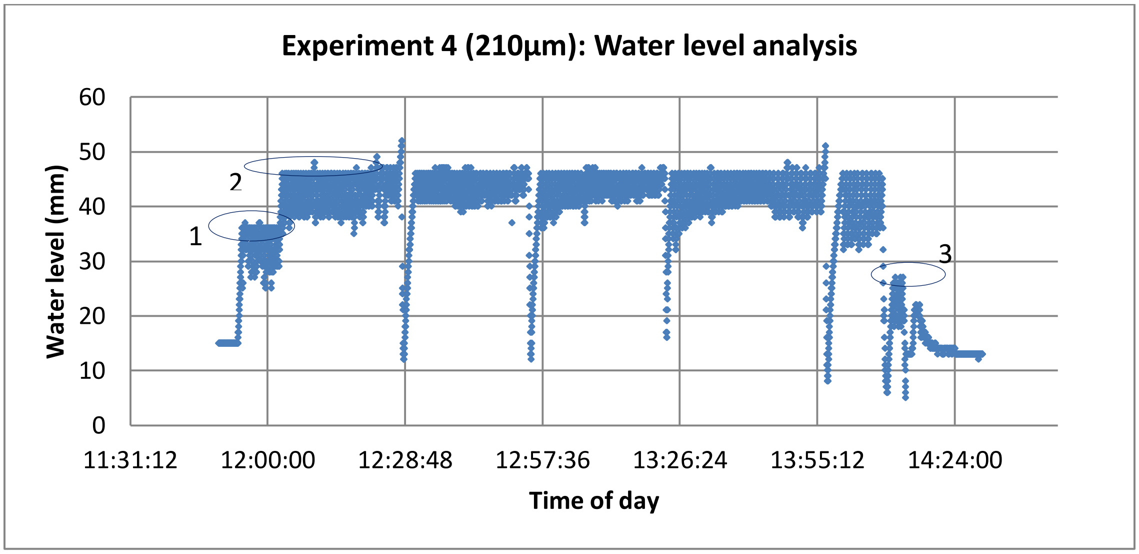

Figure 4.28: Experiment 4: Water level analysis.

1. Water level set point in filter was set at 36 mm at the beginning.
2. During major time of Experiment 3, nivel set point in filter was set at 46 mm.
3. Water level set point in filter was set at 26 mm during 1 minute.

4.3.4.3 Filter Cloth Speed Analysis for Experiment 4

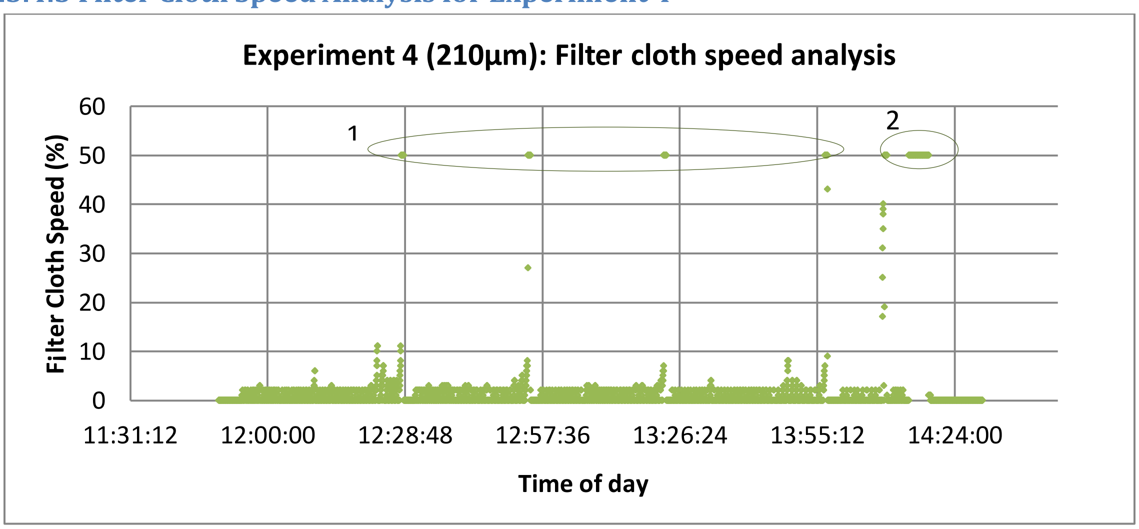

Figure 4.29: Experiment 4: Filter cloth speed analysis.

1. Cleaning procedure went on 4 times so 50% velocity was reached, with a frequency of 29 minutes approximately.
2. At the end of the experiment cleaning procedure was set on manually during two minutes to see if mesh could be cleaned completely, by this effort was unsuccessful.

4.3.4.4 Power Consumption Analysis for Experiment 4

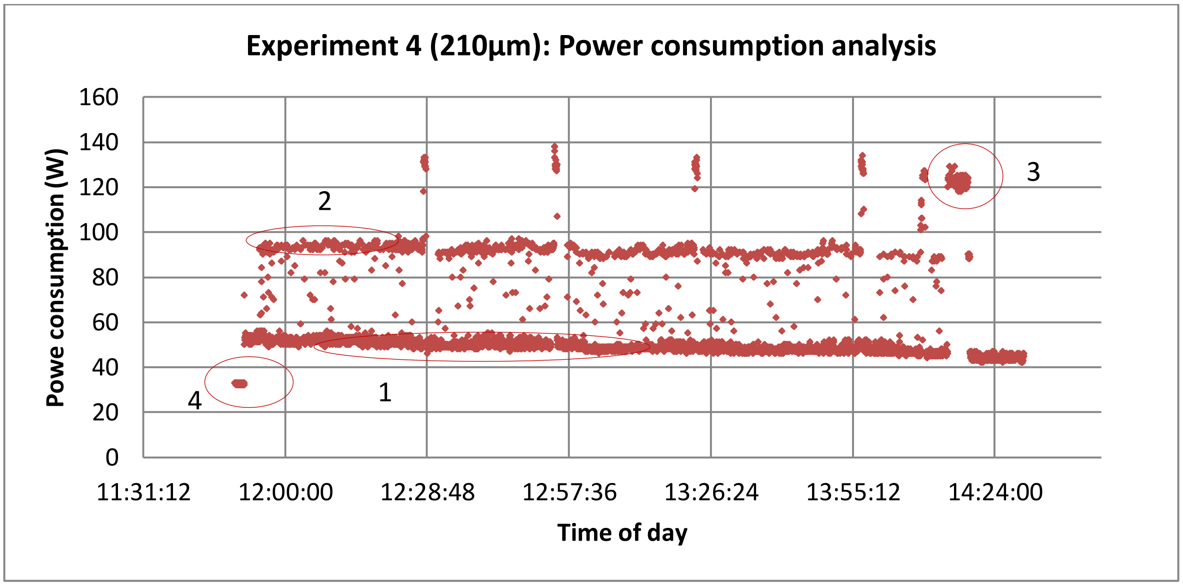

Figure 4.30: Experiment 4: Power consumption analysis.

1. During major time of the experiment, filter cloth was not moving, so power consumption was in a range between 45 – 50 W.
2. When filter cloth speed was moving at 1- 6 %, power consumption was 90 – 95 W.
3. Since cleaning procedure was set on manually during more time than when is on automatically, a representation of 50% filter cloth velocity during relatively long time is draw on Figure 4.30.
4. Those points circled are equivalent to control panel power consumption 33 W.

4.3.5 Experiment 5 (210 µm)

A second experiment with same pore mesh size was used, 210 µm.

Objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3 were met.

Harvesting efficacy reached was 96,88% TSS removal. TSS value for raw water algae was 231,25 mg/L and effluent TSS was 7,21 mg/L.

Turbidity of raw algae was 134 NTU and effluent turbidity had a value of 2,63 NTU, using Equation 3.2 a turbidity removal value of 96,88% was obtained.

Total Solids (TS) for this experiment was 65,32 g/Kg.

PAX-18 dose (114 mg/L) was 2,3 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (4,1 mg/L) was 1,64 times the theoretical value (2,5 mg/L).

Average power consumption was 49,17 W, considering flow treated during experiment (0,54 m^3/h), power consumption is equal to 0,091 kWh/m^3, Equation 3.6. In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 16,17 W, doing previous calculations a power consumption of 0,03 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3).

Pictures related to Experiment 5 can be seen on Appendix F.

4.3.5.1 Experimental Conditions for Experiment 5

Table 4.5 Experimental conditions for Experiment 5 using SWAT technology.

Description	Specification
Mesh pore size	210 µm
Experiment time	
Experiment date	2/12/2013
Start Time	14:46:00
End Time	16:56:30
Total Test Time	2 h 16 min 30 seconds
PAX-18 dosage	
PAX-18 dosage (mg/L algae)	114
PAX-18 dosage (mg/g algae)	494
Active material (Al_2O_3) (mg/g algae)	84
Alum (III) (mg/g algae)	44
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	4,1
Chemifloc CM25 dosage (mg/g algae)	17,8
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	45
Water level start filter cloth (mm)	45
Water level stop filter cloth (mm)	45
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	301

Influent Characteristics	
pH Algae water average	8,36
Water temperature average (ºC)	13,52
TSS of raw algae (mg/L)	231,25
Turbidity of raw algae (NTU)	134
Dissolved oxygen average (mg/l)	11,61
Operating Conditions	
Algae flow rate (m^3/h)	0,54
HRT of coagulation (seconds)	43
HRT of flocculator tank (minutes)	11,11

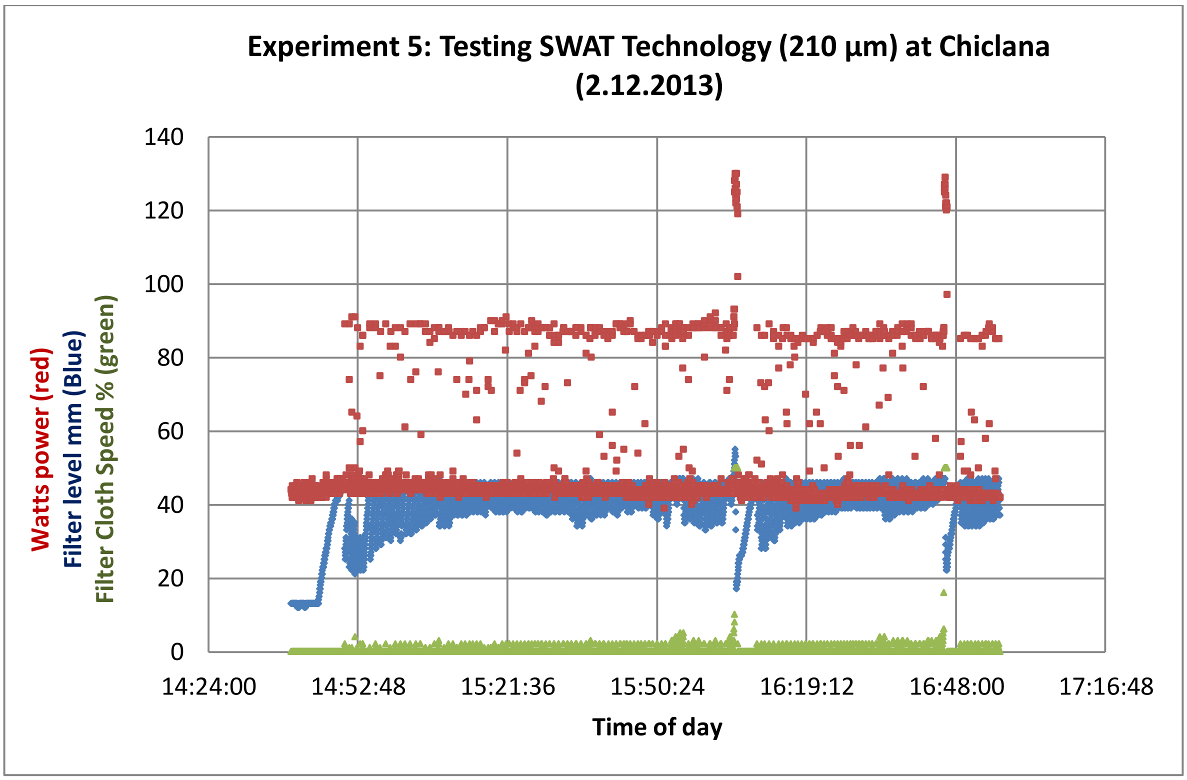

Figure 4.31: Overview results for Experiment 5.

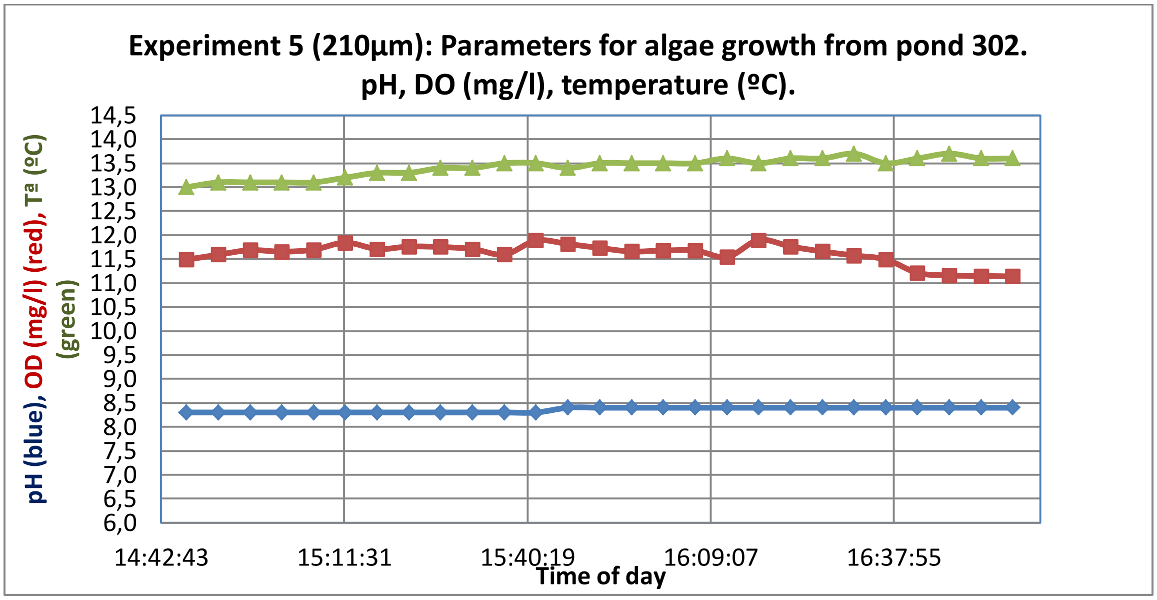

Figure 4.32: Experiment 5: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH moved between two values 8,3 and 8,4.

Water temperature fell in a range between 13,0ºC and 13,7ºC, with an average value of 13,52ºC.

DO concentration fell in a range between 11,9 and 11,1 mg/L. Looking at Figure 4.32 it can be seen that DO and water temperature values does not experiment high variations. Experiment was carried out when solar radiation kept almost constant.

4.3.5.2 Water Level Analysis for Experiment 5

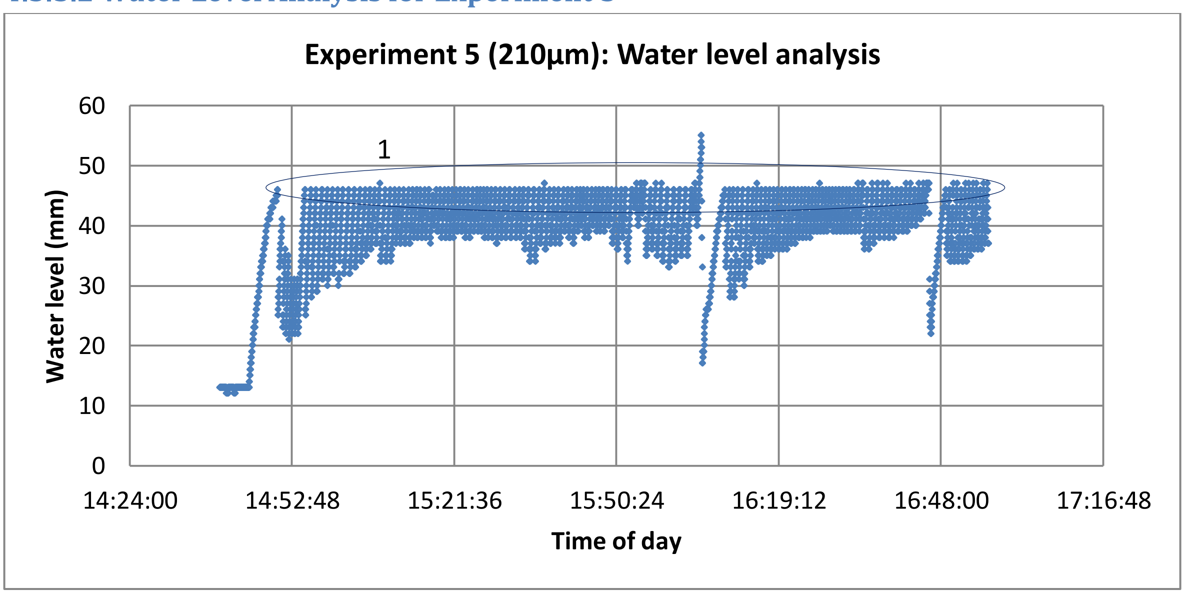

Figure 4.33: Experiment 5: Water level analysis.

1. Water level set point in filter was set at 46 mm.

4.3.5.3 Filter Cloth Speed Analysis for Experiment 5

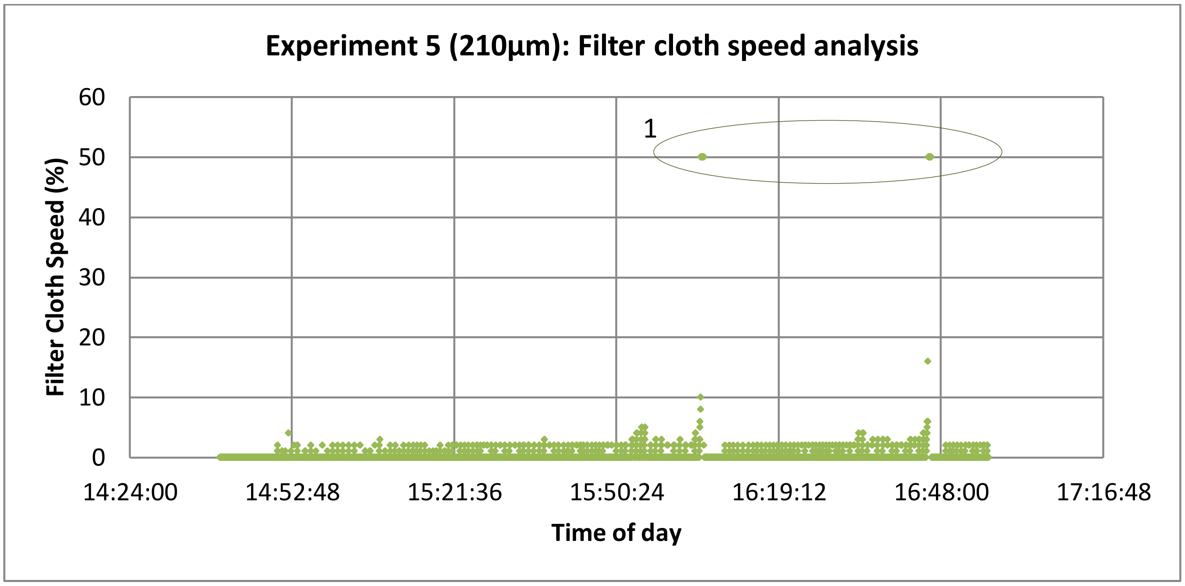

Figure 4.34: Experiment 5: Filter cloth speed analysis.

1. Cleaning procedure went on only twice, and with a frequency of 40 minutes.

4.3.5.4 Power Consumption Analysis for Experiment 5

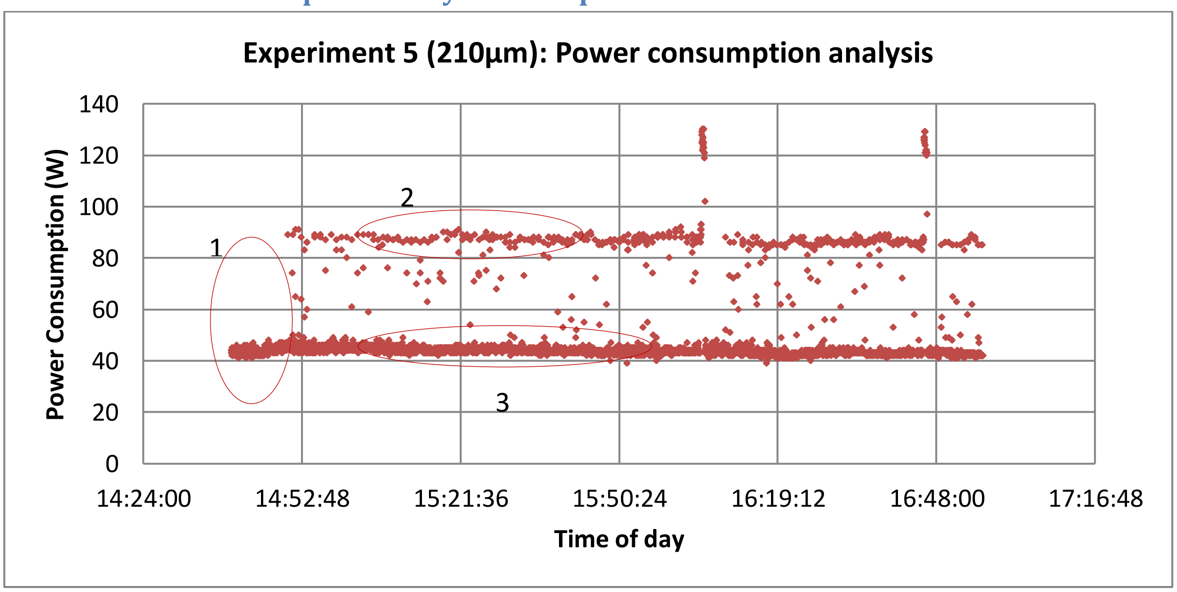

Figure 4.35: Experiment 5: Power consumption analysis.

1. Since a wider mesh pore size is being used, higher filtration capacity the mesh has, so at the beginning could filter water for a long time without moving the filter.
2. When filter cloth speed was moving at 1- 6 %, power consumption was 83 – 88 W.
3. During major time of the experiment, filter cloth was not moving, so power consumption was in a range between 43 – 48 W.

4.3.6 Experiment 6 (250 µm)

During this experiment pore mesh size used was 250 µm.

Objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3 were met.

Harvesting efficacy reached was 95,85% TSS removal. TSS value for raw water algae was 259,09 mg/L and effluent TSS was 10,75 mg/L.

Turbidity of raw algae was 128 NTU and effluent turbidity had a value of 2,54 NTU, using Equation 3.2 a turbidity removal value of 98,02% was obtained.

Total Solids (TS) for this experiment was 62,91 g/Kg.

PAX-18 dose (114 mg/L) was 2,3 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (4,1 mg/L) was 1,64 times the theoretical value (2,5 mg/L).

Average power consumption was 61,28 W, considering flow treated during experiment (0,54 m^3/h), power consumption is equal to 0,113 kWh/m^3 (using Equation 3.6) . In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 28,28 W, doing previous calculations a power consumption of 0,052 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3).

Pictures related to Experiment 6 can be seen on Appendix G.

4.3.6.1 Experimental Conditions for Experiment 6

Table 4.6 Experimental conditions for Experiment 6 using SWAT technology.

Description	Specification
Mesh pore size	250 µm
Experiment time	
Experiment date	2/12/2013
Start Time	10:41:22
End Time	12:41:32
Total Test Time	2 h 10 seconds
PAX-18 dosage	
PAX-18 dosage (mg/L algae)	114
PAX-18 dosage (mg/g algae)	441
Active material (Al_2O_3) (mg/g algae)	75
Alum (III) (mg/g algae)	40
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	4,1
Chemifloc CM25 dosage (mg/g algae)	17,8
Chemifloc CM25 theoretical dose (mg/L algae)	2,5

Control panel settings	
Water level set point in filter (mm)	45
Water level start filter cloth (mm)	45
Water level stop filter cloth (mm)	45
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	301
pH Algae water average	7,86
Water temperature average (ºC)	11,83
TSS of raw algae (mg/L)	259,09
Turbidity of raw algae (NTU)	128
Dissolved oxygen average (mg/l)	7,82
Operating Conditions	
Algae flow rate (m^3/h)	0,54
HRT of coagulation (seconds)	43
HRT of flocculator tank (minutes)	11,11

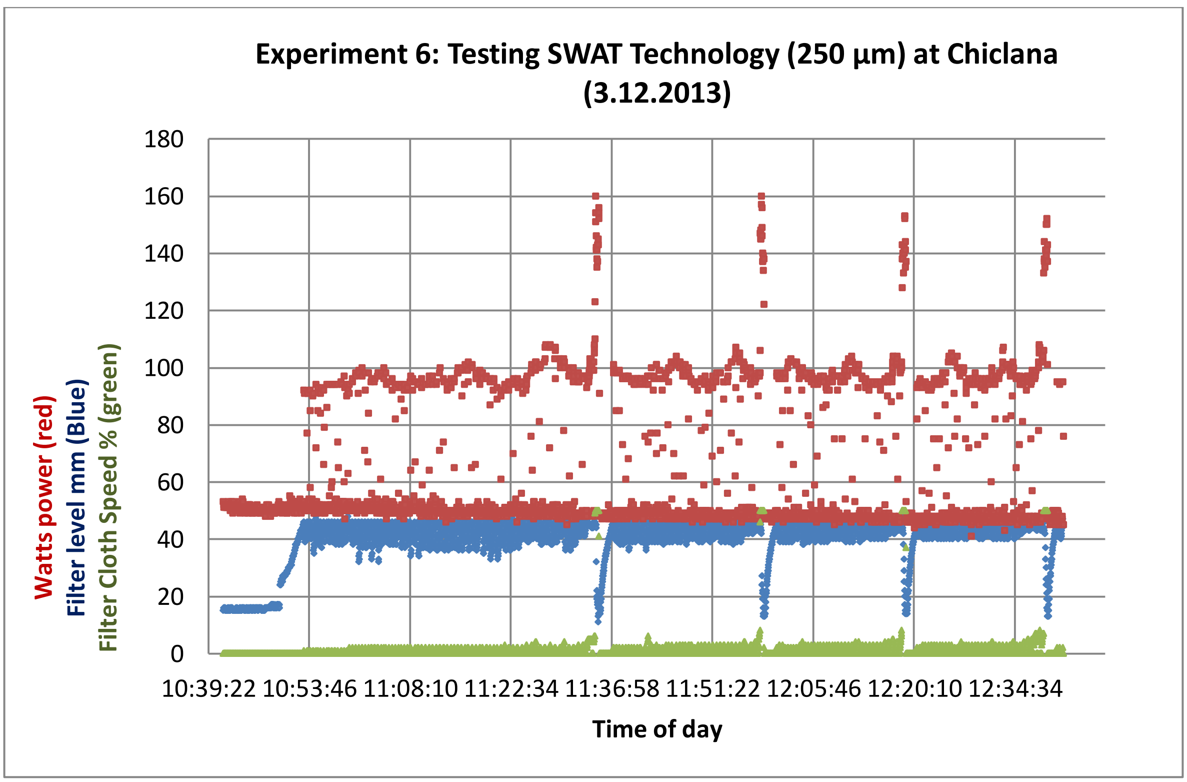

Figure 4.36: Overview results for Experiment 6.

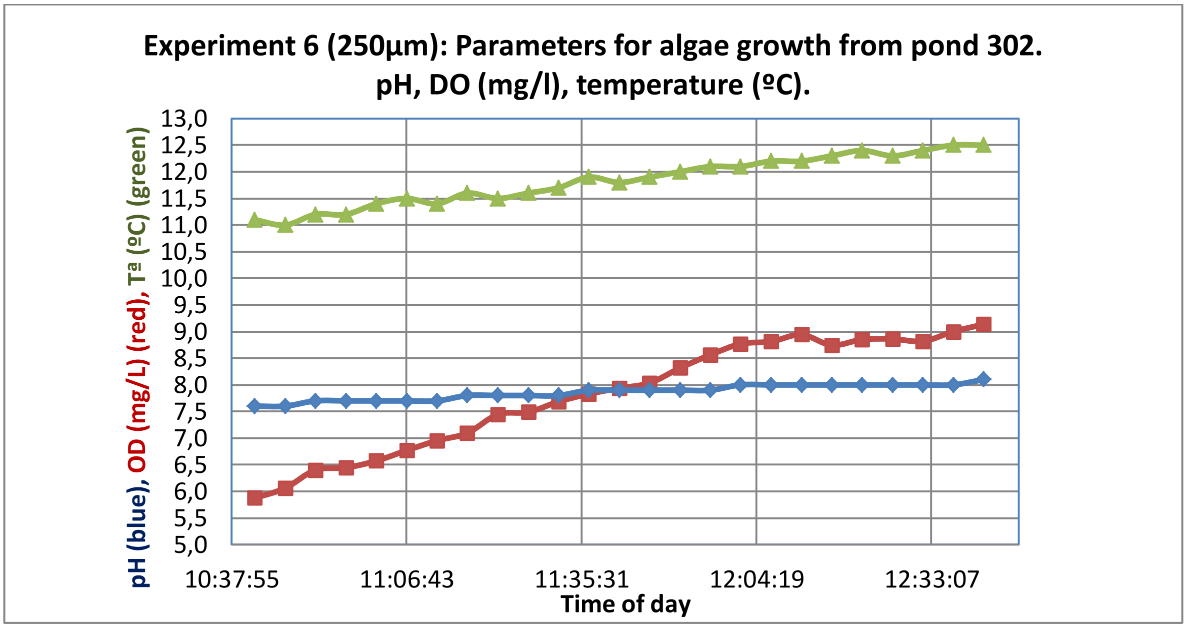

Figure 4.37: Experiment 6: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH moved between two values 7,6 and 8,1.

Water temperature fell in a range between 11,0ºC and 12,4ºC, with an average value of 13,52ºC.

DO concentration fell in a range between 5,9 and 9,1 mg/L. DO increases with a rate of 1mg/L per 30 minutes, which is 50% higher than in experiment number 4, considering a constant TSS, is due to experiment time.

4.3.6.2 Water Level Analysis for Experiment 6

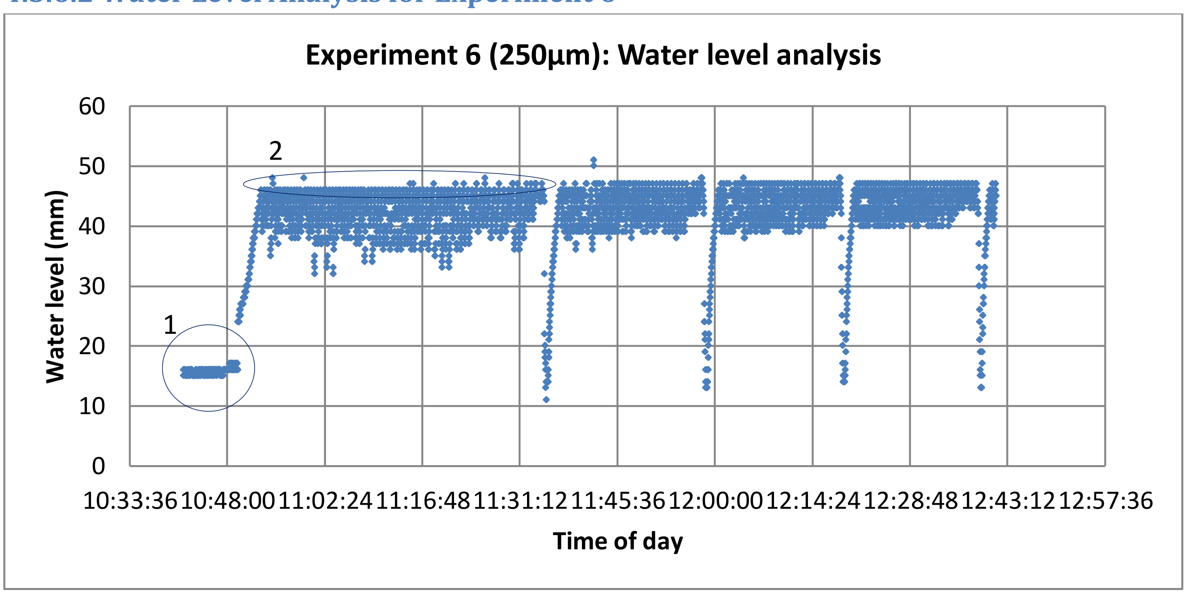

Figure 4.38: Experiment 6: Water level analysis.

1. Using this 250 µm, there is a high filtration capacity at the beginning, when mesh is completely clean. So water level does not increase.
2. Water level set point in filter was set at 46 mm.

4.3.6.3 Filter Cloth Speed Analysis for Experiment 6

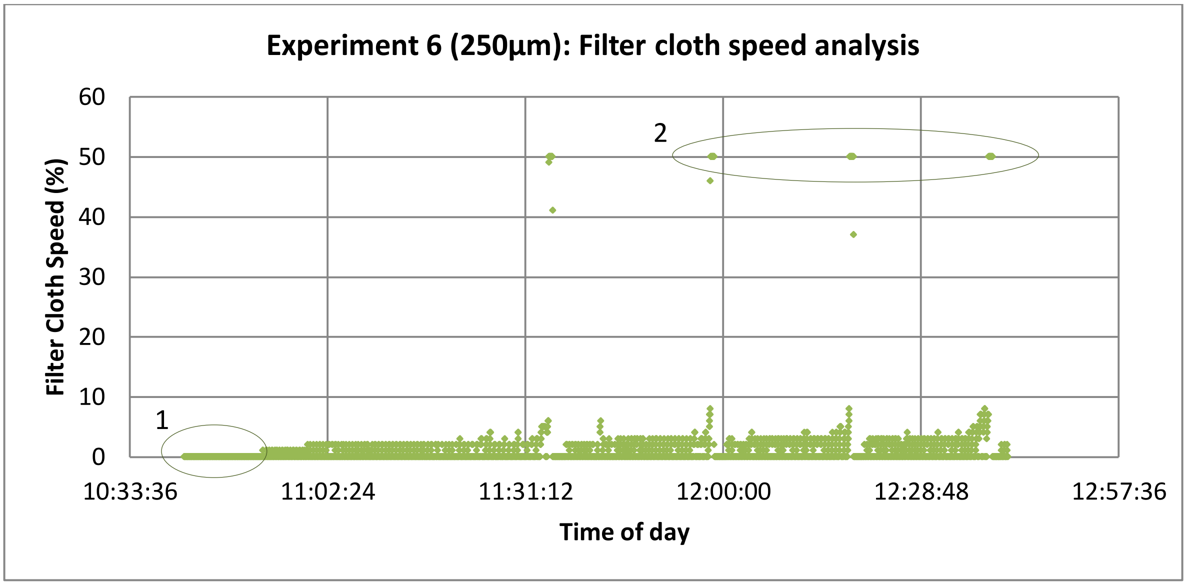

Figure 4.39: Experiment 6: Filter cloth speed analysis.

1. Filter cloth was not moving at all during the time that mesh was filtering at the beginning.
2. Cleaning procedure frequency was 20 minutes.

4.3.6.4 Power Consumption Analysis for Experiment 6

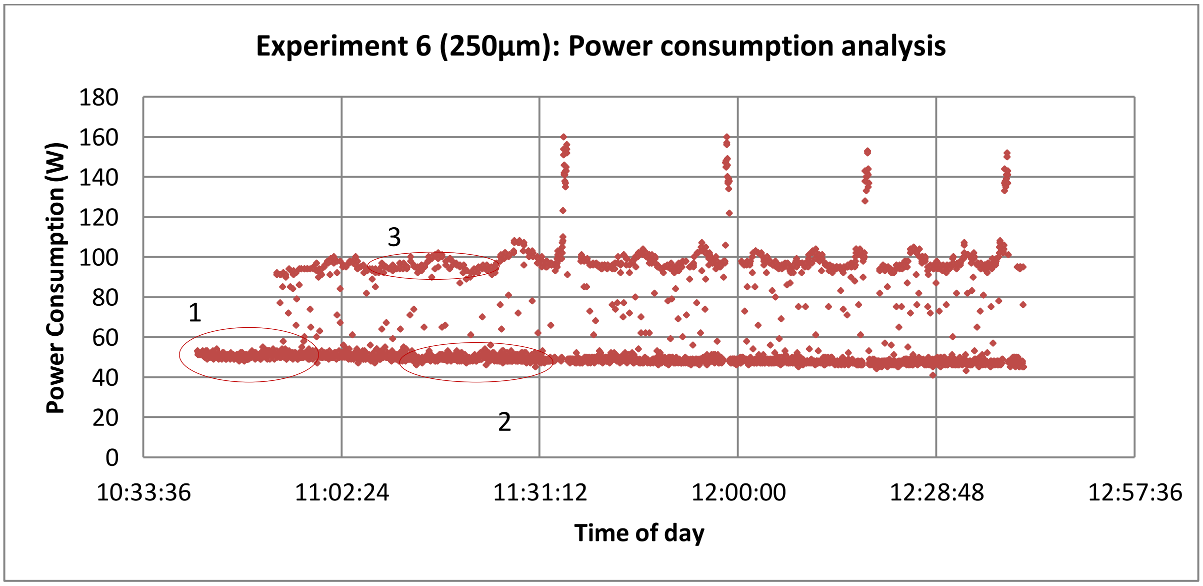

Figure 4.40: Experiment 6: Power consumption analysis.

1. During the time filter mesh is filtering water without moving power consumption is minimum approximately 50 W.
2. That power consumption is the same as Circle 2, which represent power consumption when filter is not moving.
3. When filter is moving in a range 1 – 6 %, power consumption is in the range of 95-99 W.

4.3.7 Experiment 7 (250 µm)

The same pore mesh size was used 250 µm.

Objectives of 95% algae removal and lower power consumption than 0,08 kWh/m^3 were met.

Harvesting efficacy reached was 96,74% TSS removal. TSS value for raw water algae was 282 mg/L and effluent TSS was 9,2 mg/L.

Turbidity of raw algae was 169 NTU and effluent turbidity had a value of 3,12 NTU, using Equation 3.2 a turbidity removal value of 98,16% was obtained.

Total Solids (TS) for this experiment was 50,46 g/Kg.

PAX-18 dose (114 mg/L) was 2,3 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (4,1 mg/L) was 1,64 times the theoretical value (2,5 mg/L).

Average power consumption was 54,23 W, considering flow treated during experiment (0,54 m^3/h), power consumption is equal to 0,100 kWh/m^3 (using Equation 3.6). In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 21,23 W, doing previous calculations a power consumption of 0,039 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3).

Pictures related to Experiment 7 can be seen on Appendix G.

4.3.7.1 Experimental Conditions for Experiment 7

Table 4.7 Experimental conditions for Experiment 7 using SWAT technology.

Description	Specification
Mesh pore size	250 µm
Experiment time	
Experiment date	4/12/2013
Start Time	11:31:00
End Time	16:59:30
Total Test Time	5 h 28 min 30 seconds
PAX-18 dosage	
PAX-18 dosage (mg/L algae)	114
PAX-18 dosage (mg/g algae)	405
Active material (Al_2O_3) (mg/g algae)	69

PAX-18 dosage	
Alum (III) (mg/g algae)	36
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	4,1
Chemifloc CM25 dosage (mg/g algae)	14,2
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	45
Water level start filter cloth (mm)	45
Water level stop filter cloth (mm)	45
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	302
pH Algae water average	7,96
Water temperature average (ºC)	14,61
TSS of raw algae (mg/L)	282
Turbidity of raw algae (NTU)	169,5
Dissolved oxygen average (mg/l)	13,15
Operating Conditions	
Algae flow rate (m^3/h)	0,54
HRT of coagulation (seconds)	43
HRT of flocculator tank (minutes)	11,11

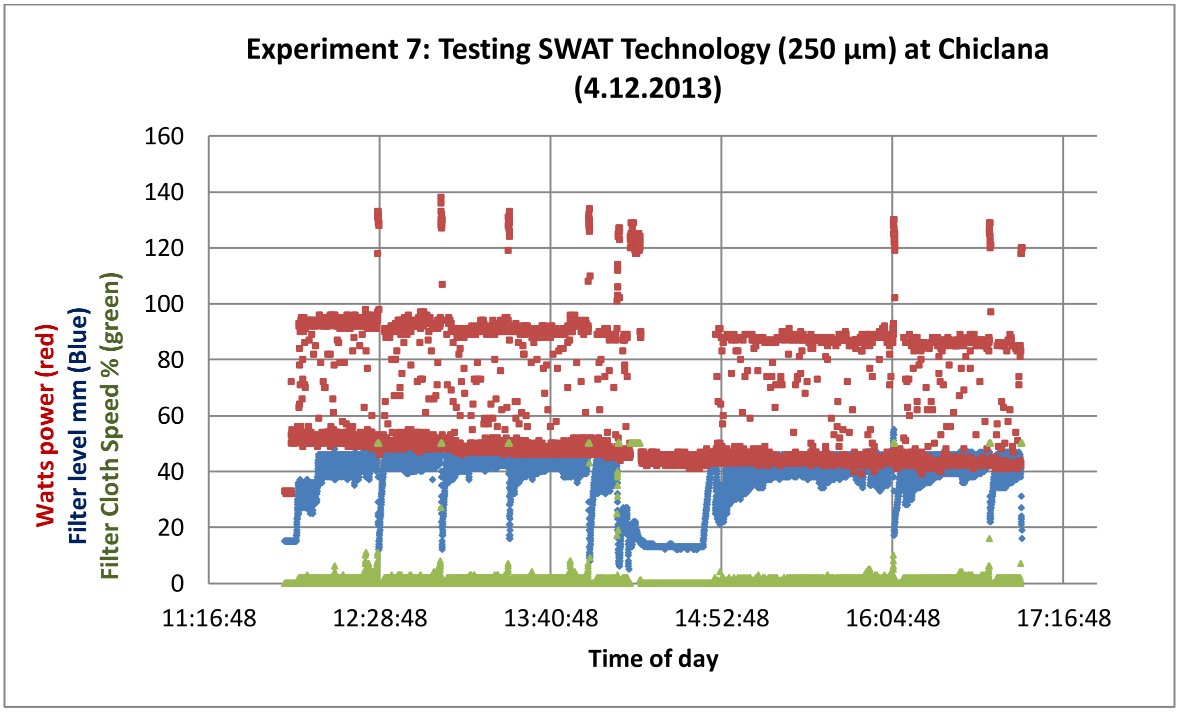

Figure 4.41: Overview results for Experiment 7.

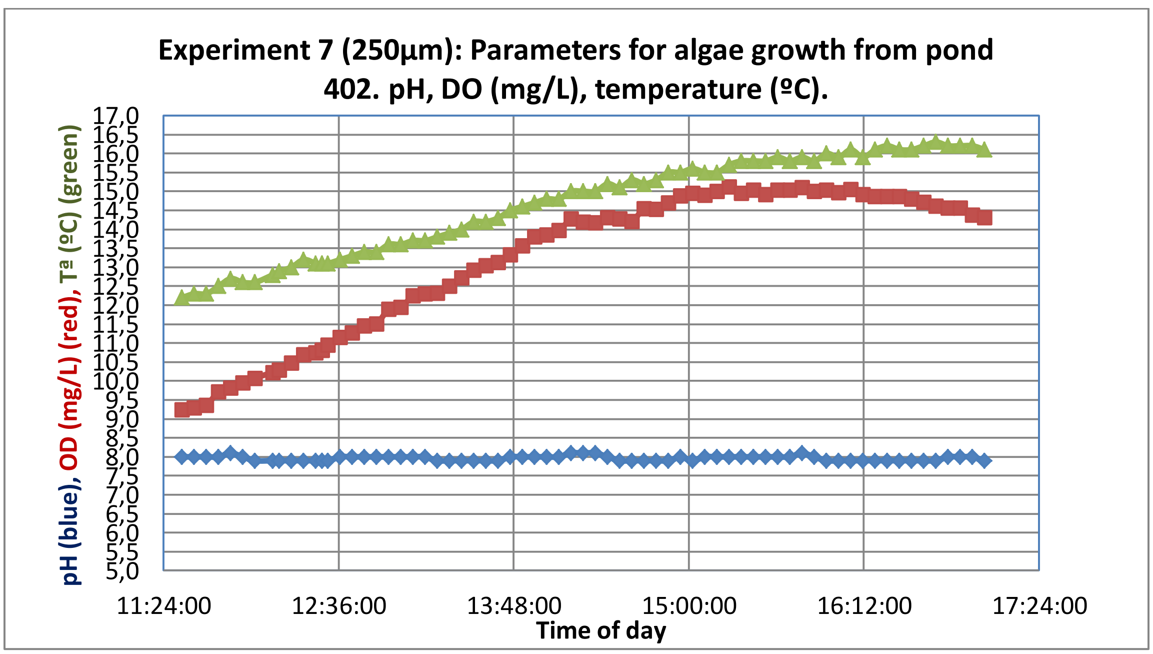

Figure 4.42: Experiment 7: Parameters for algae growth from pond 302 (pH, temperature and DO).

During this experiment pH average value was 8.

Water temperature fell in a range between 12,2ºC and 16,3ºC, with an average value of 14,61ºC.

DO concentration fell in a range between 9,2 and 15,5 mg/L. What makes different this experiment from previous one, is the total test time, which is 5 hours and 28 minutes, this makes possible to analyze DO concentration values from a wider point of view. On Figure 4.42 it can be seen how DO increases at a high rate from the time when experiment starts 11:31:00 until DO reaches a maximum value, then DO keeps nearly constant at that maximum value, and then DO starts to decrease.

If increasing DO rate (0,95 mg/L) during this experiment is 45% higher than increasing DO rate at Experiment 4 (0,656 mg/L), this is provoked by the higher TSS concentration at Experiment 7 (282 mg/l) and 255 mg/L for TSS at Experiment 4. This TSS difference is due to the fact that algae was taken from a different algae pond (nº 402) which had higher algae concentration than pond number 302.

4.3.7.2 Water Level Analysis for Experiment 7

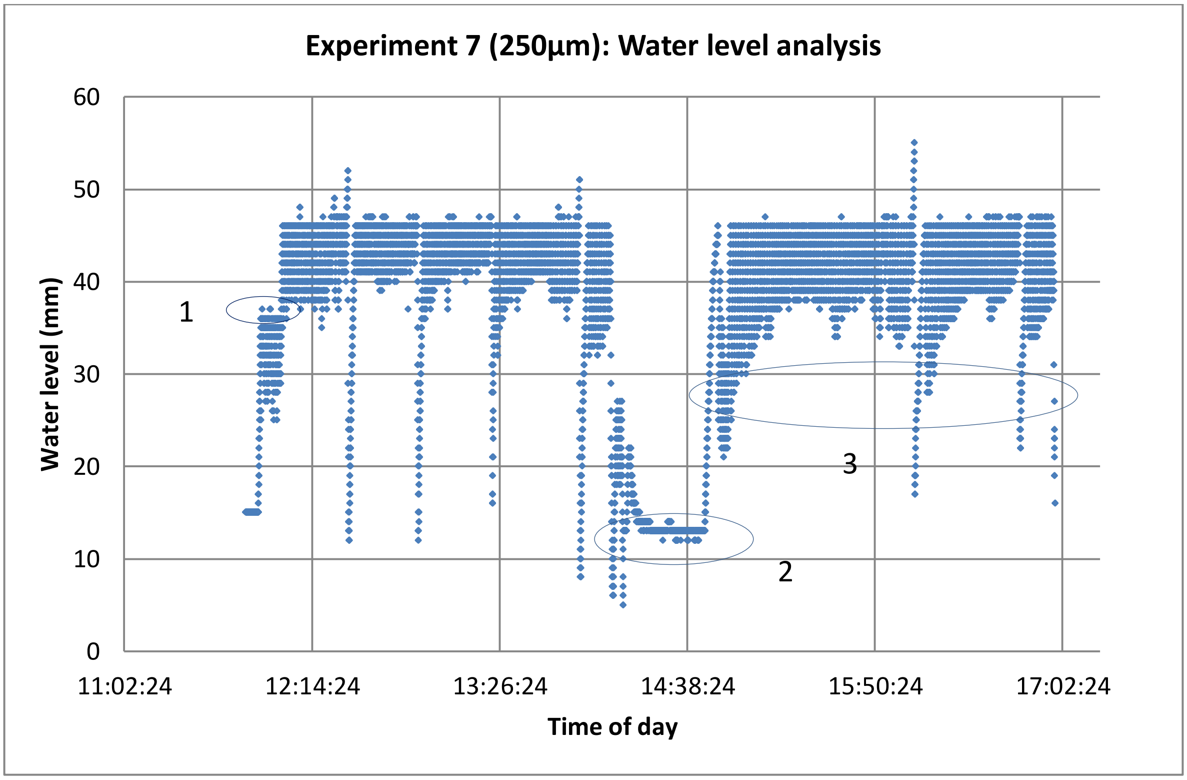

Figure 4.43: Experiment 7: Water level analysis.

1. Filter water level set point was set at 36 mm at the beginning.
2. During experiment mid-time cleaning procedure was manually set on for 5 minutes, and a manual cleaning of mesh was carried out, for that reason filter showed a high filtration capacity, therefore water level kept on minimum for 20 minutes.
3. After a complete cleaning of mesh, cleaning procedure didn't need to start until a long time past. After that, cleaning procedure was more frequent.

4.3.7.3 Filter Cloth Speed Analysis for Experiment 7

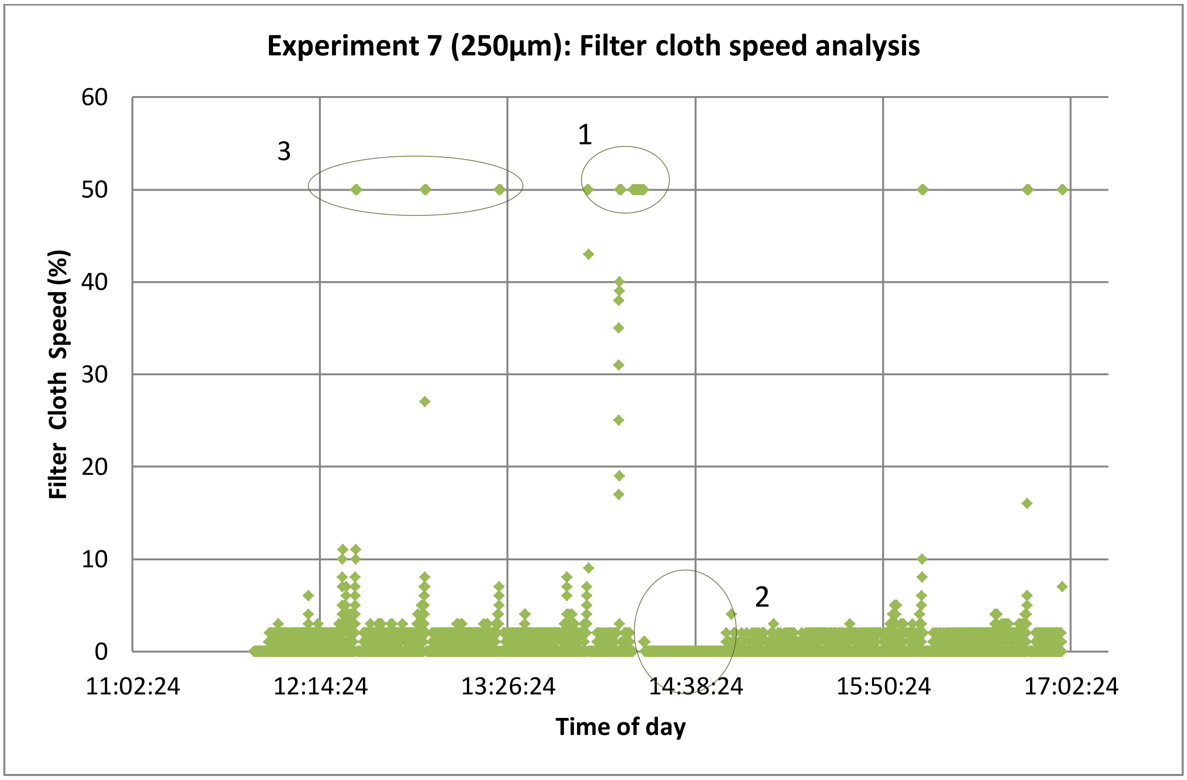

Figure 4.44: Experiment 7: Filter cloth speed analysis.

1. Circle one shows the time that cleaning procedure (water wash) was on, approximately 5 minutes.
2. After a complete cleaning of mesh, there was no need of moving the mesh because of the high filtration capacity.
3. Cleaning procedure frequency was 27 minutes approximately.

4.3.7.4 Power Consumption Analysis for Experiment 7

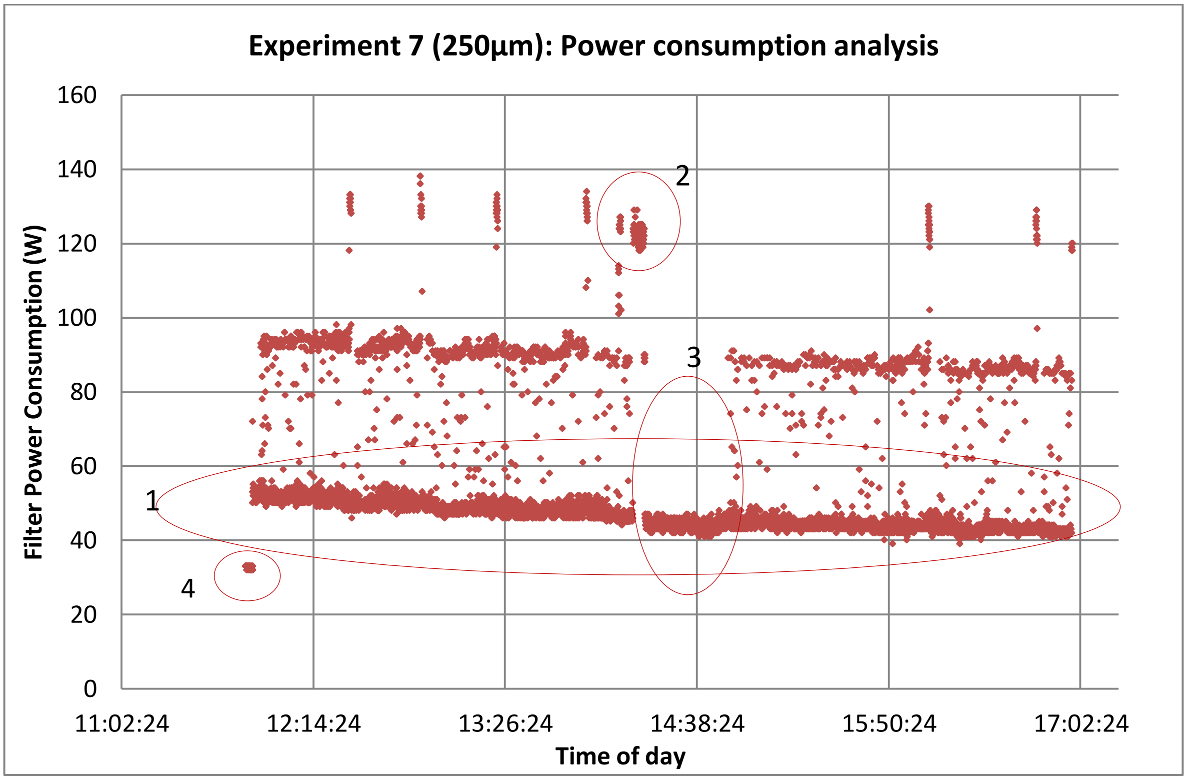

Figure 4.45: Experiment 7: Power consumption analysis.

1. Power consumption when filter cloth is not moving shows a tendency to decrease during time experiment, this can be due to control panel sensitivity.
2. Power consumption was in a range of 120 – 130 W during the 5 minutes cleaning procedure was on.
3. After that, there was a period of time when minimum power consumption was made.

4.3.8 Experiment 8 (350 µm)

The widest pore mesh size was used for this last experiment, 350 µm .

Objectives of 95% algae removal was not achieved however lower power consumption than 0,08 kWh/m^3 was met.

Harvesting efficacy reached was 93,36% TSS removal. TSS value for raw water algae was 266 mg/L and effluent TSS was 17,67 mg/L.

Turbidity of raw algae was 171 NTU and effluent turbidity had a value of 3,43 NTU, using Equation 3.2 a turbidity removal value of 97,99% was obtained.

Total Solids (TS) for this experiment was 54,92 g/Kg.

PAX-18 dose (114 mg/L) was 2,3 times higher than theoretical value (50 mg/L), and Chemifloc CM25 dose (4,1 mg/L) was 1,64 times the theoretical value (2,5 mg/L).

Average power consumption was 50,25 W, considering flow treated during experiment (0,54 m^3/h), power consumption is equal to 0,093 kWh/m^3 (using Equation 3.6) . In addition considering that control panel has a power consumption of 33 W by itself, the net power consumption is 17,25 W, doing previous calculations a power consumption of 0,032 kWh/m^3 is resulted, a lower value than objective established (0,08 kWh/m^3). Pictures related to Experiment 8 can be seen on Appendix H.

4.3.8.1 Experimental Conditions for Experiment 8

Table 4.8 Experimental conditions for Experiment 8 using SWAT technology.

Description	Specification
Mesh pore size	350 µm
Experiment time	
Experiment date	3/12/2013
Start Time	15:47:56
End Time	17:38:50
Total Test Time	1 h 50 min 54 seconds
PAX-18 dosage	
PAX-18 setting (mg/L algae)	114
PAX-18 dosage (mg/g algae)	429
Active material (Al_2O_3) (mg/g algae)	73
Alum (III) (mg/g algae)	39
PAX-18 theoretical dose (mg/L algae)	50
Chemifloc CM25 dosage	
Stock solution Chemifloc CM25 concentration (g/L)	1
Chemifloc CM25 dosage (mg/L algae)	4,1
Chemifloc CM25 dosage (mg/g algae)	15
Chemifloc CM25 theoretical dose (mg/L algae)	2,5
Control panel settings	
Water level set point in filter (mm)	45
Water level start filter cloth (mm)	45
Water level stop filter cloth (mm)	45
Cleaning procedure parameters	
Belt speed threshold to begin cleaning (%)	6
Belt speed during cleaning (%)	50
Rotations of cloth to be cleaned	1
Cloth travel time per revolution at 50% (s)	34
Influent Characteristics	
Weather conditions (sunny, cloudy, rainy)	Sunny
Pond number	303
pH Algae water average	8,60
Water temperature average (ºC)	14,62

Influent Characteristics	
TSS of raw algae (mg/L)	266
Turbidity of raw algae (NTU)	171
Dissolved oxygen average (mg/l)	16,03
Operating Conditions	
Algae flow rate (m^3/h)	0,54
HRT of coagulation (seconds)	43
HRT of flocculator tank (minutes)	11,11

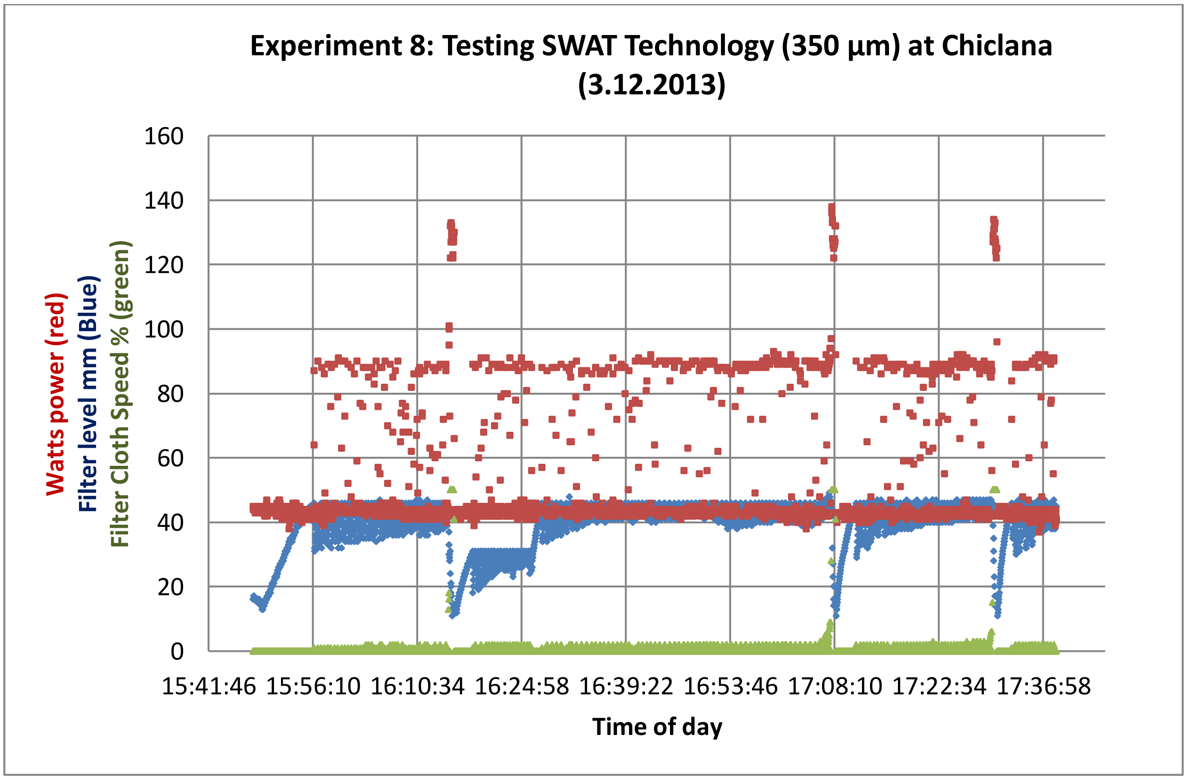

Figure 4.46: Overview results for Experiment 8.

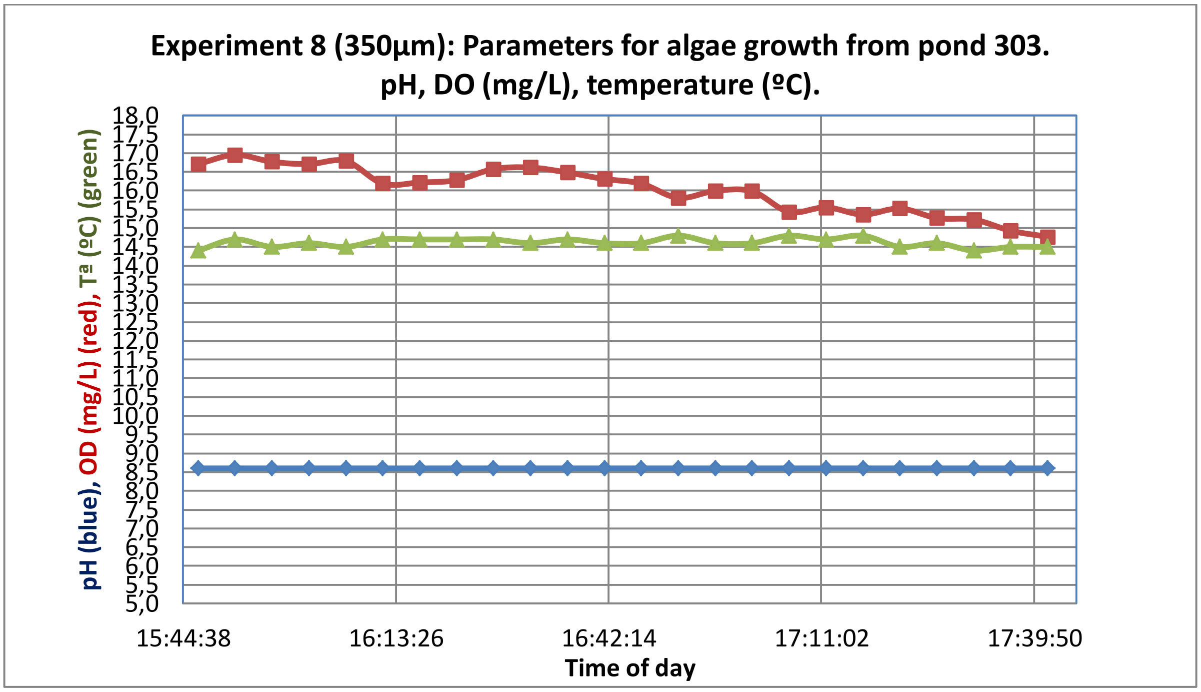

Figure 4.47: Experiment 8: Parameters for algae growth from pond 303 (pH, temperature and DO).

During this experiment pH kept constant at a 8,6 value. Water temperature fell in a range between 14,8ºC and 14,4ºC, with an average value of 14,62ºC. DO concentration fell in a range between 14,8 and 16,8 mg/L, in this case it was noticed that water temperature and DO had a decreasing tendency due to the fact that experiment was conducted after highest solar radiation hours.

4.3.8.2 Water Level Analysis for Experiment 8

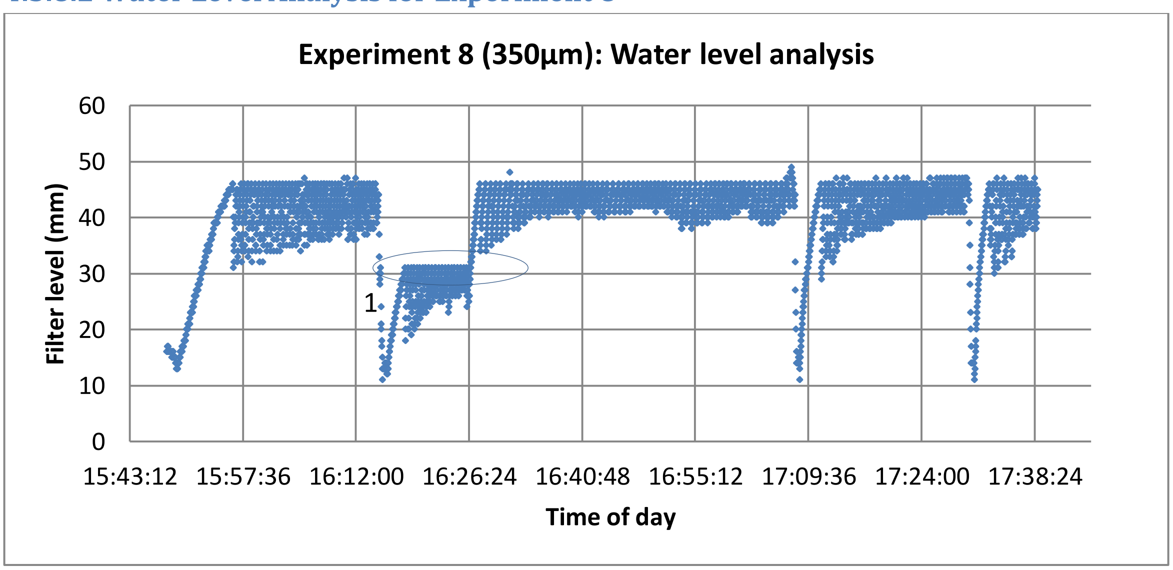

Figure 4.48: Experiment 8: Water level analysis.

1. For seven minutes water level filter set point was set at 31 mm.

4.3.8.3 Filter Cloth Speed Analysis for Experiment 8

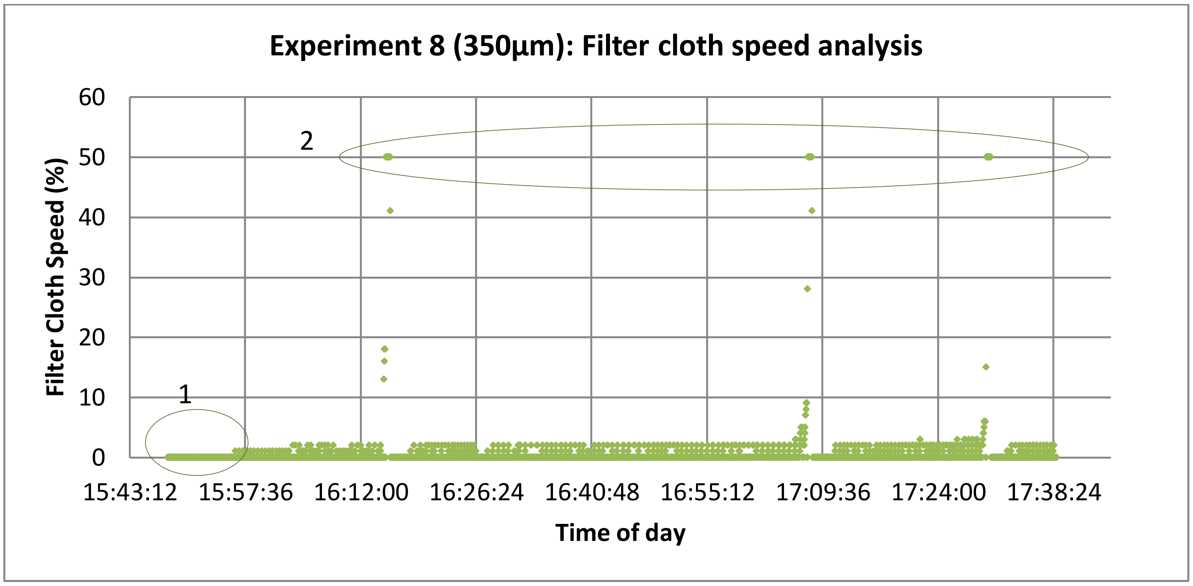

Figure 4.49: Experiment 8: Filter cloth speed analysis.

1. In this experiment the widest mesh pore size was used (350 µm), this means that highest hydraulic capacity was achieved, so there was no need of moving the filter for long time.
2. In this Circle 2 is noticed that more time past, the frequent are cleaning procedure, the first one was after 53 minutes and second one after 23 minutes.

4.3.8.4 Power Consumption Analysis for Experiment 8

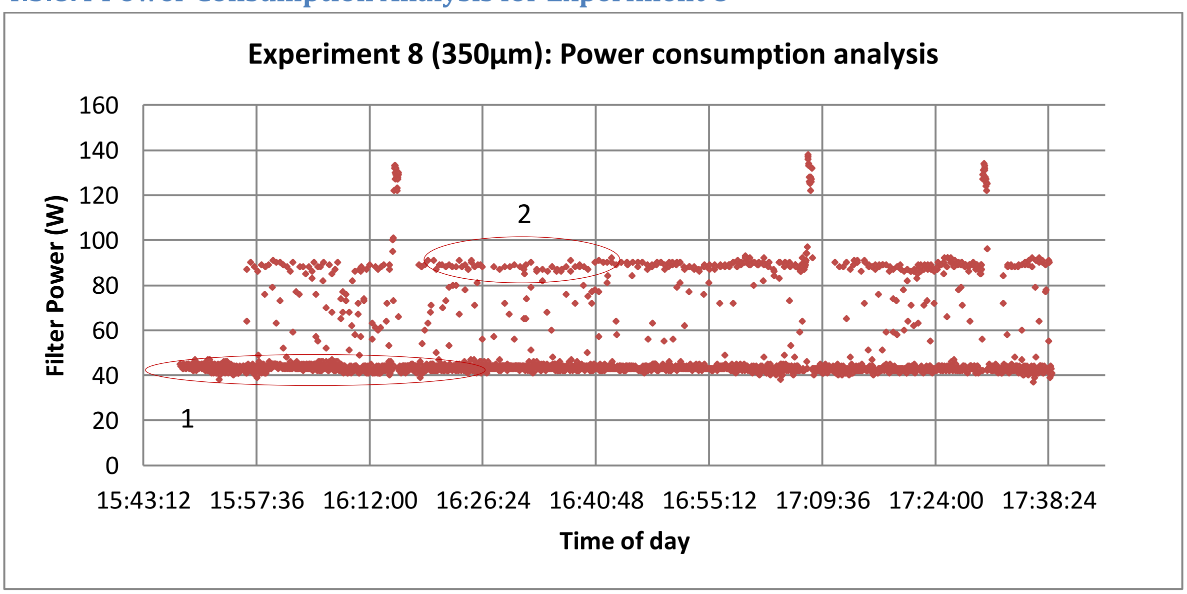

Figure 4.50: Experiment 8: Power consumption analysis.

1. Power consumption when filter is not moving is in the range of 42-45 W.
2. Power consumption when filter cloth speed is 1 – 6% is in the range of 87- 90 W.

4.4 Experiments Results Overview

Table 4.9: Experiment results overview.

Specification	**Experiment number**							
	1	2	3	4	5	6	7	8
Mesh pore size (µm)	90	158	158	210	210	250	250	350
TSS removal (%)	96,95	95,15	97,03	96,95	96,88	95,85	96,74	93,36
Turbidity removal (%)	97,82	97,94	98,10	98,07	96,88	98,02	98,16	97,99
TS (g/Kg)	27,52	56,01	56,21	58,79	65,32	62,91	50,46	54,92
Flow (m^3/h)	0,51	0,36	0,47	0,54	0,54	0,54	0,54	0,54
Average Power Consumption without control panel (W)	37,58	20,87	22,84	26,24	16,17	28,28	21,23	17,25
Average Power Consumption without Control Panel (kWh/m^3)	0,074	0,058	0,049	0,049	0,030	0,052	0,039	0,032
PAX-18 dose (mg/g algae)	718	893	959	555	494	441	405	429
PAX-18 dose (mg/L algae)	168	205	221	142	114	114	114	114
Chemifloc CM25 dose (mg/L algae)	5,4	6,5	5,9	5,2	4,1	4,1	4,1	4,1

(It should be noted that power consumption has been calculated only for the period of time in each Experiment when water level value was constant).

For all Experiments TSS removal results are quite similar, above 95%, except for Experiment 8, that due to the fact that widest mesh pore size was used, lower TSS removal was obtained.

The reason why TSS removal is so even for mesh pore size range of 90 – 250 µm, is because no algae particle can cross the mesh due to algae cake on top of the mesh, which behaves as a filtration cake. The algae not harvested, is because of scraper limitations, which cannot remove all particles from mesh surface. Figure 4.51:

Figure 4.51: Up: Scraper working on a 350 µm mesh pore size, the green mesh is the result of algae particles not harvested. Left Below: Algae not harvested on 250 µm mesh. Right Below: Algae not harvested on 350 µm mesh.

TS value are in a range of 56 – 65 g/Kg, except for Experiment 1 which due to lowest filtration capacity more water was retained on mesh, therefore producing lower TS value.

Looking at results, it can be seen that highest power consumption (0,074 kWh/m^3) was made during the use of 90 µm mesh. This is consequence of the low filtration capacity due to small pore size, so filter needed to move more to filter same flow as wider meshes.

Average power consumption for Experiments is 0,05 kWh/m^3, however for Experiment 5 an unusual low power consumption was made. This was an unusual result since coagulant and flocculant added, flow treated were similar to another Experiments. For Experiment 8, power is clearly low 0,032 kWh/m^3, due to the high filtration capacity of a 350 µm mesh.

Regarding to coagulant and flocculant consumption, coagulant consumption is considerably higher than theoretical values, this is due to three reasons, one because when using sump pump to feed SWAT technology all autoflocculated algae flocs are destroyed, secondly because rapid mixing tank is clearly a deficient design and third one is because organic matter present in the medium also compete with microalgae cells for positives charges of the coagulant and thus increase the required flocculant dose.

5. Conclusions

The results of this thesis validates SWAT technology as a highly effective and low-energy consumption harvesting system, so SWAT objectives were met, TSS algae removal is higher than 95% and power consumption lower than 0,08 kWh/m^3.

In order to achieved 95% TSS removal, flocculation of *Coelastrum sp*. algae is necessary, for that purpose PAX-18 coagulant was used, in a dose of 141,67 mg/L, and Chemifloc CM25 flocculant in a dose of 4 mg/L. Coagulant dose is significantly higher than theoretical values due to coagulant mixing tank limitations, which is clearly not design for this purpose.

TS values achieved were in a range between 50 – 60 g/Kg, if lower dose of PAX-18 were used, a higher TS could be achieved because its hydrolysis product provokes an increment on sludge volume.

Four different flocculation configuration were used for SWAT technology, two of them presented a limitation on hydraulic retention time (did not achieved the necessary 10 mintes), another flocculator presented a conflict with algae floating tendency, therefore final flocculation configuration used was a 20 liters coagulation mixing tank which was filled partially, and mixed at 100 rpm (maximum motor velocity), and a 100 liters tank mixed at 70 rpm, with 3 outlets feeding SF500.

Power consumption (without taking into account control panel) is in the range of 0,04 – 0,05 kWh/m^3. Lower power consumption could have been achieved if higher flow was used, but due to flocculator limitation which did not have the necessary hydraulic retention time.

For filtration, the mesh pore size which suited the best is in a range between 210 – 250 µm, and control panel parameters (water level set point, water level start filter cloth, water level stop filter cloth) were at 45 mm. For cleaning procedure belt speed threshold to begin cleaning was 6%, belt speed during cleaning at 50% and 1 rotation of cloth to be cleaned was set.

6. Future Work and Recommendations

Experiments carried out during this thesis proved the suitability of this technology for harvesting algae, and as any other technology, improvements need to be made continuously to be more attractive to algae market.

Those improvements should be oriented to reduced power consumption and polymer consumption.

In order to reduce power consumption:

a) Flocculator limitations did not allow a use of higher hydraulic capacity for SF500, therefore a flocculator design capable of handling at least 1 m^3 should be made. This modification could lower significantly SWAT technology power consumption.
b) A new water knife design should be made. Cleaning 100% of mesh surface will improve SF500 hydraulic capacity by more than 30%. In order to clean whole mesh surface more nozzles should be installed with a closer distance between them, so crossing point between water sprayed should be lower, to have an optimal performance crossing point should be some millimeters before mesh (Figure 6.1):

c) Another solution could be to increase the distance between mesh and water knife.

Figure 6.1: Actual crossing point of sprayed water by nozzle.

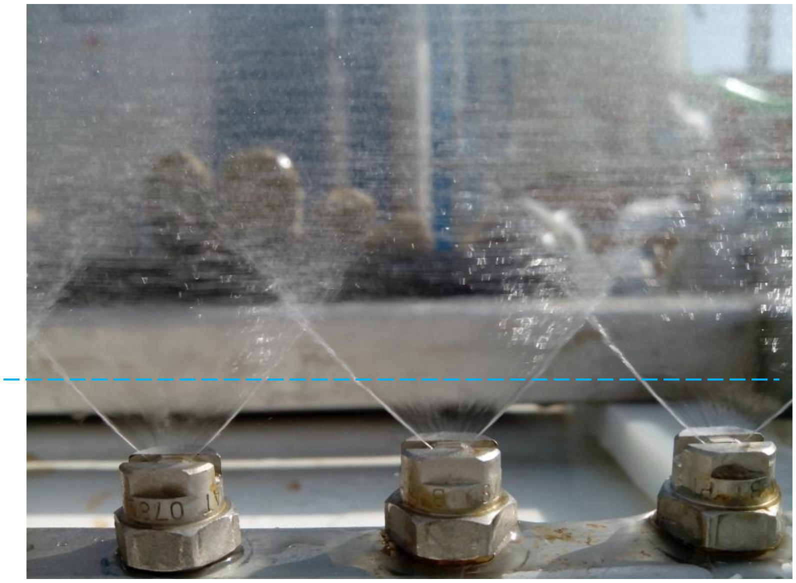

Figure 6.2: Desired crossing line for water sprayed.

In order to reduce polymer consumption:

a) More Experiments are needed to be conducted, and an analysis of relationship between polymer consumption, flocs quality and power consumption should be give the optimal dosage from economical point of view.
b) A better design of flocculator should mix more effectively polymer added, therefore polymer consumption will lower.

Other changes needed to be done:

1) From a marketable point of view, a new SF500 frame should be designed, so impression of this technology is better to be sold to potential clients.
2) A flow meter at SF500 inlet should be installed. So continuous power consumption per cubic meter can be calculated.
3) A motor with lower power consumption should be installed.
4) Pumping algae from pond to SF500 should not be done by using a sum pump which destroys small algae flocs formed by autoflocculation.
5) Installation of a new deflector which channelized the inlet turbulent flow into a laminar flow.
6) New design for SF500 inlet: keeping the concept of bringing flocculated algae to mesh gently. This was aimed when drilling three inlets on SF500, keeping that concept, the whole SF500 width should be design as inlet, Figure 6.3:

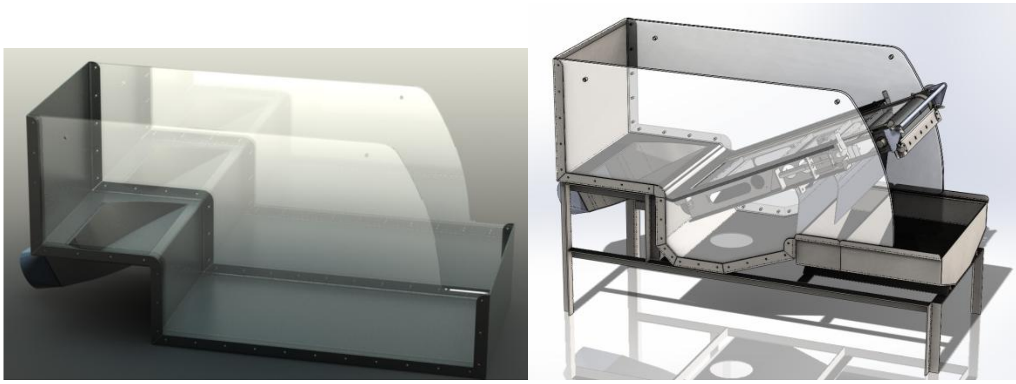

Figure 6.3: Salsnes Filter new design. (Salsnes-Filter I+D department).

Basin flocculators are useful for research because of the ease to be operated and modified in order to form adequate floc size and strength.

Coagulation and flocculation is the most important challenge for SWAT technology, therefore a further research on lowering coagulant and flocculant dose but forming good quality flocs.

7. Epilogue

Further experiments with SWAT technology have been carried out by Dr. Zouhayr Arbib (Aqualia I+D research engineer) during month of Februrary, aiming to lower PAX-18 dosage. Achieving a 90% TSS removal with a dosage of 213 mg PAX-18/g algae and 3 mg Chemifloc CM25/L algae. This represents 50% less dose of PAX-18 and 25% less dose of Chemifloc CM25 with respect to results obtained on Experiments 1-8 (440 mg PAX-18/g algae and 4 mg Chemifloc CM25/L algae).

Agreed that further experimentations and studies should be made in order to lower dosage. Also it’s remarkable the need of improving flocculator design. As a conclusion, the major challenge for SWAT technology is the formation of good quality flocs, big in size and strong (coagulation and flocculation is the critical step).

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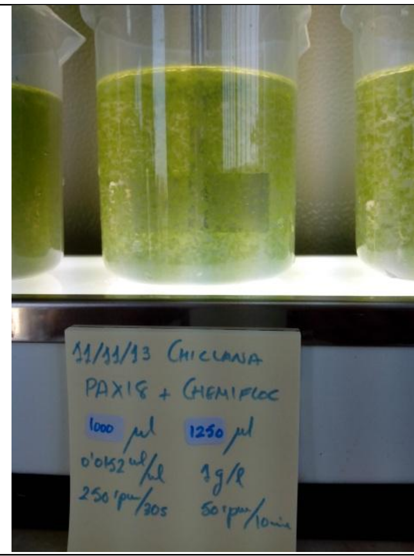
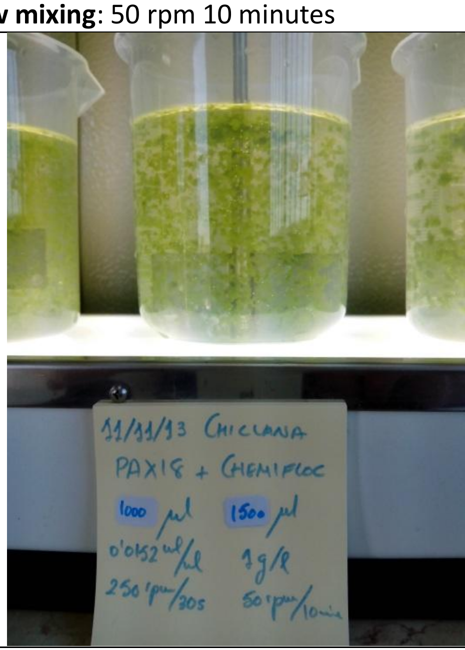
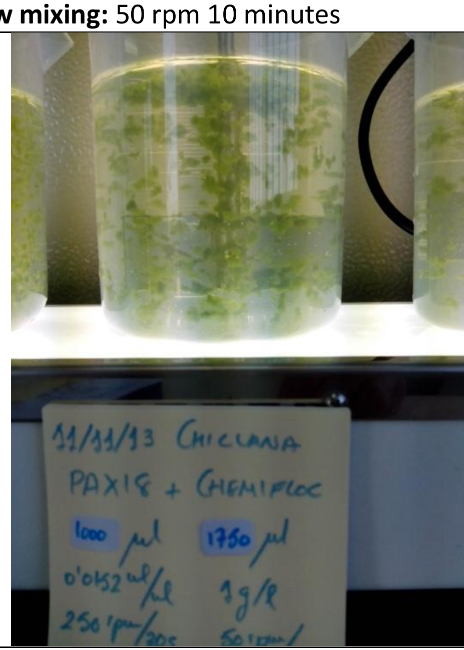
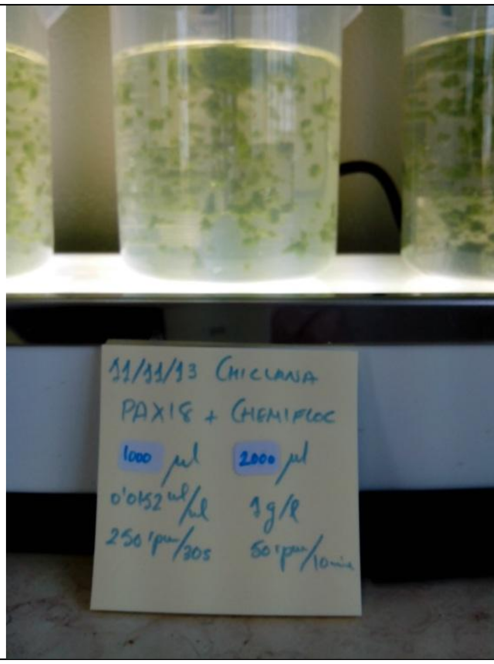
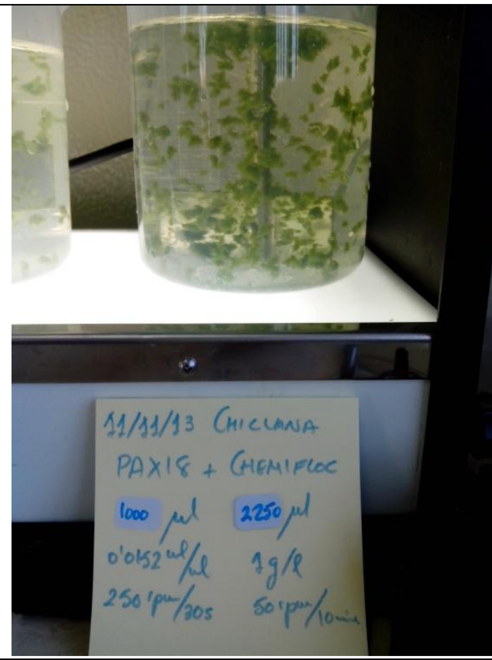
9. Appendix

Appendix A. PAX-18 coagulant and Chemifloc CM25 flocculant dose optimization.

	
PAX-18 Coagulant dosage: 40 mg/L **Chemifloc CM25 Flocculant dosage**: 2 mg/L **Rapid mixing**: 250 rpm 30 seconds **Slow mixing**: 50 rpm 10 minutes	**PAX-18 Coagulant dosage**: 40 mg/L **Chemifloc CM25 Flocculant dosage**: 2,5 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 50 rpm 10 minutes
	
PAX-18 Coagulant dosage: 40 mg/L **Chemifloc CM25 Flocculant dosage:** 3 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 50 rpm 10 minutes	**PAX-18 Coagulant dosage:** 40 mg/L **Chemifloc CM25 Flocculant dosage:** 3,5 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 50 rpm 10 minutes

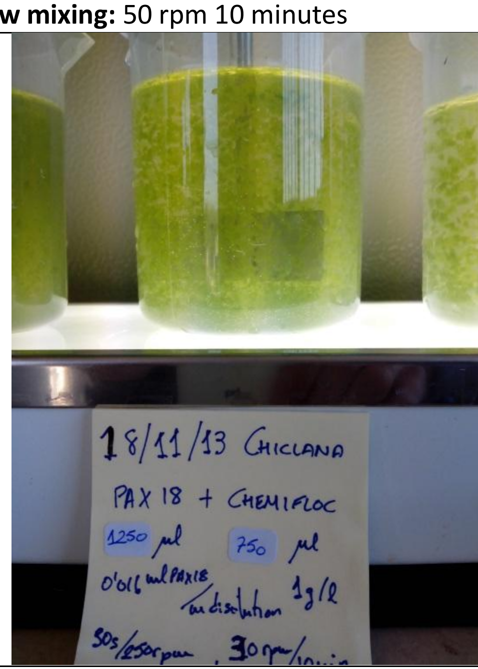


PAX-18 Coagulant dosage: 40 mg/L
Chemifloc CM25 Flocculant dosage: 4 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 50 rpm 10 minutes

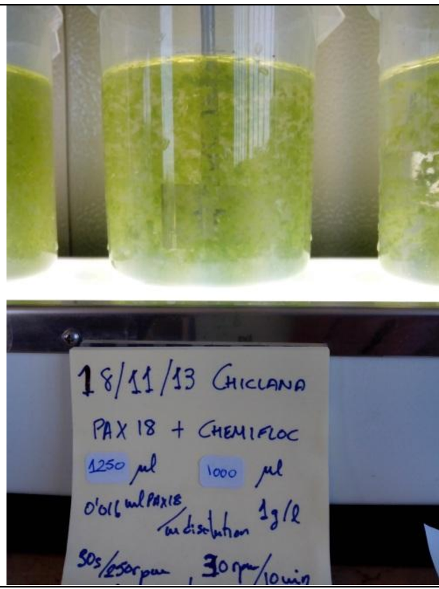


PAX-18 Coagulant dosage: 40 mg/L
Chemifloc CM25 Flocculant dosage: 4,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 50 rpm 10 minutes

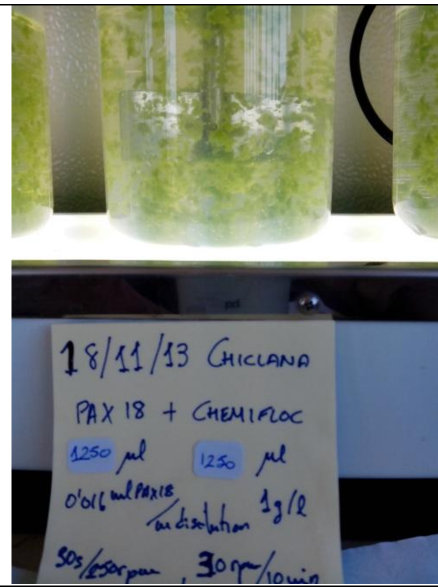
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 1 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes



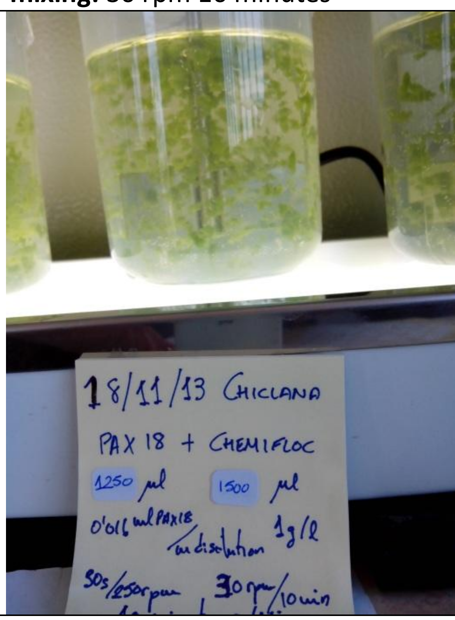
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 1,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes



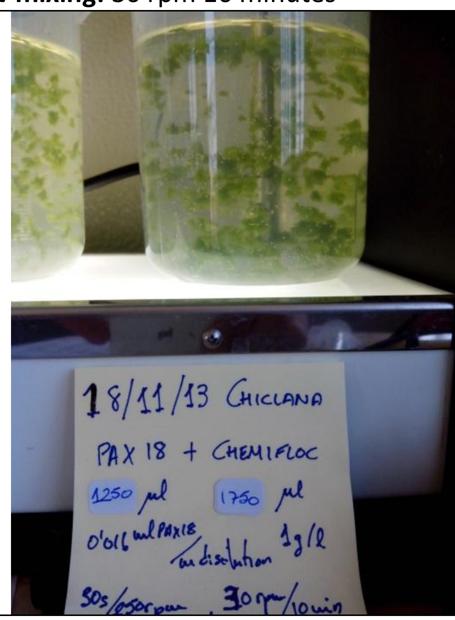
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 2 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes



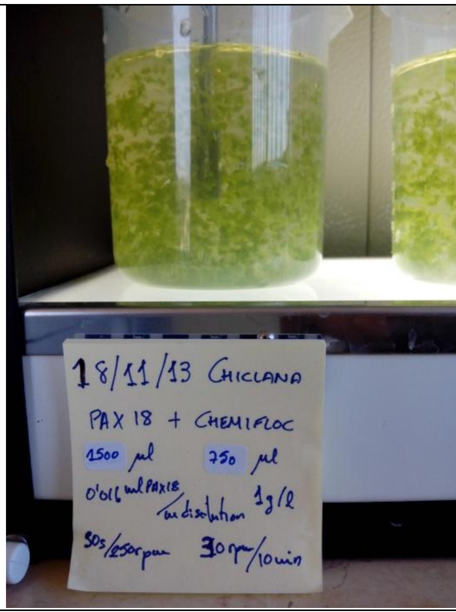
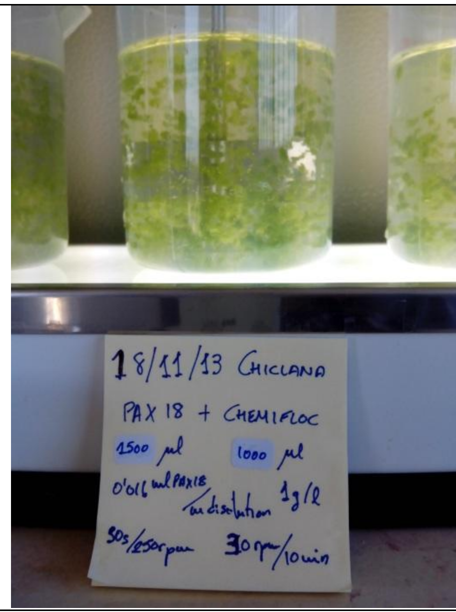
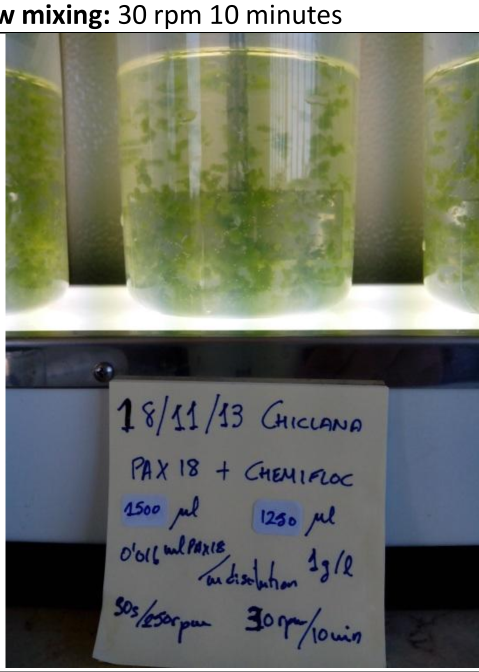
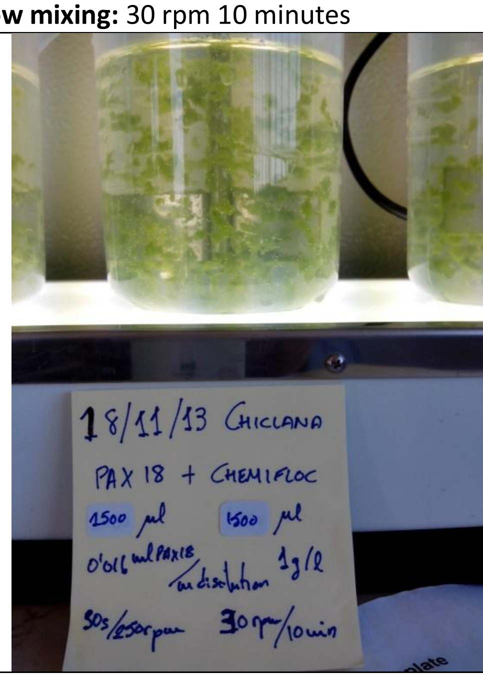
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 2,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes

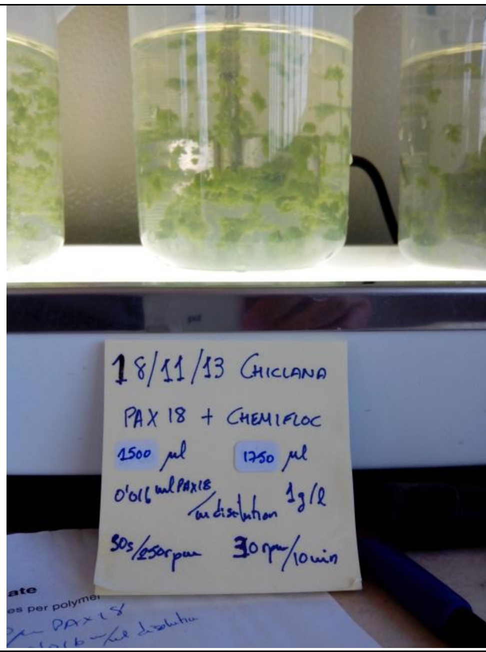
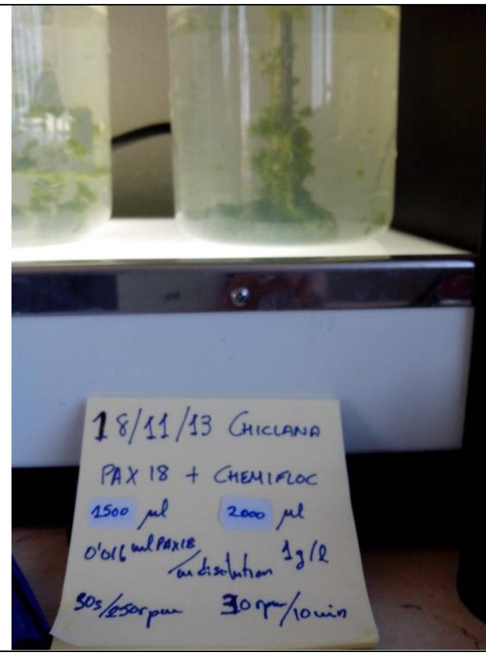


PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 3 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes

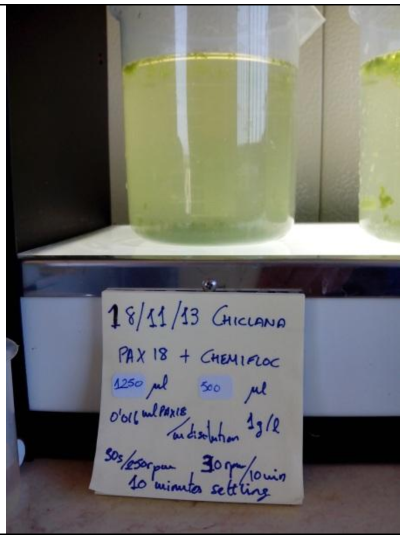


PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 3,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes

	
PAX-18 Coagulant dosage: 60 mg/L **Chemifloc CM25 Flocculant dosage:** 1,5 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes	**PAX-18 Coagulant dosage:** 60 mg/L **Chemifloc CM25 Flocculant dosage:** 2 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes
	
PAX-18 Coagulant dosage: 60 mg/L **Chemifloc CM25 Flocculant dosage:** 2,5 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes	**PAX-18 Coagulant dosage:** 60 mg/L **Chemifloc CM25 Flocculant dosage:** 3 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes

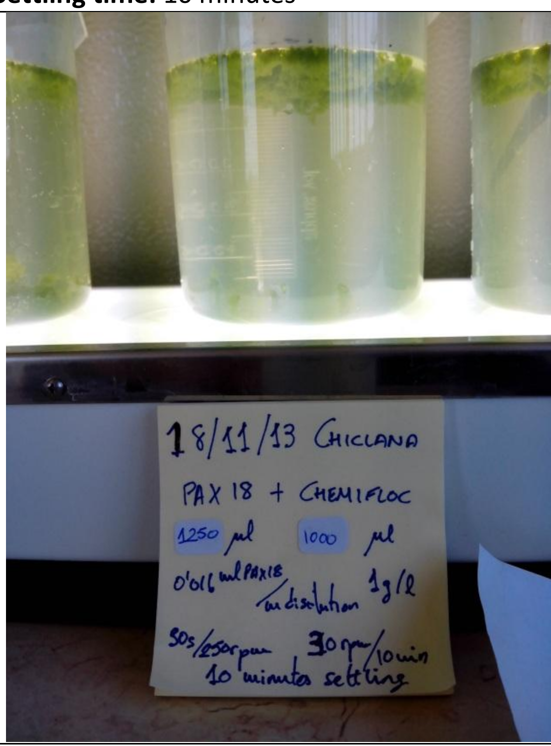
	
PAX-18 Coagulant dosage: 60 mg/L **Chemifloc CM25 Flocculant dosage:** 3,5 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes	**PAX-18 Coagulant dosage:** 60 mg/L **Chemifloc CM25 Flocculant dosage:** 4 mg/L **Rapid mixing:** 250 rpm 30 seconds **Slow mixing:** 30 rpm 10 minutes

Appendix B. PAX-18 and Chemifloc dose optimization with a settling time of 10 minutes.

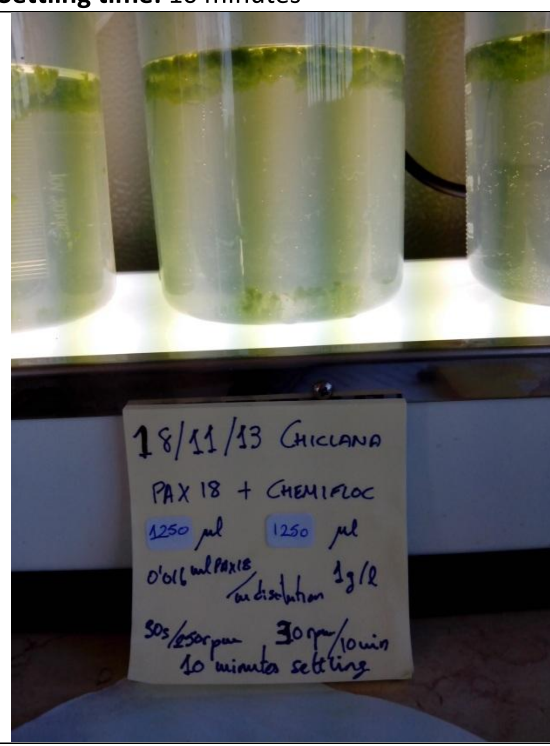


PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 1 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes

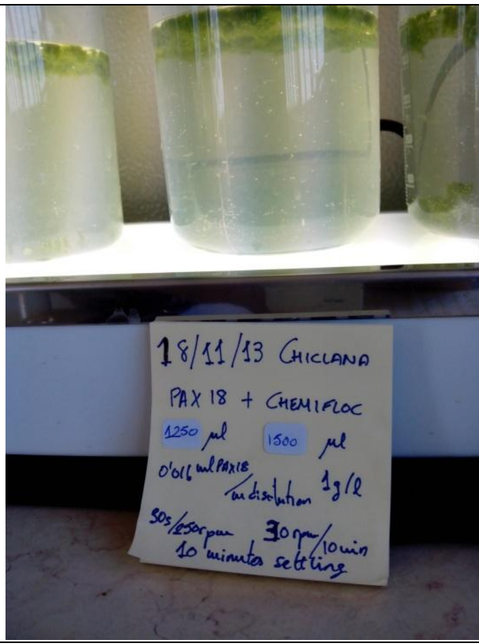
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 1,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



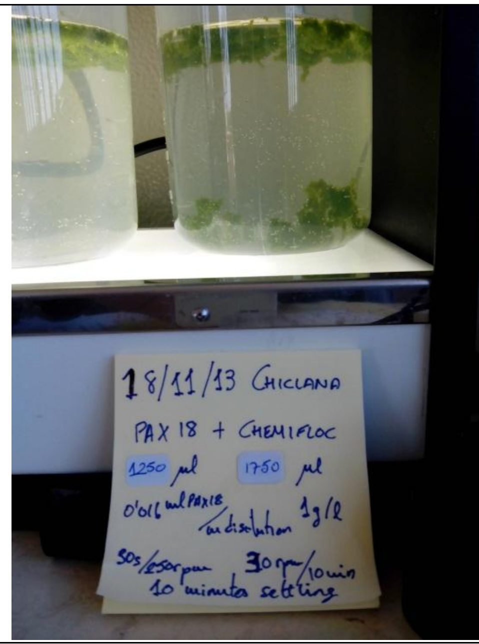
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 2 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



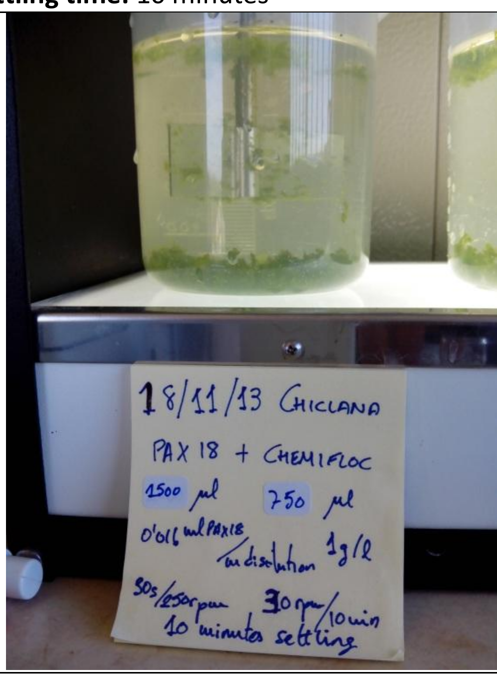
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 2,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



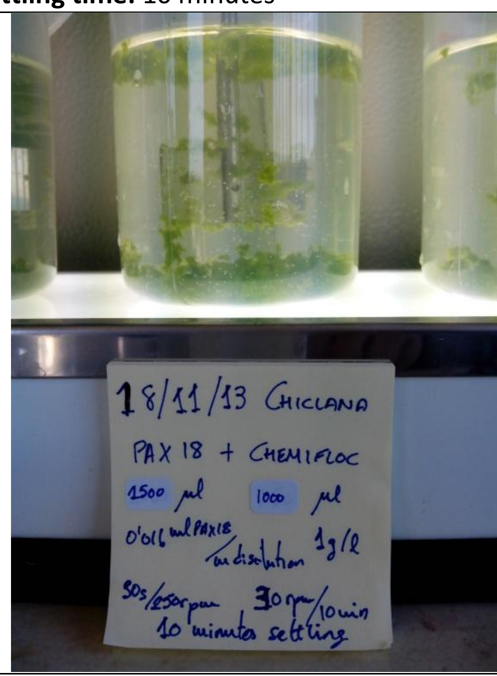
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 3 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



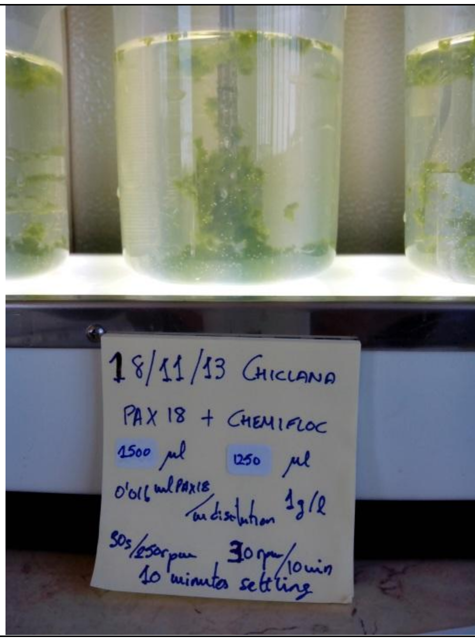
PAX-18 Coagulant dosage: 50 mg/L
Chemifloc CM25 Flocculant dosage: 3,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



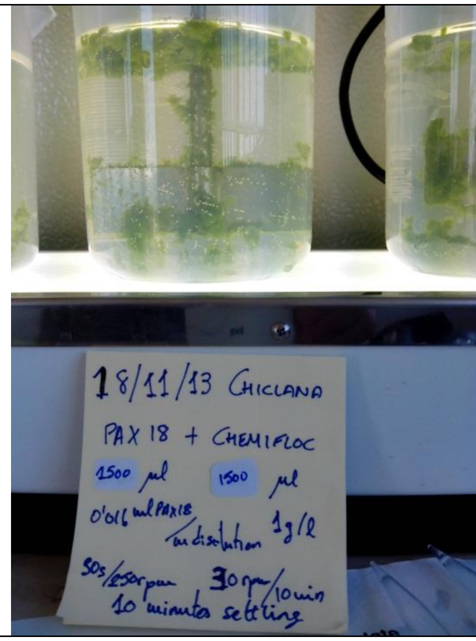
PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 1,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



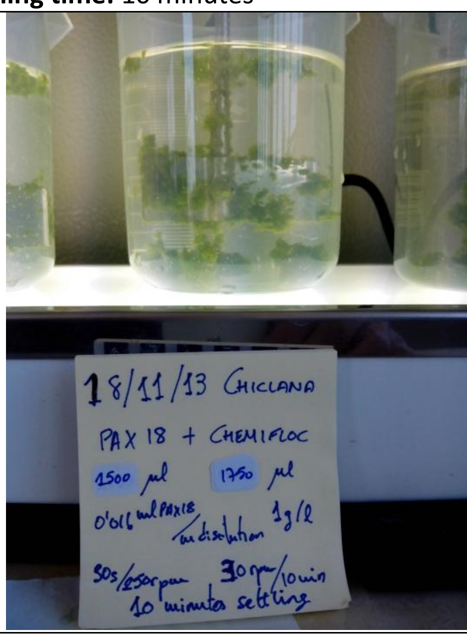
PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 2 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



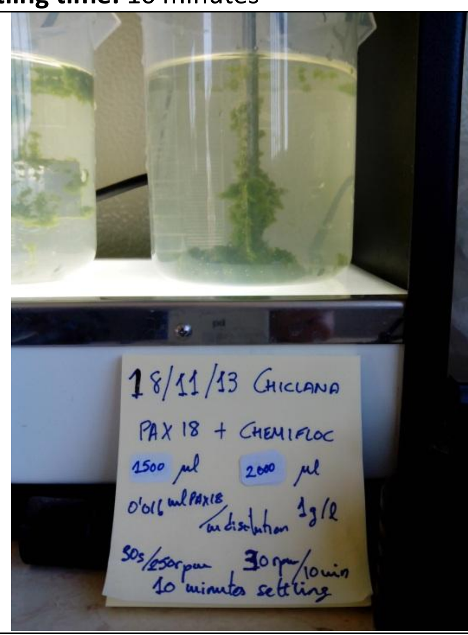
PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 2,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes



PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 3 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes

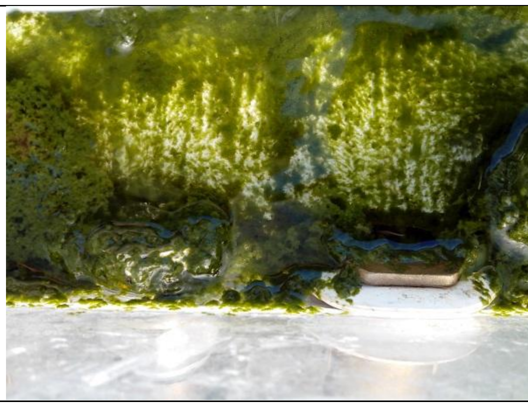
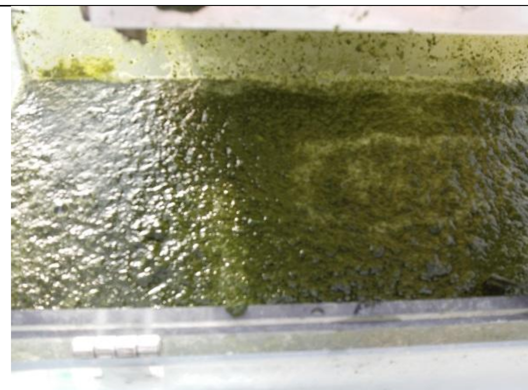
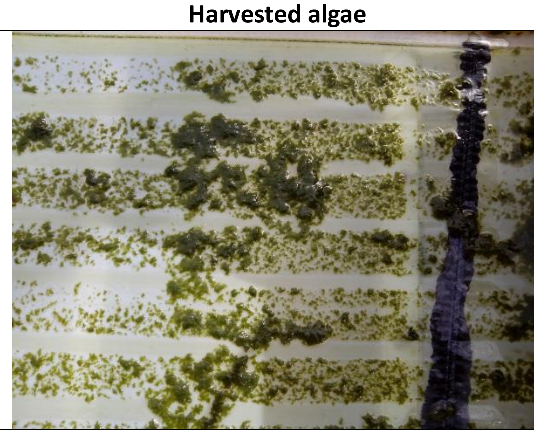


PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 3,5 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes

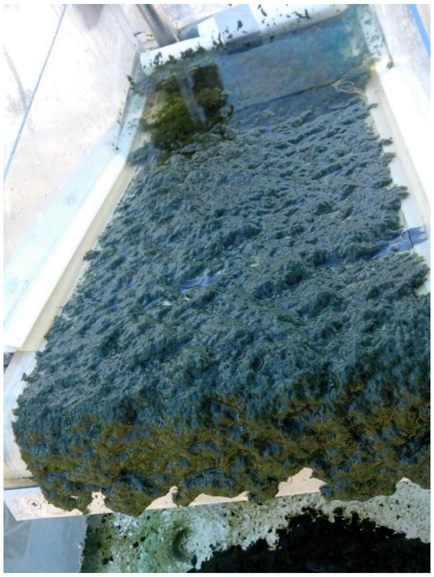
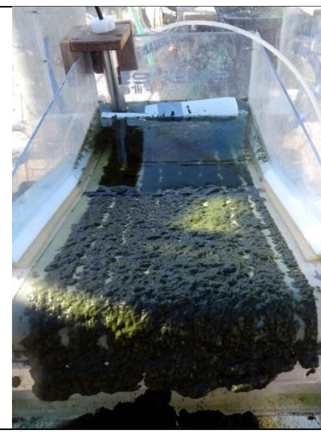
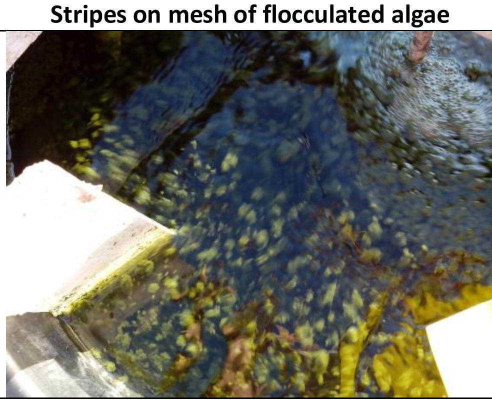
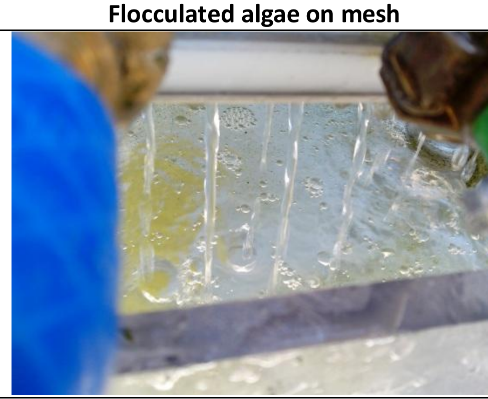


PAX-18 Coagulant dosage: 60 mg/L
Chemifloc CM25 Flocculant dosage: 4 mg/L
Rapid mixing: 250 rpm 30 seconds
Slow mixing: 30 rpm 10 minutes
Settling time: 10 minutes

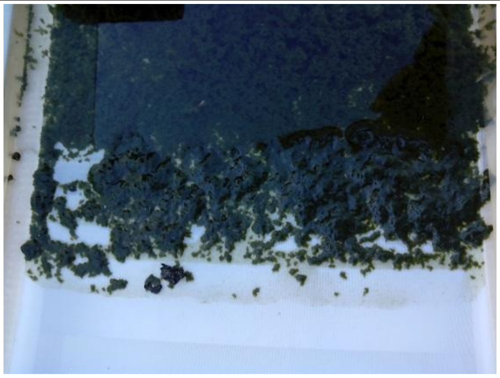
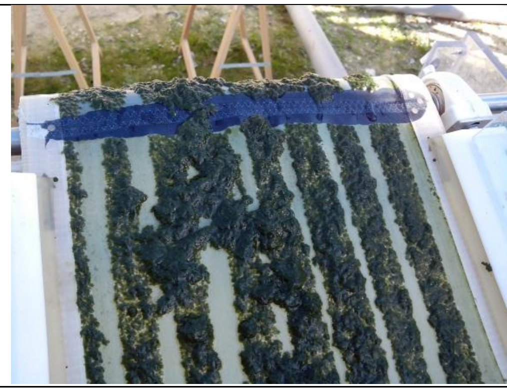
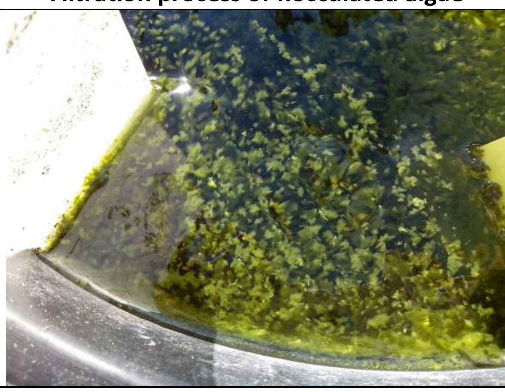
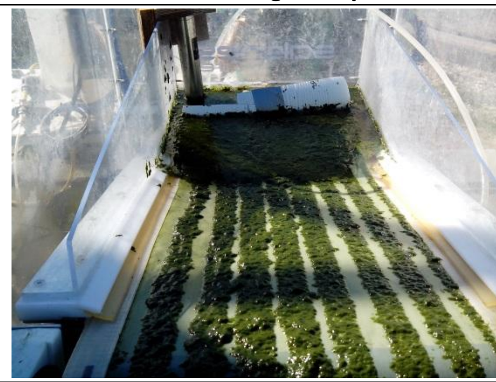
Appendix C. Experiment 1.

	
Algae stripes on mesh after water wash has been used	**Flocculated algae in slow mixing tank**
	
SF500 inlet	**Harvested algae**
	
Scraper working	**A detailed view of mentioned stripes**

Appendix D. Experiment 2 & 3.

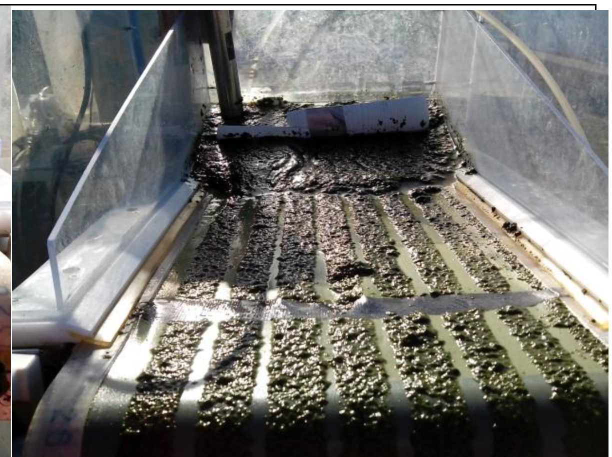
	
Mesh full cover of flocculated algae	**Backside view of mesh cover of flocculated algae**
	
Stripes on mesh of flocculated algae	**Flocculated algae on mesh**
	
Flocculated algae in slow mixing tank	**SF500 effluent**

Appendix E. Experiment 4.

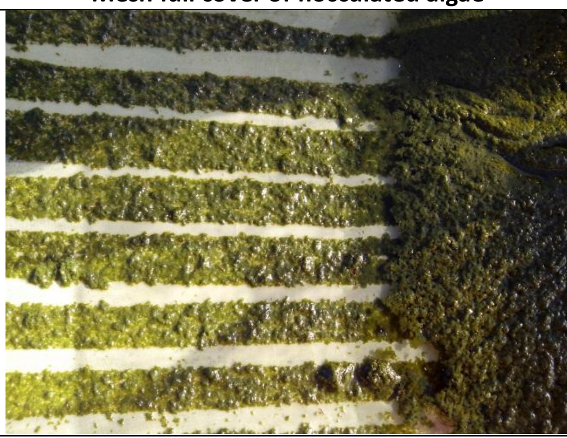
	
Filtration process of flocculated algae	**Mesh with algae stripes**
	
Flocculated algae in flocculator	**Mesh with stripes**

Appendix F. Experiment 5.

Mesh full cover of flocculated algae



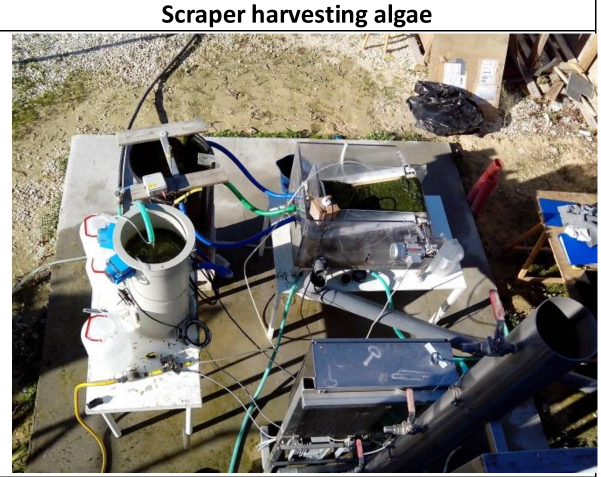
Mesh cover of algae stripes



Partially filtration of algae

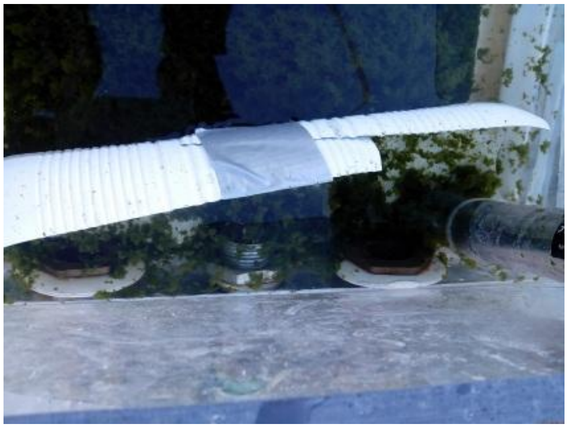
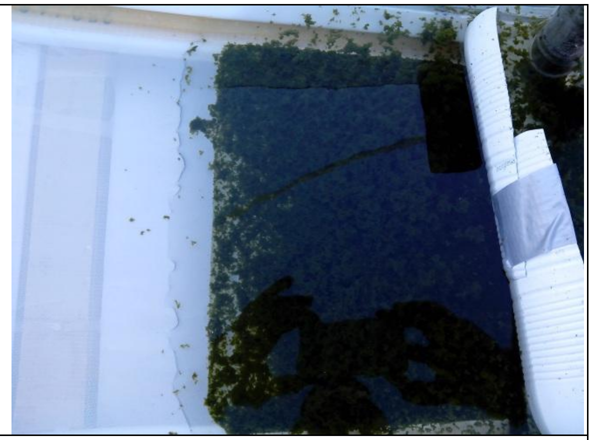
Scraper harvesting algae

Mesh cover of algae

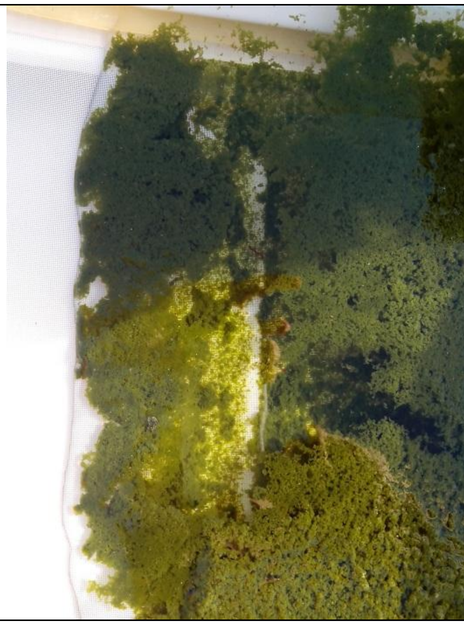


Overview of SWAT technology

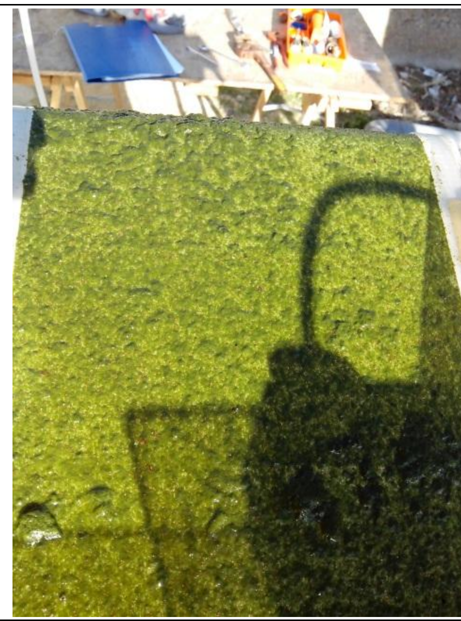
Appendix G. Experiment 6 & 7.

	
SF500 inlet and deflector	**Filtration process of algae**
	
Overview of SF500	**Mesh covered by algae**
	
Stripes on mesh	**Stripes on mesh**

Appendix H. Experiment 8.



Filtration process of flocculated algae

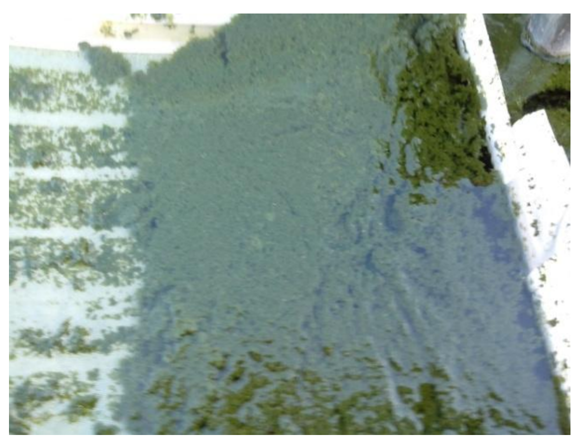


Mesh full covered by algae

Front side view of mesh

Scraper working on harvesting algae

Zoom in of algae stripes



Filtration process of flocculated algae

Appendix I. PAX-18 specifications.

Kemira Water Solutions, Inc.

PAX-18

Polyaluminum Chloride

Kemira's PAX-18 is a high performance liquid polyaluminum chloride coagulant that generally offers superior clarification in either potable or wastewater. The aluminum in PAX-18 is highly charged, enabling less of it to do more. Advantages available to many end users are ***Reduced Sludge, Minimized pH Adjustment, Longer Filter Runs, Superior Finished Water Quality, and Optimized Cold Water Performance****. PAX-18 is a general-purpose coagulant, versatile enough to handle any type of challenge.*

PRODUCT SPECIFICATION

Appearance	Yellowish Liquid
Aluminum (Al)	9.0 ± 0.2%
Al_2O_3	17.1 ± 0.4%
Iron (Fe)	< 0.01%
Specific Gravity (25°C)	1.37 ± 0.03
pH	0.9 ± 0.3
Basicity	42 ± 2%
Active Material	3.33 moles/kg
Viscosity (25° C)	30 ± 5 cP
Freezing Point	-20° C / -4° F

CERTIFICATION / APPROVAL

PAX-18 meets or exceeds all **AWWA** standards for polyaluminum chloride. PAX-18 is **ANSI/NSF Standard 60** certified for use in potable water treatment up to 200 mg/l.

DOSING

PAX-18 should be fed straight without dilution. A diaphragm-metering pump of non-corrosive material is suitable.

STORAGE

Storage tanks and piping should be constructed of suitable non-corrosive material such as fiberglass or cross-linked polyethylene. PAX-18 is mildly corrosive and will attack most metals over a period of time. PAX-18 has a recommended shelf life of 8 months. As with any chemical, it is recommended to clean the storage tank every 1-2 year.

HANDLING / SAFETY

The handling of any chemical requires care. Anyone responsible for using or handling PAX-18 should familiarize themselves with the full safety precautions outlined in our Material Safety Data Sheet.

DELIVERY

55 gal. plastic drums / 275 gal. tote bin
Bulk tank trucks, Railcar
Corrosive Liquid, Acidic, Inorganic, n.o.s. 8, UN, 3264, P.G. III

PRODUCTION

Kemiron has coagulant production plants in

Bartow, FL	Rowley, UT
Fontana, CA	Saint Louis, MO
Houston, TX	Savannah, GA
Mojave, CA	Spokane, WA
	East Chicago, IN

CUSTOMER SERVICE

If you have any questions concerning this material, please contact our Customer Service Department.

(800) 879-6353
(800) 342-8755

KEMIRON 05/25/01

Appendix J. Blank sheets for experiments

Jar Tests Template

Use one form per microalgae species per polymer

Tests conducted by:

Date of testing (DD/MM/YY):

Rapid Mixing: 300 rpm 20 seconds
Slow Mixing: 50 rpm 10 minutes
Settling: 10 minutes

Name of Polymer:

Polymer concentration (g/L):

Date when polymer was prepared:

Microalgae species:

Jar Test Date:

Time of sample collection:

pH of sampled algae:

Water temperature (°C) :

Suspended solids of sampled algae (mg/L):

Turbidity of raw sample (NTU):

Polymer dosage	Amount of polymer added	Sample volume in jar test	Height of liquid column	Height of settled solids	Turbidity of clear liquid	pH after settling	Labelled photograph
mg/L	µL	L	cm	cm	NTU		Y or N

Jar test template

Operation SWAT Field test Spain (18 February – 18 April 2013)

Total Solids (Template) by Weight

$$TS\left(\frac{g\ TS}{kg\ sludge}\right) = \left(\frac{Wt\ at\ 105\ (g) - empty\ wt\ of\ dish\ (g)}{Wt\ of\ mat. + dish\ (g) - empty\ wt\ of\ dish\ (g)}\right) \times 1000$$

Date (DD/MM)	Sampling location	Dish nr	Weight of empty dish	Weight of material + dish	Wt after 105*C	TS
			g	g	g	g/kg

Total Solids by Weight template

Total Suspended Solids (Template)

$$TSS\left(\frac{mg}{L}\right) = \frac{Wt\ at\ 105\ (g) - Empty\ wt\ of\ filter\ (g)}{Amount\ filtered\ (mL) * 10^{-3}} \times 1000$$

Date (DD/MM)	Sampling location	Petri dish nr	Empty weight of filter (A)	Amount filtered	Weight after 105*C (B)	B-A	TSS
			grams	mL	grams	g	mg/L

Total Suspended Solids Template

Salsnes Screening Test with Flocculated Microalgae at Chiclana

Algae Conditions

Pond no:

Date of expt:

Experiment Start time:

Experiment End time:

pH of pond:

Water temperature: °C

Weather (sunny/rainy/cloudy):

Lux:

Polymer Conditions

Polymer name:

Polymer/Chemical (mg/L):

$Q_{in\ polymer\ for\ pipe}$ (L/min):

Dial settings (no):

Polymer dosage (opt / %):

Flocculation Conditions

Tank Flocculator

Tank flocculator No:

Rapid Mixing (rpm):

Time of rapid mixing (s):

Slow Mixing (rpm):

Time of slow mixing (min):

Pipe Flocculator

Sampling Port No (Pipe flocculator):

Q_{in} (m^3/h):

pH (flocculator):

Est. HRT (minutes):

Diameter of Pipe flocculator (DN):

Number of Stirrers:

ID	Sieve cloth (μm)	Sample type	Total water volume (liters)	SS (mg/L)	Tur-bidity (NTU)	Volume filtered (mL)	Time taken for filtrate (sec)	Comments/ Observations
1	None	Pond algae	NA			NA	NA	
5	210	First liter	1,0					
6	158	First liter	1,0					
7	90	First liter	1,0					
8	74	First liter	1,0					
10	55	First liter	1,0					
11	33	First liter	1,0					
12	18	First liter	1,0					
15	Floc	Floc	NA			NA	NA	
16	None	Pond algae	NA			NA	NA	

NA: No measurement or analysis; RED indicates test for SF600

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Salsnes Screening Test with Flocculated Microalgae at Chiclana