*Desalination and Water Treatment*
www.deswater.com

49 (2012) 1–18
November


doi: 10.1080/19443994.2012.708191

# On the concept of the future drinking water treatment plant: algae harvesting from the algal biomass for biodiesel production—a review

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Received 24 July 2011; Accepted 24 May 2012

ABSTRACT

It is well established that the drinking water treatment has several disadvantages such as it may rupture the algae, thereby releasing the taste- and odour-producing oils before the whole algae are removed from the treatment system. This review aims to present the concept of algae recovery instead of its removal in drinking water treatment plant. Control of algae in water supplies and some coagulation/flocculation and electrolysis experiments as harvesting methods are discussed. In fact, algae recovery instead of its removal in water treatment plant is a promising perspective and a suitable issue when the surface water comes from dams where algae blooms occur frequently. Micro-algae are a sustainable energy resource with great potential for $CO_2$ fixation. The micro-algae could be grown in photo-bioreactors or in open ponds. A new interesting field of research would be fast and simultaneous algal biodiesel production with drinking water treatment in the biodiesel production/water treatment plant without chemicals. However, the fact that algal cultivation needs light and space would be very difficult challenge.

*Keywords:* Algae recovery; Algae removal; Coagulation/flocculation; Electrolytic flocculation; Water treatment; Biofuel

## 1. Introduction

The geostrategic importance of micro-algae recovery arises from the fact that algae are used in the biofuel production in the perspectives of oil substitution [1–8]. However, researchers and developers of this new research field are keeping their separation process as secret as they can even if Krohn et al. [9] mentioned that they harvested algae biomass using a continuous feed, fixed-bowl centrifuge. Recently, some authors [10–12] explained that micro-algae can be harvested by sedimentation, filtration, flotation and centrifugation. Furthermore, cost-effective harvesting of algae is often one of the main problems in different processes such as industrial algal mass production and wastewater treatment by means of stabilisation ponds or high-rate oxidation ponds or even drinking water production from surface water [13–17]. Numerous techniques for the recovery of algae have, however, been developed [14]. These include centrifugation, flocculation and flotation with flocculants. Most of these techniques have several disadvantages not only because of the high costs but also because of the often low separation efficiencies and the unacceptable quality of the harvested product. An efficient algal separation process should be applicable for all kinds of algal species, yield a product with a high dry weight percentage and require only modest investment, energy and maintenance [14].

"Electrolytic flocculation" or simply "electrolysis", as described by Aragón et al. [18], is a new algal separation technique which seems to have many advantages over the conventional techniques or

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processes, although only small-scale experiments have been carried out until now. It must not be confused with "electroflotation" as described for example by Sandbank and Shelef [19] and Moraine et al. [20]. Indeed, electroflotation uses electrolysis only to produce gas bubbles which uplift the flocculated algae to the surface. The electrodes are placed horizontally, covering the bottom of the flotation tank. Flocculation of the algae has to be performed with flocculants such as alum which makes the electroflotation technique similar to dissolved air flotation. With electrolytic flocculation, on the contrary, no flocculants are needed and the sacrificial electrodes are placed vertically [14].

This paper reviews the importance and characteristics of algae. The importance of their biological activity is briefly discussed. Control of algae in water supplies and some coagulation/flocculation and electrolysis experiments as harvesting methods are examined. The concept of biodiesel production from algae is briefly presented. Finally, algae recovery instead of its removal in water treatment plant is presented as a perspective.

## 2. Importance of algae

It is generally agreed that life is most likely originated in the ocean [21]. The elements probably came up from the magma in the centre of the earth through cracks or holes in the crust. Holes include volcanic type activity. The right combination of elements came together, and, more importantly, they managed to copy themselves in a form of reproduction. Energy came from reduction of elements such as sulphur to sulphide and oxidation of others such as iron to ferrous iron. There was no oxygen; the system was entirely anaerobic. In some way these substances must have reached the surface of the ocean, where they were exposed to a much greater energy source: the sun. They utilised this energy for further growth and reproduction and found a way to produce oxygen in what we call "photosynthesis" [22]. This was the first occurrence of aerobic conditions. These organisms, which were most likely single-celled, contained chlorophyll and are the basis of the group of organisms that we now call "algae". They are capable of producing oxygen as well as cell material from some essential nutrients with the aid of energy from the sun. This cell material serves as food for higher organisms and is thus considered the basis of our food chain. It has been estimated that 75% of the oxygen on earth is produced by algae in the ocean [21].

Algae constitute a wide variety of photosynthetic organisms from single-celled to large multicellular sheets of kelp found in the ocean [21,23]. Large numbers of varieties of species are found in both fresh and ocean salt waters, with fewer numbers that prefer or tolerate brackish waters. Generally, different species prefer fresh or salt waters. They are important in producing organic matter from inorganic materials utilising the energy from the sun. Thus solar energy is stored as organic material. At the same time they are a principal source of oxygen, maintaining the surface of the Earth under aerobic conditions. Thus algae represent the beginning of the transfer of the Earth from a primarily anaerobic life to an aerobic one in which oxygen serves as the principal transfer of energy. Not only is this more efficient than anaerobic processes, it also represents converting the energy of the sun to stored energy, thus assuring a longer duration of geological time than depending on only the resources of the Earth [21,24,25].

Certain algae represent a source of human food [21]. Probably the most common is the macro-alga used for the wrapper in sushi rolls [21]. Spirulina and dulse are also edible. Dulse (*Palmaria palmate*) is red and is eaten raw, dried or cooked like spinach by people in Ireland and Atlantic Canada. Purple laver (*Porphyra*) is used for making laverbread in the British Isles and for making jelly in Ireland. Irish Moss (*Chondrus crispus*) is used as carrageen for stiffening of milk and dairy products such as ice cream. It is also used to make a clearer beer [26]. For centuries, seaweed has been used as a fertiliser. It is high in potassium, used in the production of potash and potassium nitrate. Agar is made from seaweed [27].

Algae have been cultivated for use as food, oil or pigments [21]. Open ponds are frequently used; however, they are prone to mixed cultures that vary with season and nutrients. Therefore, establishing a constant final end product is difficult. To overcome this, closed chambers are used at constant temperature with known nutrients and at constant, usually artificial, light [28,29]. It has been suggested that $CO_2$ from fossil-fuelled power plants be used as the carbon source (Mathews [30] reviewed the concept of carbon-negative fuels), thereby simultaneously reducing discharge of that greenhouse gas [6]. Watersmart Environmental has joined US EPA's Combined Heat and Power (CHP) Partnership with a system to conserve heat and energy [31]. The remaining heat energy is wasted. Using this excess heat to heat adjacent algae ponds will not only increase the total efficiency but also serve as a cooling system for the power plant. In addition, burning fossil fuel produces a mixture of nitrogen oxides, commonly referred to as $NO_x$, which can be used as a nitrogen source when dissolved in water. With the conservation of heat in the water, nitrogen from the $NO_x$ and carbon from the $CO_2$, all that is needed is a source of phosphorus and trace nutrients to provide an optimum growth system for algae. The phosphorus could be supplied by a nearby wastewater treatment plant that would also be the source of the water for the pond. Of course sunlight is also needed. Studies could be made to provide the optimum balance of all these inputs [32]. This would alleviate some problems of fossil-fuelled power plants and at the same time produce algae that can be used as fuel or many other uses [21].

The oils extracted from algae can be used as a form of "biodiesel". It is suggested that they would make a substitute for gasoline in that they have a much faster growth rate than terrestrial crops [21].

It has been reported [21] that if *Chlamydomonas reinhardtii* is grown in a medium that is deficient in sulphur, it will produce hydrogen instead of oxygen, the normal product of photosynthesis. This could also be used as a substitute for gasoline in transportation vehicles. Algae biomass can be dried and burned similar to wood to produce heat for energy. Under anaerobic digestion, algae biomass will produce methane. The oil of *Botryococcus braunii* is different from other algal oils in that it can be cracked into gasoline, diesel and aviation-grade kerosene [33].

Spirulina (*Arthrospira platensis*) is a blue-green alga that is high in nutrients and protein. It is often used commercially as a nutrient supplement. Extracts and oils are used as additives in various food products [34,35]. They also produce Omega-3 and Omega-6 oils, which have been shown to have medical benefits [21,36].

## 3. Characteristics of algae

If algae are so important in our lives, one may ask, "Why are we concerned with means of their removal?" Basically it boils down to one thing: too much of the good thing [21]. Algae, being living organisms, respire using reduction of oxygen or oxidised materials to gain the energy to sustain life, grow and reproduce. It is only during daylight that they produce more oxygen than they consume during a 24-h cycle [32]. Respiration is relatively constant, although it varies considerably with the ambient temperature. The problem is that the excess oxygen produced during daylight is released to the surrounding water. Water can contain only a limited amount of dissolved oxygen, which is controlled by the temperature [21]. Although a limited amount of supersaturation may occur, basically all the oxygen in excess of saturation is released to the atmosphere, particularly when the water is in motion. Thus at night, if large numbers of algae are present, they may consume all of the remaining oxygen, creating anoxic conditions (lack of free oxygen) or anaerobic conditions (lack of free or combined oxygen). This may cause the death of other aquatic organisms, particularly fish that require the presence of some dissolved oxygen. Some less tolerant algae may also die from the lack of oxygen. Thus large numbers of algae tend to create undesirable conditions.

Another problem related to abundances of algae is the release of tastes and odours to the water [21]. Most algae store food as oils. Many of these oils have an undesirable taste and/or odour. Blue-green algae have a reputation for imparting undesirable tastes and odours, but other algae may also impart varying degrees of tastes and odours. When only small numbers of algae are present, these tastes and odours may not be noticeable; however, when large numbers of algae are present, their accumulation results in the noticeable tastes and odours.

Furthermore, certain species of algae are toxic either to other aquatic organisms or to humans [21]. Although not true algae, so-called blue-green algae have a tendency to produce toxins. They may also be classified as cyanobacteria. Pets and farm animals have been known to have died from drinking water containing blue-green algae. Pets may even get sick from licking their wet hair after being in the water. Human reactions to external exposure usually relate to skin irritations such as rashes. Ingestion may cause headaches, nausea, muscular pains, abdominal pain, diarrhoea and vomiting. Death is rare. Again, the toxic level is related to the abundance of the algae; however, toxins have been shown to persist in water several weeks after the bloom has subsided [21].

There are several concerns for water treatment plants. The abundance of the algae may prematurely clog any filtration systems. This is particularly true of diatoms, a group of algae that form a shell of silica. These shells are very persistent and tend to clog filters. Actually, diatomaceous earth consists of diatom shells, usually precipitated from ancient oceans that are commonly used as filtering materials or filtering aids. Another concern is that treatment may rupture the algae, thereby releasing the taste- and odour-producing oils before the whole algae are removed from the treatment system. As with other concerns, large numbers of algae, commonly called "bloom", are what cause the problem [21].

A survey by Knappe [37] showed that 73% of the water treatment plants responding experienced algae-related problems in some form or another. This included taste and odour, filter clogging, increased chemical demand, trihalomethane formation and algal toxins [21].

Algae are less likely to cause a problem when there is diversity of species in the water environment.

However, even in low nutrient environments, there may be a tendency to develop a monoculture of algae. Typically, algae increase in numbers during the summer season, with maximum numbers in July or August slightly after the summer solstice of maximum sunlight. For years, limnologists have observed a dominance of diatoms in spring followed by a dominance of blue-green algae in late summer and fall. It was questioned whether this was attributable to the increase in water temperature, the difference in solar radiation, predation or some other factors. In a study of Saratoga Lake, NY, Aulenbach [38] showed that diatoms predominated until the silicon level dropped to a level that could no longer support the diatoms. Thereafter, the blue-green algae took over due to lack of competition from the diatoms. Also, the rapid depletion in silicon was attributed to the growth of *Stephanodiscus*, a relatively large diatom. Thus the depletion of the silicon was due, not to the total numbers of diatoms, but to the mass of silicon tied up by the large diatoms. It is this situation that makes evaluation of the trophic state of a body of water based on the diversity of algae alone very difficult [21].

Furthermore, Rabalais et al. [39] reached a similar conclusion in their studies of the anoxic zone in the Gulf of Mexico. This has been a particular concern since the anoxic zone restricts the production of shrimp, a major economic crop of the Gulf of Mexico. Blue-green algae predominate in the anoxic zone, corresponding with a depleted level of silicon. They attribute the lack of silicon in the Gulf to the dams on the Mississippi River, which trap the sand and silt that normally reach the Gulf [21].

## 4. Importance of biological activity

The main direction of this paper is the removal of algae, the microscopic green plants floating in the water, by dissolved air flotation. There are larger, macroscopic algae, even up to the large kelp beds of the oceans, but their means of removal is by methods other than dissolved air flotation. In addition to algae, natural waters contain numerous other organisms of microscopic size. The floating microscopic organisms are called "plankton", which may be subdivided into two groups: the phytoplankton or plant life, which includes algae, fungi and pollens that fall into the lake, and the zooplankton or animal forms. The plankton may also be broken down into the nekton, or free swimming organisms and the benthon, which exist on the bottom. All of these microscopic organisms may be removed with the algae in a dissolved air flotation system. The algae are of particular interest because they produce oxygen in the presence of sunlight, and convert solar energy into protein, which serves as food for the larger organisms, particularly the zooplankton [21].

As has been pointed out, the algae present a problem for water supplies when they multiply into massive growths, commonly called "blooms". Blooms develop when there is an adequate supply of nutrients to support growth. Most commonly, nitrogen and phosphorus are the controlling nutrients, along with traces of sulphur, iron and several other trace substances. However, it has been shown that in the case of diatoms, silicon is an essential element, and very frequently is the limiting element in their proliferation. This corresponds with Liebig's Law of the Minimum, which states that the growth of an organism is limited to the element that is present in the lowest concentration in relation to that organism's need. This is very evident in the limit of silicon for diatoms [21].

Another need for removal of algae is their use in waste treatment processes [13]. The algae present in waters for water supply are relatively low in concentration. However, algae are also used in lagoon treatment of wastewaters, where the algae become the source of the oxygen to maintain aerobic conditions. Here the concentrations are very high. The algae produced must be separated from the treated wastewater prior to discharge to a receiving body of water or to further treatment. Thus the design range for the consideration of the use of dissolved air flotation for algae removal must include both low concentrations and very high concentrations [21].

Wastewater treatment lagoons may be designed to provide the equivalent of biological treatment (similar to activated sludge or trickling filters) of a wastewater, or they may be designed to be a polishing treatment that may include additional nutrient (nitrogen and phosphorus) removal plus reaeration [13]. The treatment lagoons may be in the order of 4–5 m deep and are usually aerated by means of an aeration system. The aerators may be either submerged or surface aerators. The aerators provide the major source of oxygen and they also provide mixing, which not only mixes the contents of the lagoon, but also brings the liquid to the surface where additional surface transfer of air takes place. Algae usually grow in this system, but are not relied upon to provide a significant source of oxygen. Polishing lagoons seldom exceed 1 m in depth and have no provisions for mixing. The algae are the major source of oxygen, and surface wind is relied upon to provide mixing. The algae may become very prolific in this type of lagoon, since the nutrient supply is generally adequate. Since there is a diversity of algal species, lack of a specific element, such as silicon for diatoms, has little effect on the total algal biomass.

It should be pointed out that this is considered a use for the algae in providing the source of oxygen to maintain an aerobic environment for aerobic treatment. Thus algae removal processes must be designed for both low levels and high levels of algae [21].

## 5. Control of algae in water supplies

Low levels of algae are desirable in water supplies. They provide oxygen to maintain lakes in an aerobic state. They also are a primary source of organic matter that becomes food for larger (higher) organisms that are subsequently eaten by fish that are a food supply for birds, bears and humans. The goal is to prevent blooms that may raise the levels of algae that impart tastes and odours, and possibly even toxins, to the water. Blue-green algae are a common source of tastes and odours [21].

As with any pollution problem, controlling inputs of nutrients to a body of water is more effective than after-the-fact remediation. This means eliminating or reducing the sources of the pollutants. A forested watershed will lessen the amount of nutrients being carried into a body of water. However, lumbering, especially clear-cutting, results in greater carriage of silt and nutrients into the water. Farmed areas contribute large amounts of nutrients and fertilisers. Human development may contribute significantly to the nutrient load in the form of more direct surface runoff to a lake and more, even treated, domestic wastes [21].

All biological systems require the presence of the proper nutrients to grow and reproduce. For larger organisms, the smaller organisms provide both the nutrients and the energy. Algae obtain their nutrients from dissolved inorganic materials and their energy from the sun. Organisms that rely on inorganic nutrients are called "autotrophic", whereas those that rely on organic matter are called "heterotrophic". Besides nutrients and energy, growth may depend upon other factors such as temperature, light, etc. [29]. However, common to most are carbon, hydrogen, oxygen or another electron acceptor, nitrogen and phosphorus. Carbon may be obtained from other organic matter (starting with algae) and from the solution of carbon dioxide. Hydrogen may be obtained from electrolysis or from bicarbonates dissolved in the water. Oxygen is most frequently obtained from the dissolved oxygen in the water. Nitrogen is secured from dissolved nitrogenous materials including ammonia, nitrites and nitrates. Certain blue-green algae can fix gaseous nitrogen from the atmosphere as a nitrogen source. Phosphorus is usually obtained from geological materials and from the breakdown of other organic materials. Some trace substances may also be essential. Sulphur may be present in the soil, and is available from decaying organic matter. Iron is usually available from dissolved mineral deposits. And, of course, silicon is required to form the shell case, called the "frustule", of diatoms [21].

When nutrients cannot be controlled and algae blooms occur, other methods have been used to control algae (and other) growths in a lake. One of the oldest techniques for algae control is the addition of copper sulphate to the lake. To be effective, this must be added at the beginning of the rapid algae growth period in order to restrict the growth. Repeat application during the maximum growing season is common. However, this relieves the symptoms without curing the disease. If the nutrients are not reduced, the growth will recur every spring and copper sulphate must be reapplied. Even though the copper sulphate addition is in the range of $0.1–1\,\mathrm{mg\,L^{-1}}$, repetitive addition can result in a build-up of copper carbonate in the bottom of the lake over a period of years. With time this can result in concentrations harmful to fish and other aquatic life. A big concern is when a lake becomes acidified as the result of acid rain, particularly in the northeast USA. At the low pH of many lakes, the copper carbonate is dissolved, releasing copper (and other precipitated metals) to the water column. This kills not only the algae, but also most other aquatic life including fish. The use of copper sulphate as an interim algal control method until nutrient releases to a lake are reduced and lower algae concentrations can be accepted, but it is not recommended for long-term remediation. Further, the proposed US EPA regulations (EPA-HQ-OPP-2005-0558) for copper risk assessment would greatly lower the acceptable copper concentration in drinking water to a point that would seriously restrict the use of copper sulphate for algae control. A point taken by the American Water Works Association (AWWA) [40] is that the toxins not removed by the copper could be a greater health hazard than the residual copper in the drinking water [21].

Today there are numerous chemicals available for use as algaecides [21]. Similarly, there are many herbicides available for terrestrial weed control. Many of these herbicides are also effective for algae control. For best control, chemicals should be added before the time of rapid growth in spring. Much literature is available concerning chemicals for algae control. However, there are many different species of algae, and just as many susceptibilities to control by a specific algaecide. The most common algaecides are designed for swimming pools. The algae in a lake may not respond to treatment by swimming pool chemicals. Each situation must be studied independently in order to find the chemical that is most effective and/or economical for a specific situation. In addition, consideration must be made for herbicides from farmland or lawns to gain access to the body of water. These could either add to the effectiveness of a specific algaecide or neutralise its effectiveness. Similar to the use of copper sulphate, chemical addition does not cure the cause of the algal bloom. If provisions are not made to reduce the inputs of nutrients, they may merely cause a problem downstream. Also not controlling the nutrient inputs will mean that the algaecides may have to be added more frequently for effective control.

If a lake or reservoir is to be used as a drinking water supply, caution must be made in the addition of chemicals. Only certain chemicals have been approved for algae control in drinking water supplies. Even these raise questions of safety by the users. Table 1 lists the algaecides certified by the National Sanitation Foundation (NSF) for application in drinking water supplies [21].

Sonar© has been approved for the control of *Eurasian milfoil* in water supply lakes, but the public does not have sufficient assurance that it is safe, so it is not used in Lake George, NY [41]. Algaecides are usually designed to break down with time so there is no residual. They should also be removed by normal water treatment processes. In the case of Lake George, the only treatment is filtration (to remove the algae) and chlorination. Thus there is a stalemate in the use of Sonar© while the milfoil continues to spread [21].

A rather unique system was studied [42] wherein the algae were co-adsorbed with magnetite in the presence of ferric chloride. Greater than 90% chlorophyll removal was achieved using a high-gradient magnetic filter. No information is available as to the development of this system [21].

A recent device to control algae without the use of chemicals is an ultrasonic transducer called SonicSolutions© [43]. An ultrasonic transducer floats just below the water surface and generates a precise frequency that destroys cellular functioning and structure of algae without harming fish, plants or other aquatic life. Installation after a bloom has been established to significantly reduce the bloom within 2 weeks. Better control is maintained by operating at the start of the spring growth. Present units require between 20 and 45 W of power. Here again, the unit does not reduce the nutrients in the body of water, so they may continue to affect downstream waters and recur in the following years in the working pond. Obviously there are no residuals from chemicals from using this system [21].

Table 1
Algaecides certified by NSF (USA) for drinking water applications [21]

| Name of algaecide |
|---|
| Sodium chlorite |
| Calcium hypochlorite |
| Sodium hypochlorite |
| Copper sulphate |
| Algimycin PWF |
| Sodium percarbonate |
| HTH® (Chlorine releasing compounds) |
| Bromochlorodimethylhydantoin |
| BULAB 6002 |
| Advanced blue (copper sulphate) |
| Chemfloc |
| Agritec |
| Earth Tec |
| Pristine blue (copper sulphate) |
| Lifespan bottled water solution |
| Lifespan ice solution |
| PHL 104 |
| Chlorine |

## 6. Harvesting of algae

### 6.1. Coagulation/flocculation and electrolysis experiments

A review of the literature suggested that chemical coagulation/flocculation followed by sedimentation or flotation would be the most likely methods of economically and reliably achieving algae removal under the conditions encountered in most wastewater lagoons [44]. In the point of view of coagulation/flocculation and sedimentation (or flotation) processes, algae can be described as hydrophilic bio-colloids with apparent negative surface charges. In addition, their small size, 3–15 μm, and low specific gravity further complicate physicochemical removal processes. Destabilisation of algae suspensions have been accomplished with lime, alum, ferric sulphate, magnesium ions and many synthetic organic polyelectrolytes. As might be expected, the effect of each coagulant is dependent on pH, algae concentration and other parameters [44].

Aragón et al. [18] carried out experiments for the separation of algae grown in effluents from the anaerobic treatment of urban wastewaters. Of all the possible methods mentioned in the literature, Aragón et al. [18] have chosen: one was classical or conventional, i.e. coagulation/flocculation with aluminium sulphate and the other advanced i.e. electrolysis.

With respect to the first method, the influence of pH on the yields obtained has been investigated, comparing the results achieved in experiments carried out with and without control of pH. Indeed, coagulation/flocculation of the algae with aluminium sulphate is verified with a much higher yield at controlled, acid pH (between 5.5 and 6.0) than at the initial, alkaline pH of the culture itself, habitually exceeding 8.5. The doses necessary, with pH control, are five times smaller than when this control is not made. As a general rule, it seems advisable to find a compromise solution with respect to the ranges of pH and concentrations of aluminium sulphate necessary to reach a high level of coagulation/flocculation of the algae: range of pH 6.0–6.5, concentration of aluminium sulphate 30–50 $mg\,L^{-1}$, percentage of algal elimination 80–90 [18].

In the second method, the influence of the various potential differences applied has been investigated, determining for each one of them the relationship between algal separation yield and duration of electrolysis. Indeed, electrolysis using aluminium electrodes has been shown to be a sensitive and efficient method for the separation of algae from the rest of the solution. Only small current strengths are needed, corresponding to very low current densities—for example, for a potential difference of 30 V, the current density was only 65 $A\,m^{-2}$. There was a clear relationship between the potential difference applied and the time of electrolysis necessary to achieve a predetermined level of algal separation. As in the case of coagulation/flocculation with aluminium sulphate, a compromise can also be arrived at with respect to the voltages used: range of potential difference 10–30 V, time of electrolysis 10–20 min, percentage of algal elimination 70–90. Furthermore, due to the lightness of the destabilised algal aggregates, an effect favoured by the trapping of gas bubbles (oxygen and hydrogen), it seems advisable that the separation of algae from the solution be carried out by flotation rather than decantation, which should be taken into account in designing a system of algal separation based on electrolysis [18].

Comparison between the two methods indicates that electrolysis presents clear advantages over coagulation/flocculation with chemical reagents:

(a) Lower cost, as the energy consumption costs will be less than those of the reagents (aluminium sulphate, HCl, etc.).
(b) Shorter time, as the time necessary to carry out electrolysis is less than that necessary to carry out the coagulation/flocculation and subsequent decantation.
(c) Lower probability that the algal aggregate will become contaminated with metallic hydroxides, as in fact happens when the algae are separated by coagulation/flocculation with chemical reagents [8]. This aspect is important in respect of possible subsequent use in animal feeding.
(d) The design of a system of algal separation by flotation (after electrolysis) is not essentially more complicated than the design of a system of separation by decantation (after coagulation/flocculation with chemical reagents), above all when large volumes of liquids are handled [18].

Later, in 1997, Poelman et al. [14] confirmed that electrolytic flocculation has several advantages over the more conventional techniques. Not only does this new technique consumes relatively little energy (0.3 $kWh\,m^{-3}$) and is easy to control and applicable to various groups of algae but, most important, it results in an efficient separation of the algae (>90%). Even if they used aluminium electrodes, for Poelman et al. [14], this technique involves no flocculants and needs only relatively little electricity to flocculate the algae from a suspension and subsequently float the algal flocs. Moreover, since it is not contaminated with toxic flocculants, the harvested algal biomass can afterwards be used for different purposes such as algal feed and food. Poelman et al. [14] concluded that further research on electrolytic flocculation would have to look for application development at the industrial scale and other groups of algae, including marine and saline algae [14].

Recently, Gao et al. [45] investigated the algae removal by electro-coagulation–flotation technology. Their results indicated that aluminium was an excellent electrode material for algae removal as compared with iron. Under the optimal conditions, 100% of algae removal was achieved with the energy consumption as low as 0.4 $kWh\,m^{-3}$. The electro-coagulation–flotation performed well in acid and neutral conditions. At low initial pH of 4–7, the cell density of algae was effectively removed in the electro-coagulation–flotation, mainly through the charge neutralisation mechanism; while the algae removal worsened when the pH increased (7–10), and the main mechanism shifted to *sweeping flocculation* and enmeshment. Furthermore, initial cell density and water temperature could also influence the algae removal. Overall, the results indicated that the electro-coagulation–flotation technology was effective for algae removal, from both the technical and economical points of view [45].

As seen above, Aragón et al. [18] and Poelman et al. [14] mentioned the fact that for electrolytic flocculation lower probability that the algal aggregate will become contaminated with metallic hydroxides (toxic flocculants), as in fact happens when the algae are separated by coagulation/flocculation with chemical reagents [8,46]. This aspect is important in respect of possible subsequent use in animal feeding. However, many reports have demonstrated that electrolytic flocculation is also toxic to algae as it is for coliforms and *Esherichia coli* [45,47,48]. On the other hand, ultra-violet (UV) irradiation may have some effects on ultrastructure and related metabolic functions [49]; consequently, some precautions must be taken especially when algae are exposed to sunlight during summer.

A good review on algae and cyanotoxins removal by coagulation/flocculation may be found elsewhere [50].

### *6.2. Algae removal (recovery?) by dissolved air flotation*

The above-described methods to control algae growths or interfere with their growth do little to alleviate the cause for their productivity: sufficient nutrients to support an undesirable level of their growth. Unless the nutrients are removed from the body of water, these remediation techniques will have to be repeated every year or continuously, depending upon the specific situation. For example, in tropical waters there is less seasonal cycle of growth, and year-round growth can exist so long as the nutrients are available. As soon as the remediation techniques are discontinued, the algae growths will resume. Any actions that kill the algae without their removal will allow the dead algae to sink to the bottom where, if the action has not already ruptured the algae cells and released their organic matter, they will rupture and release its organic matter. This organic matter is then broken down by bacteria, releasing inorganic nutrients. Thus none of these techniques will alleviate the problem by reducing the nutrients available [21].

Physical removal of the algae may lessen the taste and odour problem and slightly lower the nutrient levels because the inorganic nutrients have been converted to organic algae cell matter. However, additional incoming nutrients may be greater than the amounts removed to the algal cells. Physical removal may include straining through a porous filter or microstrainer. This is effective in removing the algae, but when blooms are present, the filters clog quickly. Similarly, a rapid sand filter as commonly used in water treatment removes most of the algae, but agitation in the sand may rupture the cells, releasing the taste- and odour-producing oils. Algae from a bloom may also require more frequent backwashing of the sand beds [21].

Plain sedimentation for algae removal is ineffective, because many of the algae are motile and can swim against their gravity. Therefore, they do not settle out [21].

Dissolved air flotation has been shown to be an effective means of removal of algae. Dissolved air is introduced as fine bubbles either by means of a diffuser or by release of air from a pressurised tank consisting of either full flow or partial flow as described by Wang et al. [51]. The attached air bubbles cause the algae to float to the surface where they can be gently skimmed off without rupturing. The float can be further treated or the oils from the algae can be retrieved for some use. In addition, coagulants are frequently used to augment dissolved air flotation, and polymers may also increase the removal. Aluminium and iron salts are commonly used as coagulants. Both of these will precipitate phosphates, enabling their reduction as described in [21]. Thus dissolved air flotation with coagulants is effective in both removing the algae and reducing the nutrients available for future algal blooms.

To be most effective, algae should be removed before the treatment plant, particularly before any chlorination. Algae, as with most organics, produce disinfection by-products that may be harmful to humans. Further, rupture of the algae cells such as by agitation or rapid sand filtration will release the taste and odour oils, and in some cases toxic substances. Thus removal of algae at the water intake pipe is recommended. In addition, if the algae are removed in the pond using the addition of alum or iron chlorides, there will be some reduction of phosphorus, which may reduce the total algae growth by limiting the essential phosphorus nutrient [21].

Algae and phosphorus removal have been demonstrated at numerous installations. The City of Pittsfield in western Massachusetts, USA was an early city to install a Krofta Sand-Float system for removal of algae. Since alum was used as a coagulant, it also served to remove phosphate. Results of a pilot study [21] using water from Stockbridge Bowl showed significant removal of turbidity (algae) and phosphate within 15 min of the start of the operation. Continuous operation for 4 h showed continuous removal. The size of the treatment system suggested that it could be mounted on a barge and floated out into the lake.

On the other hand, dissolved air flotation is more effective than sedimentation in removing algae [52]. This is an important advantage since poor removal of algae can lead to clogging of granular media filters and short filter runs. While diatoms are well-known filter clogging algae, other algae types can clog filters including green algae, flagellates and blue-green algae (cyanobacteria).

A good summary of the effectiveness of dissolved air flotation with some comparisons to sedimentation can be found in [53]. Generally, they report 90–99%

removal by dissolved air flotation of algal cells for various algae types compared to 60–90% by sedimentation. A review paper on separation of algae by Henderson et al. [54] report dissolved air flotation removals of 96% to about 99.9% when pre-treatment and dissolved air flotation are optimised. It is concluded that dissolved air flotation removes about 90–99% of a variety of algae from water supplies and is more effective than sedimentation. It is noted that when algae levels are exceedingly high, one can expect even greater removals, but when algae levels are low, the per cent removals are less [52].

### *6.3. Microbial flocculation*

Lee et al. [8] affirmed that the microbial flocculation has the potential to provide a solution without the use of contaminating metallic ions such as $Al^{3+}$. However, such flocculation would require the mixing of mega- or even giga-litres of microalgal culture on a daily basis and therefore it is important to estimate the energy required. By incorporating a baffled hydraulic flocculator into a proposed large-scale system that was designed on the basis of laboratory data, the mixing energy required for the flocculation is estimated to be equivalent to $0.893\,kWh/10^3\,kg$ of dry mass flocculated, the overall cost of the process is A\$ $0.13\,m^{-3}$ of the culture medium and the net footprint area of the flocculating system is 0.7% of the proposed 1 $km^2$ high rate algal pond. Their study [8] of microbial flocculation as a harvesting technique demonstrated that it was possible to induce the flocculation of the *P. carterae* by the addition of a low concentration ($0.1\,g\,L^{-1}$) of organic carbon, such as acetate, glucose or glycerine, followed by 24 h of mixing [8]. Glycerine and acetate may be obtained either as the by-product of biodiesel production, or the anaerobic digestion of biomass residue respectively and are therefore potentially low cost.

## 7. Biodiesel from algae: a reality!

### *7.1. Biodiesel*

Biodiesel is a biofuel consisting of monoalkyl esters that are derived from organic oils, plant or animal, through the process of transesterification [6,7,11,55–58]. The biodiesel transesterification reaction is very simple:

$$\text{Triglyceride} + 3\,\text{Methanol} \overset{\text{Catalyst}}{\longleftrightarrow} \text{Glycerine} + 3\,\text{Methyl Esters (Biodiesel)} \quad (1)$$

This is an equilibrium reaction where an organic oil, or triglyceride, can be processed into biodiesel, usually in the presence of a catalyst, and alkali such as potassium hydroxide [55,59]. An excess of methanol is used to force the reaction to favour the right side of the equation. The excess methanol is later recovered and reused. At 60°C, the reaction can complete in 90 min [7].

The triglyceride is a complex molecule that plants and animals use for storing food energy; in more simple terms, it is fat. Table 2 presents the process of making biodiesel [7,60].

Unlike petroleum fuels, the relative simplicity of biodiesel manufacture makes its production scalable. Many existing vendors are small time producers. Biodiesel is a somewhat "mature" fuel, and was used as a diesel alternative in the early twentieth century [55]. This has allowed biodiesel to attain a level of "grassroots" popularity among environmental advocates and visionaries [7].

The energy density of biodiesel is comparable to petroleum diesel. The high heating value of petroleum diesel is 42.7 MJ/kg. Values for biodiesel vary depending on the source of biomass. Typically, biodiesel derived from seed oils, such as rapeseed or soybean produces, 37 MJ/kg, while biomass derived from algae yields 41 MJ/kg [60,61]. Although the lower energy biodiesels based on seed oils are the most common, they have enough energy density to make them a viable alternative to petroleum diesel [7].

Table 3 presents some advantages and problems of adopting biodiesel [7,55,61–65].

Biodiesel can be made from virtually any source of organic oil. Typical sources include restaurant waste oil, animal fats and seed oils. The supply of waste oil is very limited; however, it is a popular source for small scale, independent producers. Large commercial producers often use seed oils, such as soybean, rapeseed, palm and corn oils. Unfortunately, biodiesel derived from seed oil diverts from the food supply and the increasing competition for seed causes the oil, and resulting biodiesel, to become increasingly expensive [7,66].

### *7.2. Algae as a source of biomass*

The algae that are used in biodiesel production are usually aquatic unicellular green algae. This type of algae is a photosynthetic eukaryote characterised by high growth rates and high population densities. Under good conditions, green algae can double its biomass in less than 24 h [59,65,67]. Additionally, green algae can have huge lipid contents, frequently over 50% [59,65]. This high yield, high density biomass is ideal for intensive agriculture and may be an excellent source for biodiesel production (Table 4). Oil

Table 2
The process of making biodiesel [7]

| The process of making biodiesel |
|---|
| (A) The triglycerides, methanol, and catalyst are placed in a controlled reaction chamber to undergo transesterification |
| (B) The initial product is placed in a separator to remove the glycerine by-product |
| (C) The excess methanol is recovered from the methyl esters through evaporation |
| (D) The final biodiesel is rinsed with water, pH neutralised, and dried |

Table 3
Advantages and problems of adopting biodiesel [7,55,61–65]

*Advantages of adopting biodiesel*

(1) Because the fuel is derived from biomass, it does not contribute to atmospheric $CO_2$ emissions
(2) Biodiesel emissions are, on the whole, lower than petroleum diesel. Substituting biodiesel for petroleum diesel results in substantial reductions of soot, sulphur, unburned hydrocarbon, and polycyclic aromatic hydrocarbon emissions
(3) The infrastructure needed for biodiesel already exists. Biodiesel can be used in existing diesel engines blended with petroleum diesel, or can be run unblended in engines with minor modifications. Because biodiesel has twice the viscosity of petroleum diesel, its lubrication properties can actually improve engine life
(4) Biodiesel has low toxicity and is biodegradable
(5) Like petroleum diesel, biodiesel has a more complete combustion than gasoline, giving a cleaner burn

*Problems of adopting biodiesel*

(1) It does produce increased $NO_x$ emissions, relative to petroleum diesel, owing to the higher compression ratios typically used in biodiesel engines
(2) Using biodiesel does reduce the power output of a diesel engine compared to using petroleum diesel; although this is only around 2% overall
(3) The production of biodiesel results in glycerine by-products and wash wastewater
(4) The price of biodiesel is typically higher than petroleum diesel. Although scale of production is a contributing factor, the high cost of biomass is the most important consideration. The rising cost of oil is changing this imbalance
(5) The biomass feed stocks, for making biodiesel, are diverted from other important uses, typically food production. This can force a trade off between food security and energy security

Table 4
A comparison of the oil content found in green algae [7,59]

| Species | Oil content (% based on dry weight) |
|---|---|
| *Chlorella sp.* | 28–32 |
| *Nitzschia sp.* | 45–47 |
| *Nannochloropsis sp.* | 31–68 |
| *Schizochytrium sp.* | 50–77 |

content is only one criterion for selecting the species for cultivation [10]. Growth rate, density and survivorship must also be considered [7,59,68].

The annual productivity and oil content of algae is far greater than seed crops. Soybean can only produce about 450 L of oil per hectare. Canola can produce 1,200 L/ha, and palm can produce 6,000 L. Now, compare that to algae which can yield 90,000 L/ha [7,59,65,69].

Algae have a number of unique benefits. As an aquatic species, they do not require arable land for cultivation. This means that algae cultivation does not need to compete with agricultural commodities for growing space. In fact, algae cultivation facilities can be built on marginal land that has few other uses. The water used in algae cultivation can be fresh water or saline, and salt concentrations up to twice that of seawater can be used effectively [62,70]. This means that algae need not compete with other users for fresh water. Algae also have a greater capacity to absorb $CO_2$ than land plants, and are also not prone to photosynthetic inhibition under conditions of intense sunlight [7,70–72].

After oil extraction from algae, the remaining biomass fraction can be used as a high protein feed for livestock [65,69]. This gives further value to the process and reduces waste [7].

Algae cultivation is typically performed in two ways; open ponds and bioreactors. Open raceway-based ponds are the preferred method of large-scale algae cultivation, and they have been used since the 1950s to produce food supplements and pharmaceuticals [59,73]. A paddlewheel circulates the material down a raceway while providing aeration, mixing and preventing the material from settling on the bottom (Fig. 1). This is a relatively simple system that uses the sun as the primary energy source. Unfortunately, raceway system suffers from relatively low algae densities, environmental variability, water evaporation and high land feet print [59,69]. Because the ponds are open to the environment, maintaining specific species of algae, to the exclusion of others, can be difficult [7,69].

Bioreactors are the preferred method for scientific researchers, and recently for some newer, more innovative production designs are introduced [73]. These systems are more expensive to build and operate; however, they allow for a very controlled environment (Fig. 2). This means that gas levels, temperature, pH, mixing, media concentration and light can be optimised for maximum production [59]. Unlike open ponds, bioreactors can ensure a single alga species is grown without interference or competition [7].

Table 5 presents some problems of biodiesel production from biomass sources which can be resolved by algae cultivation [7,69,74].

Because of its recognised potential, algae cultivation is being investigated in large pilot projects, both public and private, to determine if it may be the key to providing large quantities of oil-rich biomass for biodiesel production. This strategy is by no means recent [7]. The idea of cultivating algae for the purposes of biodiesel production was first seriously investigated by the US Department of Energy's Aquatic Species Program (ASP). This 18-year programme, started in 1978, attempted to identify the species and conditions that would maximise oil yield while minimising capital input [65,75]. Advancements were made in algal physiology, biochemistry, molecular

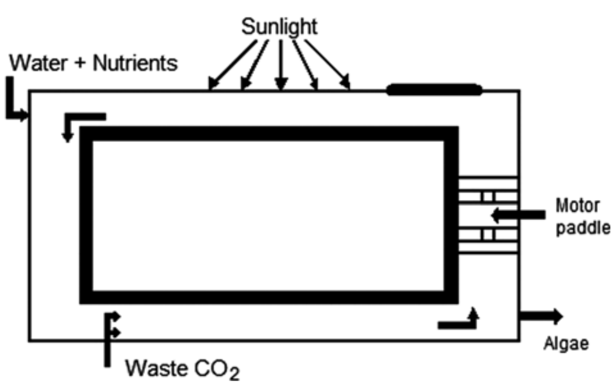


Fig. 1. Open pond system [73].

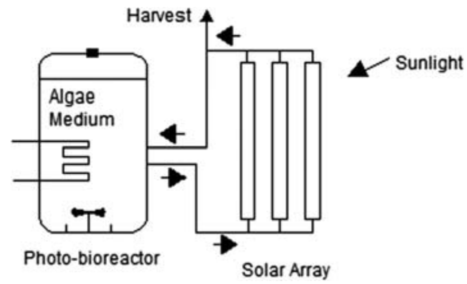


Fig. 2. A tubular photobioreactor with parallel run horizontal tubes [73].

biology and cultivation. The project also yielded a collection of high oil-producing species. The research was performed in open ponds and the yields were in the range of $30\,g\,m^{-2}\,d^{-1}$. Although this project is no longer in operation, it has provided an excellent research base for new initiatives.

The economic environment has changed since the ASP was terminated, and changed in a way to make algae cultivation more cost competitive. High oil prices, low biofuel feedstock and high government incentives are improving the outlook for private investors interested in algal biodiesel [7,69,76,77]. Large energy corporations, such as NRG Energy, Inc., have already begun pilot projects [78]. Governments, seeking fuel security and climate change mitigation, are also initiating new algae-based biofuel projects through policy and investment [79–81].

### 7.3. Perspectives of algal biodiesel production

A good discussion of innovative approaches to improving algal biodiesel production yields may be found in [7]; however, Table 6 summarises these innovative approaches [7,59,65,70,79].

Algae cultivation has four basic, and equally important, requirements: carbon, water, light and space (Table 6). The illustration in Fig. 3 [82] is a conceptual model for integrated biomass production that can be adopted for micro-algal biodiesel production. The illustration in Fig. 4 [8] is a sketch showing the top and side views of the clarifiers and flocculator (microbial flocculation [8]). By maximising the quality and quantity of these requirements, it is possible to maximise the quantity of oil-rich biomass and the return on investment. Ironically, this can often be done by using underutilised resources or waste products, which can provide additional benefits or even offset the cost of production. This requires innovative approaches [7]. Because maintaining ideal growth conditions requires a highly controlled environment, new and innovative approaches to algae production tend to use bioreactors.

Table 5
Problems of biodiesel production from biomass sources which can be resolved by algae cultivation [7,69,74]

*Problems of biodiesel production from biomass sources*

(1) Most biomass sources, such as waste oil, animal fat, and vegetable oil have a limited supply
(2) Many of these sources have competitive uses, such as food or cosmetic production
(3) The resources that were used to create the biomass have competition with other uses, and this includes arable land
(4) Because of the limited supply and competition, many sources of biomass have become increasing expensive

*Algae cultivation has the potential to address all of these issues*

(1) Algae biomass can be produced at extremely high volumes and this biomass can yield a much higher percentage of oil than other sources
(2) Algae oil has limited market competition
(3) Algae can be cultivated on marginal land, fresh water, or sea water
(4) Innovations to algae production allow it to become more productive while consuming resources that would otherwise be considered waste

Table 6
Four basic requirements: carbon, water, light, and space for algae cultivation [7,59,65,70,79]

*Carbon ($CO_2$), to be provided at very high levels*

(1) $CO_2$ needs much higher than can be attained under natural conditions. Rather than becoming an expense, this need for $CO_2$ fertilisation creates a unique opportunity to offset costs by consuming air pollution
(2) The flue gases, from industrial processes (power plants), are rich in $CO_2$ that would normally be released directly into the atmosphere and, thereby, contribute to global warming
(3) By diverting the $CO_2$ fraction of the flue gas through an alga cultivation facility, the $CO_2$ can be diverted back into the energy stream and the rate of algal production can be greatly increased. Although most of the $CO_2$ will ultimately be deposited in the atmosphere, we can realise a greater energy return for each molecule of carbon
(4) The ultimate goal will be to provide greater return on investment for the algae cultivation facility
(5) This process is being investigated at several sites using both bioreactor designs and open ponds

*Water, containing the essential salts and minerals for growth*

(1) Fresh water is a valuable resource as are the salts and minerals needed
(2) Algae cultivation can be coupled to another type of environmental remediation that will enhance productivity while mitigating pollution. High nutrient wastewater from domestic or industrial sources, which may already contain nitrogen and phosphate salts, can be added to the algal growth media directly. This allows for algae production to be improved cheaply, while simultaneously treating wastewater
(3) Salt water can be used (saline aquifer or sea water)

*Light, necessary for photosynthesis*

(1) This is often accomplished by situating the facility in a geographic location with abundant, uninterrupted sunshine such as the American Southwest. This is a favoured approach when cultivating in open ponds
(2) When working with bioreactors, sunlight quantity and quality can be further enhanced through the use of solar collectors, solar concentrators, and fibre optics in a system called "photo-bioreactors". These technologies allow optimal sunlight to reach the algal cells either by allowing them to float in arrays of thin, horizontal tubes or by directing light, through a fibre optic matrix, through the bioreactor chamber itself

*Space*

(1) Other biomass sources require terrestrial cultivation on valuable arable land. This causes a diversion of agricultural produce from the food supply to the energy supply and increases cost of production
(2) Algae cultivation is unique in that it does not require arable land; algae can be cultivated in ponds, in fresh or salt water bodies, or in bioreactors. This versatility means that an algae production facility can theoretically be located any where there is cheap, available land
(3) Bioreactor facilities have a comparatively low footprint

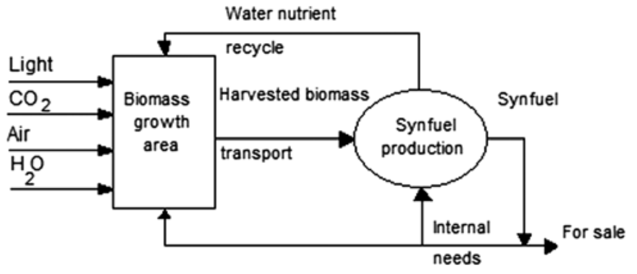


Fig. 3. A conceptual model for integrated biomass production [82].

Although this increases complexity and cost, it has resulted in some very impressive results, doubling or even tripling the $30\,g\,m^{-2}\,d^{-1}$ yields obtained in the ASP [65].

Through a combination of these light, water and carbon fertilisation techniques, the production of high density algae is starting to be achieved [7]. Two experimental facilities, the Oakridge National Laboratory and the ASP Red Hawk Power Plant, have demonstrated very high yields using advanced photo-bioreactor-based designs. The Oakridge National Laboratory yields $60\,g\,m^{-2}\,d^{-1}$ of algae, and the APS Red Hawk Power Plant yields algae with an astounding average of $98\,g\,m^{-2}\,d^{-1}$ [65].

Laboratory studies, exploring methods to maximise both density and oil content, have demonstrated that there is yet much unrealised potential. Xu et al. [60] cultivated the algae *Chlorella protothecoids* in a light deprived, heterotrophic environment with inexpensive hydrolysed corn starch as the sole food source. The algae were not only able to adapt to this environment, they reached a high population density of $15.5\,g\,L^{-1}$. As the algae adapted to the environment, they lost their photosynthetic organelles and almost doubled their oil content, going from 30 to 55.3%. The significance of research such as this is that it demonstrates that algae cultivation is still in its infancy. With time and experience, algae cultivation should be able to achieve dramatic improvements in density, growth rates and oil production. This will require improved growing methods, species selection, cultivation techniques and bio-engineering [7,68].

As concluded by Campbell [7], biodiesel has great potential; however, the high cost and limited supply of organic oils prevent it from becoming a serious competitor for petroleum fuels. As petroleum fuel costs rise and supplies dwindle, alternative fuels will become more attractive to both investors and consumers. For biodiesel to become the alternative fuel of choice, it requires an enormous quantity of cheap biomass. Using new and innovative techniques for cultivation, algae may allow biodiesel production to achieve the price and scale of production needed to compete with, or even replace, petroleum [7].

### 7.4. Economic aspects of biodiesel production

Recently, Marchetti [83] studied the effect of the most important economic variables of a biodiesel

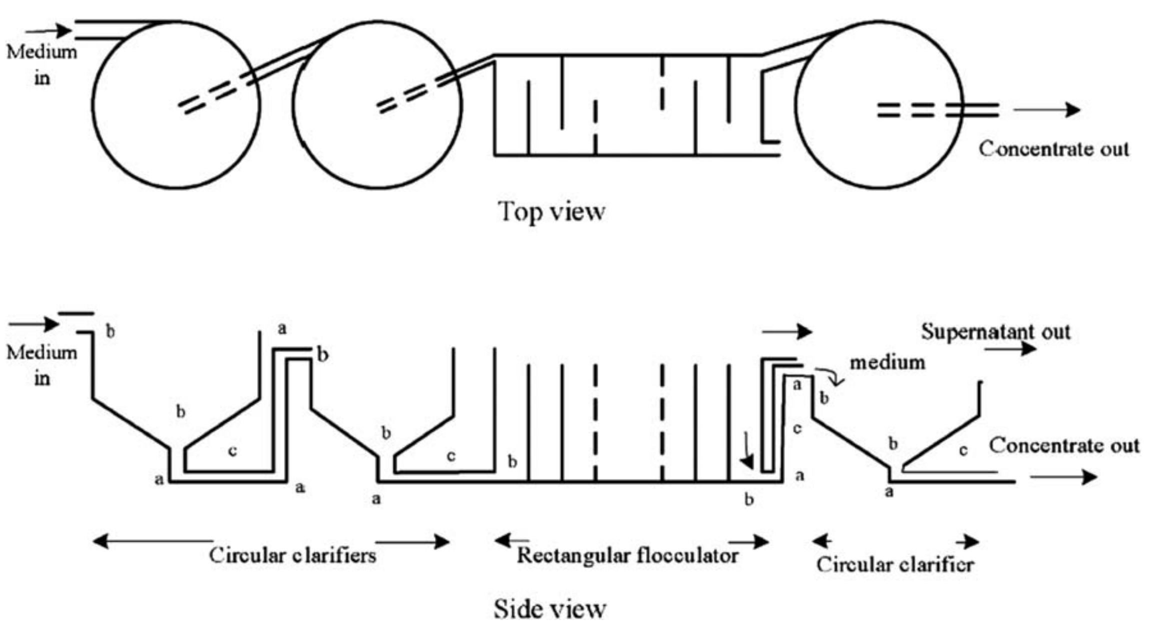


Fig. 4. Sketch showing the top and side views of the clarifiers and flocculator. The 90° bends are indicated by “a”, the entrances and exits are indicated by “b” and the frictional losses along the pipes are indicated by “c”. The energy loss associated with a, b and c is accounted in [8].

production process over the general economy of a conventional plant which employs sodium methoxide as catalyst. He analysed the effect of the oil price, the amount of free fatty acid, the biodiesel price, the cost of the glycerin, the effect due to the modification on the methanol price, the washing water price and several others. Small variations on some of the major market variables would produce significant effects over the global economy of the plant, making it non-profitable in some cases [83].

## 8. Algae recovery instead of its removal in water treatment plant

As seen above, algae are removed from water during conventional water treatment (especially by coagulation/flocculation followed by sedimentation or flotation, which are also considered as harvesting processes). The question which may be asked is about algae recovery instead of its removal in water treatment plant to join the useful to the agreeable. As mentioned in Table 1, there are only certain chemicals that have been approved for algae control in drinking water supplies.

A new interesting field of research would be fast and simultaneous algal biodiesel production with drinking water treatment in the biodiesel production/water treatment plant without chemicals. The fact that algal cultivation has four basic requirements, i.e., carbon, water, light and space (Table 6), as fast as conventional water treatment plant (2–4 h) and without chemicals would be very difficult challenge.

In a similar perspective, Chinnasamy [83] presented an interesting work on micro-algae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications. Furthermore, Park et al. [84] worked on wastewater treatment high rate algal ponds for biofuel production. Subhadra and Edwards [36] proposed an integrated renewable energy park approach for aligning renewable energy industries in resource-specific regions in the USA for synergistic electricity and liquid biofuel production from algal biomass with net zero carbon emissions. These authors [36] also discussed the benefits, challenges and policy needs of this approach. Further, recent and good reviews are presented by Pitttman et al. [85] on the potential of sustainable algal biofuel production using wastewater resources, Singh et al. [10] on the mechanism and challenges in commercialisation of algal biofuels, and Singh and Gu [86] on the commercialisation potential of micro-algae for biofuels production.

Lu [87] addressed three fundamental questions for the development of microbial synthesis of biofuels to be successful [87]. Firstly, what energy resource platform could be used to make biofuels? Secondly, what type of biofuel is the ideal fuel molecule that should be targeted? Finally, what microbial system could be used to transform energy resources into the targeted biofuel molecules [87]?

In this perspective, the potential of using photosynthetic microbes (cyanobacteria in particular) in the solar energy-driven conversion of $CO_2$ to fatty acid-based biofuels is explored [6,88–100].

At this moment, there is no economic study of algae recovery for biodiesel production in water treatment plant such as energy evaluation of coupling nutrient removal from wastewater with algal biomass production which was recently performed by Sturm and Lamer [101]. Their results show that biofuel production is energetically favourable for open pond reactors utilising wastewater as a nutrient source, even without an energy credit for nutrient removal. The energy content of algal biomass was also considered as an alternate to lipid extraction and biodiesel production. Direct combustion of algal biomass may be a more viable energy source than biofuel production, especially when the lipid content of dry biomass (10% in this field experiment) is lower than the high values reported in lab-scale reactors (50–60%) [101]. On the other hand, recent studies [102–104] attracted our attention to the dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Amaro et al. [105] presented an intensive review on the current techniques related to harvest and biodiesel production from the algal biomass and Ketheesan and Nirmalakhandan [106] developed a new air-lift-driven raceway reactor for algal cultivation.

Finally, the main economic advantage of algae recovery from water treatment plant may be the recovery of algae—a sustainable energy resource with great potential for $CO_2$ fixation [107]—for biodiesel production instead of their difficult removal (chemical removal using copper sulphate for example).

## 9. Conclusions

This paper discussed the concept of the future drinking water treatment plant where algae harvesting for biodiesel production—which would be more practical than for feedstock production due to the metal toxicity—from the algal biomass is suggested instead of algae removal which has several disadvantages. The main conclusions drawn from this review are:

(1) Micro-algae are a sustainable energy resource with great potential for $CO_2$ fixation. For biofuel production, a large quantity of algal biomass is

needed. The micro-algae could be grown in photo-bioreactors or in open ponds. By using a transesterification process, algae oil can be converted to biodiesel. The next years will show whether these promises can be kept on a pure commercial basis for a whole process chain from algae cultivation to oil extraction during a whole year and on a real hectare.

(2) Coagulation/flocculation and electrolytic flocculation are toxic to algae and UV irradiation may have some effects on ultrastructure and related metabolic functions; consequently, some precautions must be taken especially when algae are exposed to sunlight during summer.

(3) A new interesting field of research would be fast and simultaneous algal biodiesel production with drinking water treatment in the biodiesel production/water treatment plant without chemicals. The fact that algal cultivation has four basic requirements, i.e. carbon, water, light and space, as fast as conventional water treatment plant (2–4 h) would be very difficult challenge. In other words, optimising algal production and algal recovery in water treatment plant should also be addressed by the future researches.

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