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Review

Harvesting of Microalgae by Flocculation

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Abstract: Due to increasing demands for microalgal biomass and products originating from microalgae, large-scale production systems are necessary. However, current microalgal production technologies are not cost-effective and are hindered by various bottlenecks, one of which is the harvesting of microalgal biomass. Cell separation is difficult because of the low sedimentation velocity of microalgae, their colloidal character with repelling negative surface charges, and low biomass concentrations in culture broths; therefore, large volumes need to be processed in order to concentrate the cells. Flocculation is considered to be one of the most suitable methods for harvesting microalgal biomass. This article provides an overview of flocculation methods suitable for microalgal harvesting, their mechanisms, advantages and drawbacks. Special attention is paid to the role of surface charge in the mechanism of flocculation. The novelty of the review lies in the interconnection between the context of technological applications and physico-chemical surface phenomena.

Keywords: microalgae; harvesting algal biomass; flocculation; mechanism; flocculant

1. Introduction

After cultivation, the volume of microalgal suspension needs to be significantly reduced. A two-step harvesting process can achieve cost-effective downstream processing because a low-cost technique such as flocculation can be applied before the energy consuming physical cell separation processes (e.g., centrifugation, filtration) that require expensive equipment [1–3]. Thus, in the first step, the diluted cell suspension (e.g., 0.5 g/L) can be pre-concentrated 20–100 times, resulting in an algal slurry (10–50 g/L). Subsequently, the slurry is further concentrated mechanically, e.g., by centrifugation, resulting in an algal paste having a dry matter content of 25% *w*/*v* [4].

Current harvesting methods include biological, chemical, mechanical, and to a lesser extent, electrical operations [5]. In general though, there is no proven single best method for harvesting microalgae [6], as each has its advantages and disadvantages (Table 1). Typical strategies currently applied for harvesting microalgae include centrifugation, filtration, various forms of flocculation (e.g., chemical using inorganic and organic agents, alkaline flocculation, bio-flocculation using microorganisms, electro-coagulation), sedimentation, and flotation. Flocculation can increase the sedimentation rate by aggregating the microalgal cells and so ease subsequent separation by sedimentation, centrifugal recovery, or filtration [4–7].

Harvesting costs that represent 20–30% of total production costs are often reported in the literature [5,7]. Fasaei et al. assessed operational costs of different microalgal harvesting methods to be in the range of 0.1–2 €/kg and energy consumption between 0.1–5 kWh/kg, depending on the initial biomass concentration and separation technique used. These estimates are somewhat lower compared to those published previously and represent 3–15% of production costs [8]. Capital expenditures are

generally also very difficult to estimate, nevertheless, harvesting and dewatering equipment may represent 90% of the total cost in the case of microalgal production in open ponds [9]. Overall or specific costs of microalgal biomass separation are difficult to determine either due to unavailable information or they vary in a very broad range for the following reasons: (i) They depend on the used microalgae (size, surface charge) and separation method (Table 1); (ii) costs of separation depend also on cultivation systems, which determine the harvesting density of microalgae; (iii) the combinations of different separation methods are often used (e.g., pre-concentration by flocculation and subsequent dewatering by centrifugation). Moreover, innovative commercial equipment is offered on the market based on modified centrifugation—spiral plate technology (dynamic settler) [10] or advanced membrane technology—hollow fiber [11]. Nevertheless, flocculation is still regarded as a promising technique that could substantially improve the energic and economic balance of harvesting [12].

Table 1. Comparison of microalgal harvesting methods [5,13,14].

Method	Advantages	Disadvantages	Dry Solids after Harvesting (%)
Centrifugation of microalgae	Cell recovery over 90%, can handle most algal types with rapid efficient cell harvesting, reliable.	High capital and operational costs, energy intensive	12–22
Filtration of microalgae	Cell recovery 70–90%, wide variety of filter and membrane types available, reliable, can handle delicate cells.	Highly dependent on algal species, best suited to large algal cells, clogging or fouling an issue, high capital and operational costs.	5–27
Sedimentation of microalgae	Cell recovery 10–90%, low cost, potential for use as a first stage to reduce energy input and cost of subsequent stages.	Algal species specific, best suited to dense (heavy) non-motile cells, separation can be slow or unreliable, low final concentration.	0.5–3
Flotation of microalgae	Cell recovery 50–90%, can be more rapid than sedimentation, possibility to combine with gaseous transfer.	Algal species specific, high capital and operational cost, flocculants usually required.	3–6
Flocculation + sedimentation of microalgal flocs	Cell recovery over 90%, wide range of flocculants available, variable price, can be low-cost.	Removal of flocculants, chemical contamination, fragile flocs and/or longer settling times.	3–8
Electroflocculation + sedimentation or flotation of microalgal flocs	Cell recovery over 90%, low energy consumption, possibility to combine with flotation in one step	Contamination of biomass with metal ions, active chlorine can be formed by treatment of seawater	10 (sedimentation) 30–40 (flotation)
Magnetic separation of microalgae	Cell recovery over 90%, fast, can be considered as one harvesting step, cost effective.	Magnetic modification of biomass required, subsequent obtaining of pure and magnetic particle-free biomass can be problematic.	10–20

2. Flocculation

Generally, the destabilization of colloidal suspensions by an electrolyte is regarded as *coagulation*, whereas aggregation of the particles as a result of polymer addition is termed *flocculation* [15]. Nevertheless, the majority of authors that report on harvesting of microalgae do not differentiate

between these two terms; this review will use the term flocculation for different types of cell aggregation [16].

Flocculation as a unit operation is exploited in different industries such as brewing, waste and drinking water treatment and mining. While in these applications, liquid is often the end product, for harvesting microalgae it is the biomass that is the end product. In microalgal harvesting by flocculation, biomass contamination with a chemical flocculant is an important issue. Chemical flocculants can cause harm to the final product (biomass for food or feed) or biomass processing (lipid extraction) [4].

Flocculation is normally used in conjunction with other harvesting (dewatering) methods as a pre-harvesting step [17]. Water removal during flocculation decreases the costs of mechanical dewatering [18]. To maximize cost savings during mechanical dewatering, it is recommended to obtain the smallest possible volume of algal slurry over the shortest period of time [19]. Therefore, microalgal flocs should be large with a high sedimentation rate. This can also be achieved using magnetic flocculating agents [19].

Flocculation is a complex process influenced by cell surface properties, cell concentration, pH of the environment, ionic strength, and type and dosage of flocculant [20]. Crucial for flocculation efficiency is also mixing, which defines the number and intensity of collisions, enabling floc formation and influencing its properties [21]. An ideal flocculant should be inexpensive, nontoxic and effective at low concentrations and it should preferably be derived from non-fossil fuel sources, thus being sustainable and renewable [13]. Although flocculation is considered as the most suitable method for harvesting microalgal biomass, this method can involve economic or technical drawbacks, such as a high energy cost, flocculant toxicity, or non-feasibility of scaling up [15]. These aspects of flocculation will be described in more detail in the following sections.

Since the terminology concerning microalgal flocculation is somewhat misleading, this article will use the following classification of different flocculation methods: (i) Spontaneous and forced alkaline flocculation [22]; (ii) chemical flocculation with addition of flocculants [23]; (iii) physical flocculation induced by ultrasound or electric field; (iv) autoflocculation provoked by extracellular polymeric substances (EPS) [24]; and (v) bioflocculation involving other microorganisms [25].

2.1. Mechanism of Flocculation

Floc characteristics such as floc size, structure and density are determined by the formation mechanism and ultimately they affect important parameters such as settling velocity and concentration factor [26]. Settling velocity is a key parameter in the design of sedimentation vessels, while concentration factor is the most important criterion to evaluate the overall process efficiency [27].

Negatively charged microalgal cells are stable in dilute solution. This negative surface charge can be neutralized and destabilized with positively charged flocculants (polyvalent cations and cationic polymers) [28]. Flocculation of cell suspensions can be described by individual mechanisms and their combinations: (i) Charge neutralization (canceling the negative surface charge of microalgae by ion, polymer or colloidal absorption); (ii) electrostatic bridging mechanism (charged polymers locally attach to the surface of microalgae and form bridges between them) and (iii) sweeping flocculation (flocculation by massive precipitation of a mineral) [4] (Figure 1).

The most commonly used flocculants are metal salts (alum and ferric chloride), where the metal ions can cause flocculation through charge neutralization. The remaining flocculation mechanisms (charge neutralization, bridging, or sweeping flocculation) are induced by positively charged precipitates such as calcium phosphates or magnesium hydroxides [4].

Charged cationic biopolymers are also important flocculants that can electrostatically interact with different cell surfaces resulting in flocculation through bridging by charge neutralization or electrostatic patch aggregation [4]. The use of polymers leads to higher effective density (floc compaction) and thereby improved sedimentation velocity. Settling properties are further improved when biopolymers are used as flocculant aids in combination with e.g., alum as a primary coagulant [21,27].

All flocculation methods strongly depend on cell surface properties of microalgae (species, culture conditions and growth phase) [4]. Smaller species have higher specific surface areas thus requiring a higher flocculant dose per biomass weight [29]. In addition, flocculation is affected by the composition of the culture medium. Both pH and ionic strength influence the surface charge of microalgal cells and chemical flocculants. Microalgae also often excrete algogenic organic matter (AOM), consisting mainly of polysaccharides and proteins, into the growth medium [30]. The AOM compete with flocculants for the algal cell surface and thus interfere with flocculation [31,32]. Some results suggest that the requirements for flocculants are determined more by the quantity and composition of AOM than by the surface properties of the microalgal cells [33,34].

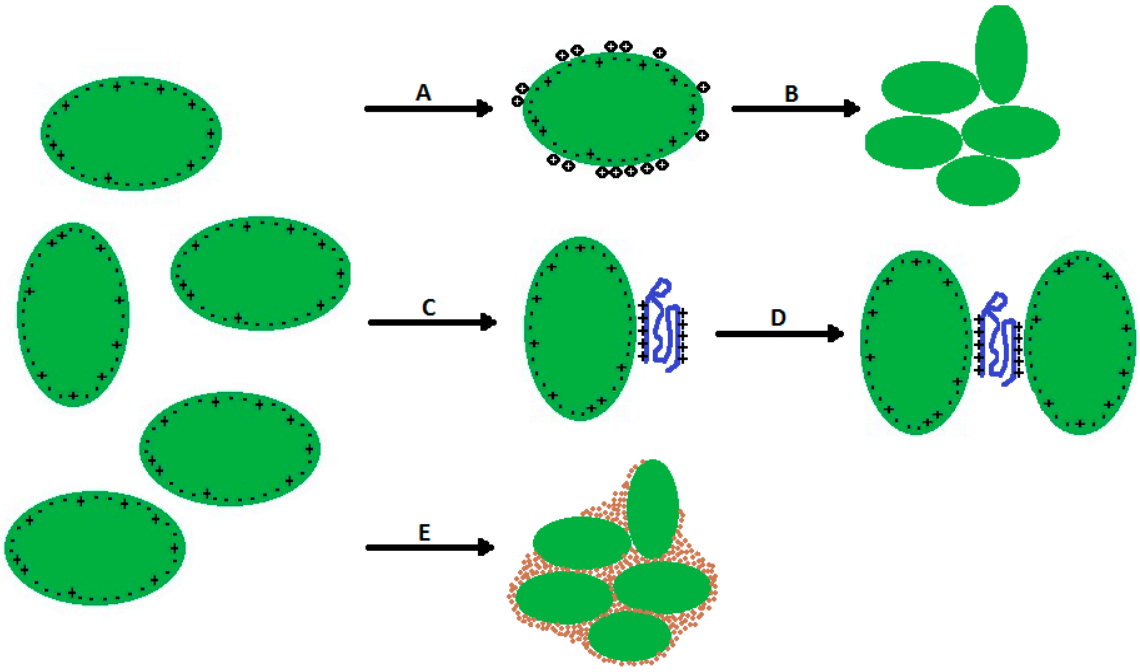

Figure 1. Basic flocculation mechanisms: **A**—canceling the negative surface charge of microalgae by ion, polymer or colloidal absorption; **B**—interaction of surface neutral microalgal cells based on the thermodynamic balance of interaction energies; **C**—charged polymers or colloids locally attach to the surface of microalgae; **D**—charged polymers or colloids form bridges between two cells; **E**—entrapment of cells in a massive precipitate.

2.2. Surface Properties Affecting Flocculation

Due to their small size, microorganisms can be regarded as colloidal particles and so colloid surface thermodynamics can be applied for microbial systems. Therefore, microbial adhesion is predictable by using classical theories of colloidal stability, i.e., Derjaguin-Landau-Verwey-Overbeek (DLVO) theory together with its extended version (XDLVO). Data input for these physicochemical models are obtained using contact angle and zeta potential (ZP) measurements of the studied cells and (a)biotic surfaces together with cell/particle size [35].

Whenever a charged particle (microbial cell) is submerged into an ionic aquatic environment it tends to attract ions of opposite charge to maintain electrical neutrality. The system of the particle surface charge and associated counter ions in the surrounding solution is called the electrical double layer. The cloud of counter ions surrounding charged particles in a suspension results in an electrical repulsion between the particles. In case the charged particles are moving, some counter ions are dragged along, while others are left behind. Subsequently, a slipping plane is created at which the potential difference between the particle surface and the bulk solution is called the zeta potential (ZP). It is determined using micro-electrophoresis (measurement of the charged particle's velocity in defined

field strength). Accurate knowledge of ZP values is used to predict and control the stability of colloidal (microbial) suspensions. The higher the value (i.e., >25 mV, positive or negative), the more likely the suspension will remain in stable form as individual particles are strongly repulsing each other. Particle ZP is dependent upon the pH value and ionic strength of the surrounding environment [4,36,37]. Ionic strength (*I*) affects the width of the electric double layer and the value of ZP. When electrolyte concentration increases, electric double layer width decreases. The resulting interaction of EL forces (attractive/repulsive) is therefore dependent upon the character of the charge of interacting surfaces and on the properties of the surrounding electrolyte [38].

Microalgal cell surface charge is created due to ionizable functional groups (i.e., hydroxyl (OH), carboxyl (COOH), and amine (NH_2) groups) present on the cell surface as part of the cell wall or in extracellular algogenic organic matter (AOM) attached to the cell surface [39]. Depending on the environment's pH value, these groups become protonated or deprotonated. ZP of an algal cell is typically electronegative for pH 4–10, ranging around −10 to −36 mV for green microalgae. In general, an isoelectric point of around pH 3–4 is determined for all algal species [4,39,40]. Additionally, algal surface charge has been shown to be species but not phyla dependent. The stage of life cycle can also influence ZP due to variations in quantity and composition of AOM attached to the cell surface, implying that it is actually the organic matter present that controls ZP [39]. The AOM originating from four algae species (*C. vulgaris*, *Microcystis aeruginosa*, *Asterionella formosa* and *Melosira* sp.) have been shown to be predominantly hydrophilic with negative ZP values at pH 2–10 [41].

Surface charges (ZP) of microalgal cells determine the resulting electrostatic forces (EL) that are present in a given system. Generally, microalgae culture media can be divided into low ionic strength (<0.1 M), or high ionic strength environments (>0.1 M) [42]. The thickness of the electric double layer of any particle is strongly dependent on the ionic strength of the surrounding environment, and the decay of electrostatic interactions (EL) occurs with distance [43]. EL are prominent under low ionic strength conditions, thus they are likely to play an important role for algal surface interactions with flocculants in freshwater culture media.

Cell surface components and cell wall composition can also have major contributions to the hydrophobic/hydrophilic, acid-base nature of the microalgal cell surface, which can be of crucial significance for interactions during harvesting with flocculation. Physicochemical approaches, such as the (X)DLVO theory, can show the interplay of all forces, and as such they were considered to be very helpful tools in predicting (un)favorable conditions for microalgal cell surface interactions in studies focusing on various different flocculation strategies [25,44,45].

3. Chemical Flocculation

Multivalent aluminum- and iron-based metal salts have been used as flocculants, but require high doses [46]. In addition, residues of metals may negatively affect both medium recycling and the quality of the products [28].

Because chemical flocculants may contain traces of toxic compounds, e.g., synthetic polyacrylamide polymers contain acrylamide, flocculants based on natural biopolymers are a safer alternative [4]. In order to interact with usually negatively charged microalgal cells, these biopolymers should possess a positive surface charge. Such a positively charged biopolymer is chitosan (Poly-(D)glucosamine), which is a very efficient flocculant but is relatively expensive [47]. An alternative to chitosan is cationic starch, which can be prepared from starch by derivatization with quaternary ammonium groups. Cationic starch acts as a flocculant over a broader pH range than chitosan [34]. Other examples for flocculation are polymers present in flour from *Moringa oleifera* seeds [48], cationic cassia gum [49], or cationic brewer's yeast walls [50]. Biopolymers described as better flocculants showed no growth inhibition, required lower dosage and had a lower environmental impact than metallic salts. Recently, cationic aminoclays were prepared and successfully applied to the harvesting of microalgae. All the biopolymers mentioned above, except *Moringa oleifera* seed flour, require chemical modification of the raw material in order to acquire cationic properties [51,52]. Despite satisfactory

harvesting performance, the cost should therefore be reduced further before this approach is applicable large-scale [28]. An economically viable option could be to use waste materials such as spent brewer's yeast [50].

The effectiveness of chemical flocculation techniques often significantly decreases when they are applied to marine microalgae, due to the high ionic strength of seawater [48,53]. This is due to the near elimination of electrostatic forces of charged particles/ions at high ionic strengths. In marine systems, the dose of flocculants required to flocculate marine microalgae has been found to be 5–10 times higher than that required for freshwater microalgae and the dose was found to increase linearly with salinity of the aqueous environment [13].

Magnetic particles are also potential harvesting agents, the attractiveness of which lies in the non-destructive nature of the magnetic field, particle biocompatibility, easy manipulation and regeneration [54–56]. Magnetic harvesting of microalgae using an external magnetic field after adsorption of a magnetic agent to microalgal cells can be considered as a single step process, since flocculation and separation occur simultaneously [4]. Magnetic particles for harvesting microalgae can be in the form of uncoated magnetic iron oxide particles [57–59] or as functional composites that can consist of a magnetic core coated with silica. This coating can additionally carry specific functional groups such as polyethylenimine or cationic polyelectrolytes such as chitosan, poly(diallyldimethylammonium chloride) and cationic polyacrylamide [55,59–61]. Nevertheless, large scale applications of magnetic particles in the harvesting of microalgal biomass can be successfully used only if the magnetic flocculant is very cheap and/or regeneratable.

4. Spontaneous and Forced Alkaline Flocculation

Among flocculation methods, high pH induced (alkaline) flocculation of algae, mediated by inorganic salt precipitates, has the advantage of using cheap hydroxides (e.g., slaked lime) instead of chemical flocculants [3]. Flocculation induced by both a natural increase in pH due to CO_2 depletion [6,62] and addition of magnesium/calcium hydroxide [63] has long been reported and various mechanisms have been suggested.

Spontaneous alkaline flocculation, also referred to as autoflocculation in some literature, can be observed in microalgal cultures when the pH increases above 9 [64]. Forced alkaline flocculation is caused by pH change-induced formation of calcium or magnesium precipitates, which can carry positive surface charges resulting in flocculation through charge neutralization. Flocculation of negatively charged *Chlorella vulgaris* cells was induced both by positively charged and negatively charged calcium phosphate precipitates. However, the negatively charged calcium phosphate precipitates interacted with negatively charged cells only at an early phase of nucleation. The oppositely charged cells and precipitate particles were attracted electrostatically, while the attraction between equally charged entities probably resulted from a negative total balance of interaction energies. The remaining medium components, other than calcium and phosphate, did not interfere with flocculation, and the effect of cellular organic matter was also very small. The flocculation efficiencies and interaction energies were interpreted from the perspective of colloidal interaction models [5,65]. This type of flocculation can be advantageous where microalgae are used for wastewater treatment and excess phosphate needs to be removed [4].

Positively charged precipitates (up to pH 12) can be formed from magnesium hydroxide (brucite) and they can also interact with the microalgal surface to cause flocculation [22,27]. It is advantageous that the magnesium content of most water is sufficiently high for this process to be possible. It is yet to be proven whether calcium carbonate (calcite) can also induce flocculation of microalgae at high pH. The biomass obtained by flocculation at high pH contains high concentrations of low toxicity minerals, which preferably should be removed [4,23]. A lack of a fundamental understanding of the mechanism of alkaline flocculation may have resulted in the low efficiency and unreliable character of flocculation for some microalgal species. Additionally, extremes of pH may cause cell damage or death, thus being unusable on a commercial scale [13].

5. Physical Flocculation Methods

Biomass contamination by flocculants can be avoided by inducing flocculation with only physical forces. An example of such a method is the application of standing ultrasound waves. High frequency ultrasound (MHz) with a low amplitude induces cell aggregation, whereas low frequency ultrasound (KHz) and a high amplitude causes cell rupture. While this method is easy to apply in the laboratory, it is difficult to carry out in scale-up [66].

Because of the negative charge of algae, the cells can be concentrated by movement in an electric field [67]. The algal cells are attracted to the anode where they lose their charge and form aggregates. Hydrogen and oxygen are released on the electrodes due to electrolysis of water, with the created bubbles rising to the surface, taking with them algal aggregates. The electrolysis thus leads to simultaneous flocculation and flotation of the microalgae, the efficiency of which can be improved by changing the polarity of the electrodes [68]. For harvesting marine species, energy requirements associated with electrolysis are advantageous [68,69]. Electrolytic harvesting of marine microalgae uses 10-times less energy than freshwater species [70] due to the high ionic strength and conductivity of seawater, which substantially reduces the amount of electricity required to release metal ions and bubbles from the electrodes, although it also reduces the effectiveness of other harvesting methods. Electrolytic recovery of marine species can be inconvenient due to the high chloride concentration (approximately 19 g/L) in seawater and the similar redox potential of chlorine dioxide (1.57 V), chlorine (1.36 V) and O_2 (1.23 V), which can result in the formation of chlorine species. Continuously harvested *Nannochloris oculata* using the electrolytic method resulted in chlorine bleaching of the harvested biomass after 20 min of operation [68]. In addition, the residual chlorine species decreased the recyclability of the medium and reduced cell viability [28]. Moreover, the electrodes were prone to fouling [13]. OriginOil Inc. claimed a solution based on using electromagnetic pulses to induce flocculation by neutralizing the surface charge of microalgae [4].

Thus, separation methods based on electrophoresis of algal cells and ultrasonic flocculation have been shown to aggregate microalgae [13]. The major benefit of approaches based on these principles is that no chemical addition is required; however, the high power requirements and electrode costs do not make for an appealing harvesting method, especially for large-scale applications [7].

In electrocoagulation-flocculation, cell aggregation is induced through electrolytic release of metal ions from a sacrificial anode [70]. This approach lies on the border between physical and chemical methods as the metal cations released from the electrode act as chemical flocculants. The electrolytic release of metal ions from a sacrificial anode offers several advantages compared with conventional cationic metal salts, including high harvesting efficiencies, low dose, wide working pH range, and the absence of coupled anions as contaminants of the biomass [71]. Electrocoagulation-flocculation also results in biomass contamination with metals; however, the extent is usually lower than for flocculation by metal salts [4]. Usually aluminum or iron electrodes are used. Cations like Al^{3+} and Fe^{2+} or Fe^{3+} released from the sacrificial anode and hydroxyl ions (OH^-) arising from electrolysis of water form large precipitates of hydroxides, which plays the same role as in chemical flocculation. Subsequently, sedimentation or flotation can be applied to separate the microalgal aggregates from the liquid phase. With respect to contamination of biomass with metal ions, biomass use may be limited to non-food applications such as biofuels [14,72].

6. Autoflocculation and Bioflocculation

Spontaneous flocculation sometimes occurs during natural blooms of microalgae in lakes or rivers [6]. Although the terms are used somewhat interchangeably, autoflocculation and bioflocculation describe different phenomena. The term autoflocculation is usually meant to describe flocculation caused by secreted extracellular biopolymers (EPS) [5], whereas bioflocculation involves other microorganisms. Whole microbial cells without EPS can also be used to induce bioflocculation [73].

Bioflocculation can be successfully used for harvesting microalgae in situations where these cells are used in wastewater treatment [74]. However, the mechanism of bioflocculation should be

better understood given that it could be applied as a chemical-free method of harvesting microalgae. Those microalgal species that flocculate readily can be mixed with other species to induce mutual flocculation [29,75]. Recently, an infochemical isolated from a senescent and flocculating culture of a *Skeletonema* species was found to be capable of inducing flocculation in other species of microalgae [73]. Specific consortia of bacteria [76] or positively charged fungi [46,77] can also induce bioflocculation of microalgae. The flocculating fungi or bacteria can be cultured separately or co-cultured with the microalgae. Co-cultivation can be carried out in wastewater, where a carbon source is usually present [78,79]. It was also observed that a bioflocculant was capable of enhancing the growth rate of microalgae in recycled medium. At the same time, a cationic salt used as a flocculant inhibited the growth of microalgae. Effective harvesting of the marine microalgae *Pleurochrysis carterae* was achieved by a mixture of microbes including *Pseudomonas stutzeri* and *Bacillus cereus* [76]. The use of whole cell bacterial or fungal flocculants masks the risk of microbial contamination, which may prohibit food or feed applications of the microalgae [4].

EPS synthesized by organisms such as bacteria, algae, fungi, and actinomycetes can act as a bioflocculant [28]. Poly (γ-glutamic acid) from *Bacillus subtilis* was effective in harvesting both freshwater and marine microalgae. Additionally, maintenance of cell integrity and the low material price of this flocculant (approximately US$5/kg) are very advantageous [80]. A bioflocculant from *Paenibacillus polymyxa* was successfully combined with cationic chemicals for harvesting *Scenedesmus* sp. with an efficiency of 95% [81].

7. Genetic Modification

Genetic modification of microalgae currently is the focus of significant research. Most recent articles and patents are aimed at increasing biomass or lipid productivity [82,83]. However, genetic modification may also be a promising approach for harvesting microalgae [5,83]. Genetically modified yeast strains have been developed to allow triggered expression of flocculins (proteins) on their cell walls, causing the cells to flocculate [84]. A similar method for flocculating microalgae using interacting ligand–receptor pairs has been described. For example, a culture expressing an antibody could be mixed with a separate culture expressing the corresponding antigen to induce flocculation [4]. Another option is the expression of a ligand/receptor pair in the same strain, which is then sequentially induced to initiate flocculation [85]. Flocculation can also be facilitated by selection. A cell wall-deficient mutant of *Chlamydomonas* has been found to flocculate much more readily under alkaline conditions than the wild type strain [86]. However, for most microalgae, a genetic platform for modification is not yet available. Therefore, the cost of flocculation based on genetic modifications is likely to be high [4,5].

8. Conclusions

Different goals for microalgal biotechnologies often require different harvesting priorities. For high value-added products, harvesting methods should not interfere with the final product, particularly in terms of quality (food grade) and reproducibility. Conversely, low cost microalgal products require low cost harvesting methods, with the possibility of safe and simple waste management.

Despite the numerous harvesting methods available for microalgal biomass, it is not clear which ones may be applicable on a large scale. There are no reliable comparisons of promising methods, including mass and energy balances. Future development in the area of microalgal harvesting methods should focus on comparative case studies carried out at sufficiently large scale. This review summarizes the current knowledge and therefore may serve as a springboard for selecting harvesting methods intended for comparison and testing.

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