REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

ASPECTS RELATED TO THE MICROALGAE HARVESTING PROCESS

ASPECTOS RELACIONADOS CON EL PROCESO DE RECOLECCIÓN DE MICROALGAS

Jacqueline Rêgo da Silva Rodrigues
PhD, Federal University of Sergipe, Brazil
E-mail: jrodrigues@academico.ufs.br

Keilla Santos Cerqueira
PhD student, Federal University of Bahia, Brazil
E-mail: keillascerqueira@gmail.com

Graziella do Nascimento Silva
PhD student, Federal University of Bahia, Brazil
E-mail: graziellanas.silva@gmail.com

Iago Hudson da Silva Souza
PhD, Federal University of Sergipe, Brazil
E-mail: iago_hudson@hotmail.com

Raiane Vieira Chaves
PhD student, Federal University of Sergipe, Brazil
E-mail: raianeufma@gmail.com

Werlisson Santos Souza
PhD student, Federal University of Bahia, Brazil
E-mail: werlissonsouza18@gmail.com

Miguel de Jesus Pereira
Graduate, Federal University of Sergipe, Brazil
E-mail: migueljpr@hotmail.com

José Raí de Jesus Coelho
Master´s student, Federal University of Sergipe, Brazil
E-mail: raijcoelho@gmail.com

Roberto Rodrigues de Souza
PhD, Federal University of Sergipe, Brazil
E-mail: rrsouza.br@gmail.com

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

Abstract

Microalgae harvesting represents a critical step in biotechnological processes due to the low cell concentration and high colloidal stability of microalgal suspensions, which directly affect technical efficiency and operational costs. This review article compiles and analyzes studies related to the main microalgae harvesting methods, with emphasis on low-complexity and potentially cost-effective techniques, such as coagulation and flocculation processes. Different harvesting approaches are qualitatively compared in terms of biomass recovery efficiency, energy demand, economic feasibility, and environmental impact. In addition, the physicochemical mechanisms involved in each method are discussed, aiming to elucidate how factors such as surface charge, particle size, and cell–coagulant interactions influence process performance. The literature indicates that simple methods, such as gravitational sedimentation, present significant limitations, making the integration of processes such as coagulation, flocculation, centrifugation, and filtration essential to overcome efficiency and cost barriers. Although synthetic polymers provide rapid and effective harvesting, concerns regarding residual toxicity have driven the search for environmentally compatible alternatives, including natural biocoagulants. In this context, hybrid solid–liquid separation strategies emerge as promising solutions by reconciling technical performance, environmental sustainability, and economic viability. Advances in the understanding of coagulation and flocculation mechanisms, combined with the careful selection of separation technologies, represent a strategic pathway to optimize large-scale microalgae biomass harvesting and to enhance its potential as a renewable resource for industrial and environmental applications.

Keywords: Coagulation; Electrocoagulation; Filtration; Flotation; Harvest; Microalgae.

Resumen

La cosecha de microalgas representa un paso crítico en los procesos biotecnológicos debido a la baja concentración celular y la alta estabilidad coloidal de las suspensiones de microalgas, lo que afecta directamente la eficiencia técnica y los costos operativos. Este artículo de revisión recopila y analiza estudios relacionados con los principales métodos de cosecha de microalgas, con énfasis en técnicas de baja complejidad y potencialmente rentables, como los procesos de coagulación y floculación. Se comparan cualitativamente diferentes enfoques de cosecha en términos de eficiencia de recuperación de biomasa, demanda energética, viabilidad económica e impacto ambiental. Además, se discuten los mecanismos fisicoquímicos involucrados en cada método, con el objetivo de dilucidar cómo factores como la carga superficial, el tamaño de partícula y las interacciones célula-coagulante influyen en el rendimiento del proceso. La literatura indica que los métodos simples, como la sedimentación gravitacional, presentan limitaciones significativas, lo que hace que la integración de procesos como la coagulación, la floculación, la centrifugación y la filtración sea esencial para superar las barreras de eficiencia y costo. Si bien los polímeros sintéticos

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

proporcionan una cosecha rápida y efectiva, la preocupación por la toxicidad residual ha impulsado la búsqueda de alternativas compatibles con el medio ambiente, incluyendo biocoagulantes naturales. En este contexto, las estrategias híbridas de separación sólido-líquido surgen como soluciones prometedoras al conciliar el rendimiento técnico, la sostenibilidad ambiental y la viabilidad económica. Los avances en la comprensión de los mecanismos de coagulación y floculación, combinados con la cuidadosa selección de tecnologías de separación, representan una vía estratégica para optimizar la recolección de biomasa de microalgas a gran escala y potenciar su potencial como recurso renovable para aplicaciones industriales y ambientales.

Palabras clave: Coagulación; Electrocoagulación; Filtración; Flotación; Cosecha; Microalgas.

1. Introduction

Microalgae are predominantly characterized as unicellular, photosynthetic, and mostly aquatic eukaryotic microorganisms (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019; THORÉ; MUYLAERT; BERTRAM; BRODIN, 2023). However, due to their size and cellular organization, they can also be classified as simple multicellular organisms (FERNANDES; PINTO; AGUIAR; CORREIA, 2020; RIVERA-SÁNCHEZ; VILLARÓ-COS; SALINAS-GARCÍA; LAFARGA, 2025), being able to develop in different aquatic environments, such as freshwater, saltwater, and even wastewater (RIVERA-SÁNCHEZ; VILLARÓ-COS; SALINAS-GARCÍA; LAFARGA, 2025).

Microalgae cells constitute an important source of bioactive compounds, including natural vitamins, proteins, minerals, antioxidants, β-carotenes, proteins, polysaccharides, triglycerides, and fatty acids, which have high potential for biomedical applications due to their antimicrobial, antioxidant, and anticancer properties (ABUHASHEESH; BANAT; SHOW; HASAN, 2025; ESTEVES; ALMEIDA; GONÇALVES; PIRES, 2020). These compounds are associated with cell walls, which have functional groups of interest, such as carboxyl (-COOH), hydroxyl (-OH), phosphate (-PO3), amine (-NH2), sulfate (-SO4), and alginic acid; whose chemical characteristics enable a wide range of technological applications (BHATT; KHANCHANDANI; RANA; PRAJAPATI, 2022; EL-TAWEEL; MOHAMED; ALREFAEY; HUSIEN et al., 2023).

Due to the high concentration of high-value-added products (HVAs), microalgae have attracted increasing attention from various industrial sectors, including the cosmetic, food, pharmaceutical, biofertilizer, animal feed, natural dyes, and biofuel segments (BHATT; KHANCHANDANI; RANA; PRAJAPATI, 2022). In addition to the production of bioactive compounds and PAVs, these organisms have also been widely used in bioproduction processes, carbon sequestration, and treatment of wastewater from municipal, agricultural, and industrial sources (ABUHASHEESH; BANAT; SHOW; HASAN, 2025; BHATT; KHANCHANDANI; RANA; PRAJAPATI, 2022; ESTEVES; ALMEIDA; GONÇALVES; PIRES, 2020); as

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

well as exhibiting a high bioremediation capacity, contributing to water purification through oxygen production and pollutant removal (MANEECHOTE; CHEIRSILP; ANGELIDAKI; SUYOTHA et al., 2023).

According to BHATT, KHANCHANDANI et al. (2022), the microalgae production process consists of cultivation, harvesting, drying, conversion of biomass into desired products, as well as extraction and purification. However, in many cases, the operational costs of the process are dominated by the cultivation and harvesting stages, which represent one of the main obstacles to its application on an industrial scale. It is estimated that the costs associated with microalgae harvesting represent 20-30% of the total production cost (WANG; YERKEBULAN; ABOMOHRA; EL-KHODARY et al., 2019).

Given this scenario, several studies have been dedicated to developing technological advances aimed at improving the economic viability of processes involving microalgae (BHATT; KHANCHANDANI; RANA; PRAJAPATI, 2022; LEITE DE SOUZA; HOFFMANN; DANIEL, 2019). In this context, a viable and efficient harvesting method must have low energy consumption and minimize or avoid the use of potentially harmful chemicals, especially concerning toxicity. In addition, the choice of the most suitable cultivation system is directly related to the type of microalgae strain, nutrient availability, and desired biomass (ÁLVAREZ; JIMÉNEZ; CANCELA; VALERO et al., 2021).

From a conceptual point of view, as described by GHAZVINI et al. (2022), harvesting refers to the initial stage of separating the biomass from the culture medium, while biomass recovery comprises the subsequent stages aimed at increasing cell concentration and preparing the material to obtain the final products. The ideal recovery of microalgae biomass can occur at different stages of its growth cycle, such as at the beginning or end of the exponential phase, or even during the stationary phase (SILVA; SPERANZA; QUARTAROLI; MORUZZI et al., 2021).

The processing of microalgae biomass occurs sequentially and involves different unit steps. Harvesting constitutes the primary step, in which the biomass concentration can reach a factor of 10 to 20 (GHAZVINI; KAVOSI; SHARMA; KIM, 2022). Next, thickening corresponds to the second step, in which the primary concentrate is further condensed by a concentration factor of 10, resulting in a pasty-looking substance. Dehydration represents the third step of the process, where the thickened biomass is dehydrated until it reaches 15–25% solids (GHAZVINI; KAVOSI; SHARMA; KIM, 2022). Finally, drying is the final recovery step, responsible for removing free and bound water from the biomass, converting it into dry solids (GHAZVINI; KAVOSI; SHARMA; KIM, 2022).

The main techniques currently applied in microalgae harvesting include physicochemical and mechanical methods, such as coagulation and flocculation (chemical or biological), flotation, sedimentation, centrifugation, and membrane filtration, which can be used in isolation or in combination to increase biomass recovery efficiency (DEEPA; SOWNDHARARAJAN; KIM, 2023). The cost of the process can be minimized by combining methods, such as coagulation and flocculation followed by sedimentation with centrifugation or filtration (UDAYAN; SIROHI; SREEKUMAR; SANG et al., 2022). In general, thickening methods, such as flocculation, flotation, and gravity sedimentation, have a lower cost when

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

compared to dehydration techniques, such as filtration and centrifugation (BRANYIKOVA; PROCHAZKOVA; POTOCAR; JEZKOVA et al., 2018).

Given the above, this review article brings together studies related to microalgae harvesting methods, with an emphasis on less complex and potentially more economical techniques, such as coagulation and flocculation processes. The work seeks to qualitatively compare the different approaches employed in harvesting, highlighting their efficiencies, advantages, and limitations. Furthermore, the mechanisms involved in each method are analyzed, aiming to identify strategies that favor the recovery of microalgae biomass with greater operational and environmental viability.

2. Techniques and mechanisms for harvesting microalgae

2.1. Coagulation, flocculation and sedimentation

Coagulation and flocculation can be used alone or combined with other methods. Coagulation and flocculation are low-cost processes, therefore are used for harvesting different microalgal species (BRANYIKOVA; PROCHAZKOVA; POTOCAR; JEZKOVA et al., 2018). In general, coagulation and flocculation are the most used methods for harvesting microalgae, because microalgae carry a negative surface charge which facilitates colloidal stability in medium suspension (RUGGERI; GODOY; ARROYO; TREVISAN, 2021). However, the charge-repulsive forces overcome Van der Waals attractive forces and microalgae cells remain in a stable dispersed state (KOYANDE; SHOW; GUO; TANG et al., 2019). To favor biomass separation, repulsive forces should be reduced by allowing microalgae cells aggregation and enabling attractive forces to prevail by coagulation/flocculation techniques (physical, chemical or biological). Moreover, some physicochemical parameters, such as dosage of coagulant, coagulant type, cells concentration, pH value of culture, reaction time, mixing speed, and ionic strength affect the coagulation and flocculation processes efficiency, and therefore the sedimentation speed (KOYANDE; SHOW; GUO; TANG et al., 2019) . For coagulation and flocculation processes associated with gravitational sedimentation or other processes such as centrifugation and filtration, the effect of the medium pH interferes with the coagulant activity (KOYANDE; SHOW; GUO; TANG et al., 2019).

Coagulation and flocculation are the most widely used method for separating colloidal substances in water or liquids and to harvest microalgae. The difference between agent coagulant and flocculant is that the agent coagulant destabilizes the colloidal system by neutralizing the forces that keep it stable. Moreover, the coagulation is induced by adding salt metals, natural or biological compounds and rapid mixing to promote the destabilization of particles in the solution (LEITE DE SOUZA; HOFFMANN; DANIEL, 2019). The coagulation process involves mechanisms, such as charge neutralization, adsorption, particle bridging, sweep coagulation, and ionic layer compression. During the mechanisms of adsorption and charge neutralization, positively charged coagulants interact with negatively charged colloidal particles, which leads to the precipitation of the suspended materials (LABEEUW; COMMAULT; KUZHIUMPARAMBIL; EMMERTON et al., 2021). In scavenging coagulation, the particles become trapped inside the porous precipitate

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

formed, while in the pitting mechanism, the coagulant forms polymeric chains to which the dispersed particles adhere (GOMES, 2017; LABEEUW; COMMAULT; KUZHIUMPARAMBIL; EMMERTON et al., 2021).

The interaction between charges of the cells' surface microalgae and the coagulant allows the coagulation process; hence the aggregation formed with algal cells leading the precipitation of these flakes by gravity sedimentation (QI; CHEN; HU; HU et al., 2022). According to FUAD et al. (2018), flocculation is referred to as coagulation; however, flocculation is the step subsequent to coagulation, where flocs are formed from solute particles dispersed in the medium (ESTEVES; ALMEIDA; GONÇALVES; PIRES, 2020). The mechanism of neutralization of the charge on the cells surface stimulates the destabilization of the microalgae solution; hence the flocculation occurs, which means, the aggregation of particles (BRANYIKOVA; PROCHAZKOVA; POTOCAR; JEZKOVA et al., 2018). That is to say, the flocculation process occurs after the destabilization of the suspension; it means that the dosage of the coagulant agent in the suspension eliminates the repulsive surface charges (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). Therefore, with suitable velocity gradients with appropriate time to ensure the mix, the flakes become large and compact enough and separate from the suspension; the next step is sedimentation (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023).

In general, saline coagulants trigger coagulation by charge neutralization; coagulation induced by pH occurs through the sweeping mechanism and cationic coagulants happen through the bridging effect (ZHAO; LI; MUYLAERT; VANKELECOM, 2020). The flocculant increases the size of flocs produced by coagulation, reduces the surface charge of particles of microalgae, and agglomerates the suspended particles for their sedimentation (KOYANDE; SHOW; GUO; TANG et al., 2019; LABEEUW; COMMAULT; KUZHIUMPARAMBIL; EMMERTON et al., 2021).

Gravity sedimentation is the most rudimentary and economical method for harvesting microalgae, standing out for its low energy consumption, simplicity of equipment, and reduced operating costs (ESTEVES; ALMEIDA; GONÇALVES; PIRES, 2020). Harvesting can occur in simple open-air settling tanks or in cylindrical tanks in controlled environments, such as laboratories. However, due to the low energy involved in the process, gravity sedimentation tends to have reduced speeds, making flocculation an auxiliary step to facilitate and accelerate sedimentation. In addition, flocculation helps to minimize biomass degradation associated with long sedimentation times, which can limit future applications of microalgae cells (KIM; CHOI; KIM; WI et al., 2014). The main function of flocculation is to accelerate the sedimentation process, thereby removing solid particles from the water.

Focculation is suitable for several microalgal specie, because it can aggregate the biomass into larger particles to form flakes; which is a promising approach for the large-scale harvest of biomass (KIM; CHOI; KIM; WI et al., 2014). It is possible to relate the low density as a cause of long sedimentation times in crops (KIM; CHOI; KIM; WI et al., 2014).

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

When microalgae cultivation is prolonged, the biomass microalgal can effectively separate from water by gravity sedimentation method (KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022; ZHAO; LI; MUYLAERT; VANKELECOM, 2020). However, these flake aggregates may be prone to bacterial contamination, which can affect the quality and the potential of the final product from microalgal biomass (ZHAO; LI; MUYLAERT; VANKELECOM, 2020).

According to Stokes' law, the sedimentation velocity is linearly correlated to the densities between microalgal cells and the culture medium, according to Equation 1(KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022). When the sedimentation time is high, it is probable that leads to biomass deterioration which may contribute to the worse quality of the final product. Therefore, the sedimentation speed is a valuable parameter to be taken into account in the design of sedimentation systems (RUGGERI; GODOY; ARROYO; TREVISAN, 2021). Figure 1 represents the coagulation, flocculation, and sedimentation processes:

$$setting\ velocity = \frac{2}{9} g(\rho_s - \rho_l) \frac{r^2}{\eta} \quad (1)$$

where:
g – gravity acceleration (m s^{-2})
ρ_s – density of cells (kg m^{-3})
ρ_l – density of medium (kg m^{-3})
r – radius (µm)
η – viscosity (kg m^{-1} s^{-1})

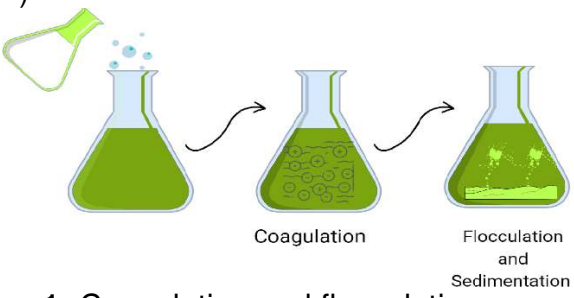

Figure 1: Coagulation and flocculation processes.

Three typical coagulation/flocculation techniques for microalgae harvesting can be described as physical, chemical, and biological (KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022). The mechanical method for harvesting microalgae is based on separating algal biomass from the culturing medium. The techniques are gravity sedimentation, flotation, centrifugation, filtration, and sieving.

In light of the above, microalgae harvesting is influenced by the colloidal stability conferred to the suspension by the negative surface charge of the cells, hindering spontaneous sedimentation. Although gravity sedimentation is a simple and low-cost method, its isolated application is limited by low cell density and long sedimentation times. Thus, coagulation and flocculation processes reduce repulsive forces, promoting cell aggregation and accelerating the formation of flocs that will sediment. In this way, the integration of coagulation/flocculation and gravitational sedimentation is a viable technical approach for microalgae biomass harvesting, especially on a large scale.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

2.1.1. Mechanisms for harvesting microalgae by coagulation, flocculation, and sedimentation

The surface of microalgae cells is negatively charged, because most groups are ionizable, like hydroxyl and carboxyl, which may be neutralized by positive ions of coagulants added into the suspension (AJALA; ALEXANDER, 2020). The neutralization of the charge happens on the cells' surface when the suspensions' stability is interrupted. The low cell density of microalgae, the small size of algal cells, and the repulsive electrostatic forces among cells reduce the formation of flakes (AJALA; ALEXANDER, 2020). This phenomenon induces knowing the optimal dosage of coagulant on the medium (MAIA; CARDOSO; DA SILVEIRA MASTRANTONIO; BIERHALS et al., 2020).

Flocculation conditions under optical dosage may not reach the efficiency, because the small flakes stay remain suspended in the medium, besides reducing unbound the agglomeration of extracellular organic matter (EOM) in the medium (ZHAO; LI; MUYLAERT; VANKELECOM, 2020). On the other hand, high dosages of coagulants, especially the cationic, do not increase harvesting efficiency significantly, due to positive ions neutralizing the negative charge on the surface of microalgae cells; when the dosage exceeds a threshold, the repulsive electrostatic forces among cells tend to repel each other, because of excessive positive charge (MAIA; CARDOSO; DA SILVEIRA MASTRANTONIO; BIERHALS et al., 2020). Moreover, high dosages of coagulants may highly cover the microalgal surface without leaving enough vacant sites for electrostatic attraction between the negative charges of cells microalgae and positive charges of coagulant (PETRÓLEO, 2011). Therefore, the excess positive charge can result in the resuspension of the flocs.

The mechanism through charge neutralization occurs when the positive charge of the coagulants/flocculants is hydrolyzed into the medium and interacts with the microalgae cells (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). Hence, the surface charge of microalgae cells is destabilized by the interaction between microalgae cells and coagulants/flocculants. Moreover, the interaction allows the elimination of the energy barrier, and the repulsive charges are decreased; therefore, the microalgae cells agglomerate and settle (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). Figure 2 represents the mechanism through charge neutralization.

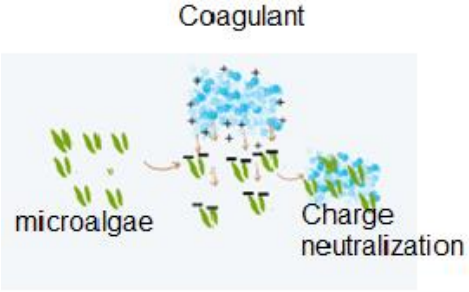

Figure 2: The mechanism through charge neutralization.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

Sweep coagulation occurs through pH adjustment, usually under basic conditions, by adding a chemical or natural coagulant/flocculant (biocoagulant) to the microalgae culture medium (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). In this mechanism, microalgae are precipitated by the interaction of the metal with hydroxide ions under basic or after hydrolysis into the aqueous medium (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022).

Bridging is the mechanism that occurs when the polymer and starch-based compounds are used to harvest the microalgae. Biocoagulants/bioflocculants connect between them and microalgae, forming flakes with a density greater than that of water. Figure 3 describes this mechanism of connection and settle-bridging mechanism. Biocoagulants utilize the bridging mechanism to harvest microalgae biomass, due to the polymer molecule increasing the cell aggregation, producing large and heavy flocs that facilitate sedimentation (ANP, 2021).

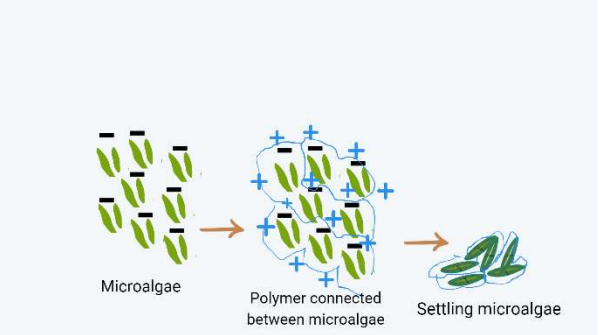

Figure 3: Bridging mechanism.

In the adsorption mechanism, the pores of microalgae adsorb biocoagulants/bioflocculants; therefore, in some parts of the microalgal structure occur a change in zeta potential (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). Patchy flocculation results from the interconnected chain between regions of the microalga that adsorb biocoagulants/bioflocculants and others that do not, due to differences in zeta potential (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). The biocoagulants/flocculants with low molecular weight can realize the adsorption mechanism, due to they have no capacity to charge neutralization. Therefore, they are adsorbed into the microalgae pore and act as the positive functional group side (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022).

In summary, microalgae coagulation/flocculation is governed by the negative surface charge of the cells and the combined action of mechanisms such as charge neutralization, sweep coagulation, bridging, and adsorption. The efficiency of the process depends on the dosage and operating conditions, since both underdosing and excess coagulant can compromise the formation of stable flocs, either by maintaining repulsive forces or by charge reversal and coating of the cell surface. Therefore, an integrated understanding of these mechanisms is essential for optimizing microalgae harvesting and for developing more efficient and sustainable solid-liquid separation strategies.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

2.1.2 Coagulants

Three main classes of coagulants can be used in microalgae biomass harvesting: inorganic metallic salts, synthetic polymers, and biopolymers (KHALATBARI; TUPPURAINEN; BELLO; SOTANIEMI et al., 2025). The inorganic coagulants have valency cations, such as chemical coagulants (Mg2+, Zn2+, Al3+, Fe3+). Most of the synthetic polymers are cationic, such as polyacrylamide and polyelectrolytes. Whereas, the biopolymers or biocoagulants (chitosan, tannin-based polymers, cationic starch and opuntias) have been highlighted because of the eco-friendly characteristics, since they are non-toxic and biodegradable (KHALATBARI; TUPPURAINEN; BELLO; SOTANIEMI et al., 2025). The efficiency of harvest using cationic coagulants is > 90%. The performance of process coagulation/flocculation depends on the dosage of the agent coagulant, type, and concentration of microalgae species (WANG; OSHITA; TAKAOKA, 2021). The choice of coagulants interferes with the final product cost (biomass). The dose may range from 10 to 50mg L-1 in scale-lab (LV; LIU; FENG; LIU et al., 2020).

The efficiency of flocculation is also influenced by the phase of the algal growth cycle, including the beginning and end of the exponential phase, as well as the intermediate stationary phase (SILVA; SPERANZA; QUARTAROLI; MORUZZI et al., 2021). This means, the impact of the flocculant on the harvested biomass quality. Therefore, the cultivation medium and growth stage affects coagulation/flocculation, as well as, cell sizes, cell surface features, cell stabilities, and zeta potential of kind microalgae species (WANG; OSHITA; TAKAOKA, 2021). Microalgae cells have a negative surface charge, while inorganic and natural coagulants/flocculants have a positive charge. The interaction between the charges positive and negative causes flocculation by charge neutralization (ANP, 2021).

The chemical coagulation is considered a traditional method that can adsorpt and neutralize the surface negative charge of microalgae cells (MAIA; CARDOSO; DA SILVEIRA MASTRANTONIO; BIERHALS et al., 2020). The most common coagulants/flocculants used for the treatment of freshwater and wastewater are compounds based on polymeric metal salts, aluminum, ferric salts, magnesium hydroxide, calcium hydroxide, iron sulfate, and calcium chloride. Aluminum sulfate, iron sulfate, iron chloride are polyvalent salts commonly applied to promote the neutralization of cells' surface charge and facilitate the spontaneous formation of flocs (MUSA; WOLF; STEPHENS; HANKAMER et al., 2020). These inorganic coagulants promote the neutralization of charges when the respective cations interact with hydroxyl and carboxyl groups present on the cells' surface, thus reducing electrostatic repulsive forces between cells and allowing particles to be aggregated together (BRANYIKOVA; PROCHAZKOVA; POTOCAR; JEZKOVA et al., 2018).

Furthermore, the efficiency of coagulation/flocculation with chemical coagulants is influenced by the electronegativity and ionic strength of the culture medium (VANDAMME; MUYLAERT; FRAEYE; FOUBERT, 2014). Some industries prefer chemical coagulants because their coagulant and flocculant activities promote a quick aggregate formation from particles dissolved in the medium. Although they are often preferred in industrial applications due to the rapid formation

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

of aggregates, metallic salts can remain adsorbed on the cell surface, promoting contamination and hindering lipid extraction (LI; YIN; TIAN; YANG et al., 2025; VANDAMME; MUYLAERT; FRAEYE; FOUBERT, 2014). The great disadvantage of the use of these inorganic coagulants/flocculants is the toxicity which contributes to high the cost of the purification of drinking water and recovered microalgae biomass. Inorganic coagulants are toxic, they can damage the shape, change the color or discoloration pigments of the microalgae cells, floc weakening and modifications in lipid composition (MAIA; CARDOSO; DA SILVEIRA MASTRANTONIO; BIERHALS et al., 2020; PETRÓLEO, 2011). Moreover, the presence of aluminum has been associated with potential health risks, such as carcinogenesis and Alzheimer's disease.

For this reason, natural or biological coagulants/flocculants are taking the place of chemicals, for example, the cationic polymers (chitosan, tannin, cellulose, surfactants, polyacrylamide, *Nirmali seeds - Strychnos potatorum, Moringa oleifera*), seeds, plants, microorganisms (bacteria or fungi) which are non-toxic, biodegradable and that is why they are considered environmentally friendly (RUGGERI; GODOY; ARROYO; TREVISAN, 2021). Biocoagulants develop the adsorption followed by charge neutralization or polymeric bridging to agglomerate the particles into an aqueous medium to form flakes and then they are settled (RUGGERI; GODOY; ARROYO; TREVISAN, 2021).

Polymers coagulants can be cationic or anionic. They have long chains acting as particles connect. The anionic polymers use the mechanism of the addition of bridging ions to connect with the cells of microalgae (FERREIRA; DIAS; SILVA; COSTA, 2016). The cationic uses the neutralization charges. The ability to neutralize the surface charge of microalgae is associated with the high charge density of polyelectrolytes and high molecular weight, with the efficiency of coagulation mechanisms depending directly on the charge density and the length of the polymer chain (FERREIRA; DIAS; SILVA; COSTA, 2016). The efficiency of each coagulation mechanism is based on the charge density and chain length of the polymer (FERREIRA; DIAS; SILVA; COSTA, 2016). However, in media with high ionic strength, such as in the cultivation of marine microalgae, polymeric coagulants may exhibit limited performance and even cause damage to cells and the flocs formed (FERREIRA; DIAS; SILVA; COSTA, 2016). Most biocoagulants exhibit cationic character due to the presence of multiple functional groups on their surface, acting through charge neutralization, adsorption, and bridging mechanisms, while anionic biocoagulants tend to act primarily through scavenging coagulation (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022).

Polyacrylamide's high charge and molecular weight contribute to a fast settling time for harvest biomass. This synthetic polymer is non-toxic and readily hydrolyzed when dissolved in aqueous suspension (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019); the charge of the polymer impacts the effectiveness of the flocculation. In low dosage, it can work with high efficiency, for the reason of the organic matter (e.g. microalgae) be predominantly hydrophilic with a negative zeta potential which can interact with cationic polymers (SILVA; SPERANZA; QUARTAROLI; MORUZZI et al., 2021). However, low cationic degrees can compromise flocculation, while high concentrations and excessive

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

dosages can promote system restabilization by charge reversal, reducing process efficiency (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019). Furthermore, the presence of potentially carcinogenic acrylamide residues raises environmental and safety concerns in large-scale applications (KHATIB; AYARI; YASIR; TALHAMI et al., 2021; TEIXEIRA; KIRSTEN; TEIXEIRA, 2012).

The flocculation mechanism developed by polyacrylamide is the neutralization of the microalgae cells. The electrostatic repulsion among microalgae cells is decreased when the cationic polymer is added and mixed on the microalgae medium. On the other hand, over polymer dosage can cause restabilization; it means to decrease in the flocculation efficiency, due to the over dosage that can cause charge reversal of microalgae cells (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019).

The amino groups of the chitosan have positive charges, which can neutralize the negative charge of algal cells, allowing algae to settle through the bridging of polymer chains of the coagulant (LI; YIN; TIAN; YANG et al., 2025; NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019). It is a cationic polyelectrolyte that can aggregate negatively charged microalgae cells through mechanisms such as polymer adsorption, bridging, and charge neutralization, and then the agglomeration (KHALATBARI; TUPPURAINEN; BELLO; SOTANIEMI et al., 2025). The first step of the synthetic cationic polymer is the neutralization of the microalgal charge followed by entanglement and bridging between algal cells and the polymer (KHALATBARI; TUPPURAINEN; BELLO; SOTANIEMI et al., 2025; NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019).

Chitosan is a biopolymer obtained from fungi or components of crustacean shells, has low toxicity, and has a long chain with charge density (FERREIRA; DIAS; SILVA; COSTA, 2016). Moreover, it has a cationic electrolyte with active adsorption sites such as amino (–NH2) and hydroxyl (–OH) (ABOMOHRA; EL-HEFNAWY; WANG; HUANG et al., 2021). The negative microalgae cells are adsorped by the high charge density and result in destabilization through neutralization (FERREIRA; DIAS; SILVA; COSTA, 2016). Chitosan has a dual mechanism: (i) at low pH, the biocoagulant can form interactions existing with polymers at the cells' surface microalgae; (ii) at higher pH, this coagulant forms precipitations with cells which get entrapped (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). It is relevant to emphasize that the chemical structure of biocoagulants/bioflocculants is formed by polysaccharides, protein polymers, and functional groups (amine, hydroxyl, carboxyl groups) (KURNIAWAN; AHMAD; IMRON; ABDULLAH et al., 2022). The functional groups are responsible for aggregating the suspension particles and consequently, to contribute the formation of the big flakes. Charge neutralization is a significant mechanism for operating cationic polyelectrolyte flocculation because it eliminates the energy barrier for flake aggregation. Because of these properties, the biocoagulants/bioflocculants have been a great success in harvesting microalgae. Despite its high efficiency, high concentrations of chitosan can lead to system restabilization due to excess cationic charge, which makes rigorous dosage control essential (FERREIRA; DIAS; SILVA; COSTA, 2016). Therefore, new researches with chitosan are being developed to increase the settling efficiency (LI; YIN; TIAN;

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

YANG et al., 2025). In this context, recent strategies have explored the functionalization of chitosan through methods: crosslinking, functional hybridization, and magnetic loading, aiming to increase sedimentation efficiency (LI; YIN; TIAN; YANG et al., 2025).

The seeds of *Moringa oleifera* are a polyelectrolyte compound with high coagulant potential, due to protein content. This plant may promote the recovery of biomass in a sustainable way because it is a natural coagulant with a harvest efficiency of > 80% (DIAS; BORGES; ROSA; MARTINS, 2021). The performance *Moringa oleifera* is strongly dependent on dosage, pH, mixing time, and sedimentation time (DIAS; BORGES; ROSA; MARTINS, 2021),), with pH being one of the main parameters to favor the colloidal destabilization of cells (DANESHVAR; ZARRINMEHR; KOUSHA; BHATNAGAR, 2020).

Tannin is a natural coagulant that comes from tree bark like the coconut tree, *Pinuspinaster*, *Eucalyptus globules*, and *Acacia melanoxylon* (VU; NGUYEN; LESAGE; NGHIEM, 2020). The extraction of the tannin is simple and involves the Soxhlet extractor method. Its chemical composition is formed by phenolic molecules that form complexes with proteins, other macromolecules, and minerals (RUGGERI; GODOY; ARROYO; TREVISAN, 2021). The optimal tannin dosage depends on the morphology characteristics of each microalgae species and the polyelectrolyte concentration of tannin during the coagulation/flocculation processes (RUGGERI; GODOY; ARROYO; TREVISAN, 2021; VU; NGUYEN; LESAGE; NGHIEM, 2020). Tannin coagulants can also achieve destabilising negatively charged microalgal cells through neutralisation and sorption mechanisms (KHALATBARI; TUPPURAINEN; BELLO; SOTANIEMI et al., 2025). For both *Moringa oleifera* and tannin, the control parameters (dose, pH, mixing conditions, and sedimentation time) are the same. The harvest of biomass with the *Moringa oleifera* and the tannin can be facilitated with pH variation being a relevant strategy to intensify floc formation. Currently, the increase in the use of tannin, chitosan, *Moringa oleifera*, and other biocoagulants for wastewater treatment, microalgae harvesting, and reuse of the culture medium is the low cost, low energy, high biodegradability, and good efficiency of these coagulants. Using biocoagulants in coagulation/flocculation processes is more effective than natural sedimentation and more economical than centrifugation (VU; NGUYEN; LESAGE; NGHIEM, 2020). The natural coagulants are not toxic for harvesting microalgae; due to biodegradability and non-toxicity, they are considered environmentally friendly coagulants (VU; NGUYEN; LESAGE; NGHIEM, 2020).

Double coagulation/flocculation has emerged as an effective strategy to increase the efficiency of microalgal biomass harvesting. The synergistic effect between an inorganic and a biocoagulant increases the coagulation and flocculation efficiency processes. This synergistic effect efficiency depends on the type of inorganic salts, microalgae species, dosages of both coagulants, and the order of addiction of the coagulant on the microalgal medium (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019). Typically, an inorganic coagulant is added in the rapid mixing step to neutralize the suspension. Then, the collision among cells leads to the formation of small flocs. Following by the addition of the biocoagulant in slow mixing, favoring the pitting mechanism and floc growth; in this

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

case, the bridging mechanism takes place on what biocoagulant chains speed up the agglomeration and the increase the size of the flocs (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019). According to RODRIGUES; SANTOS; MATOS; PIRES et al. (2023) the result of combining coagulation and flocculation mechanisms, for example, neutralization and bridging, using ferric chloride with chitosan or aluminum sulphate with chitosan has been efficient for harvesting the biomass, minimizing process time, and cost with coagulants. The dosage of coagulant is an important parameter, for example, in a low dosage of chitosan, the effect synergistic is not induced because chitosan works mostly on the bridging mechanism rather than charge neutralization (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019). Nevertheless, the addition of chitosan at the higher dose in the dual coagulation/flocculation increase the bridging and the charge neutralization mechanisms, which may contribute to the high efficiency of harvesting microalgal biomass (NGUYEN; LABEEUW; COMMAULT; EMMERTON et al., 2019) . Moreover, chitosan does not contaminate the harvested microalgae biomass.

The immobilization of microalgae cells by biological materials (algicidal bacteria or fungi) is a current tendency to ensure the high quality of biomass. Biocoagulation may be used for harvesting or immobilization of microalgae cells. Bacteria can also interact with microalgae and promote flakes by flocculant agents extracted from bacteria or flocculant agents excreted by bacteria when in co-cultivation with microalgae (ESTEVES; ALMEIDA; GONÇALVES; PIRES, 2020).

For the immobilization, filamentous fungi must be applied for biocuagulation. In this relation, the fungi use the sugars and other organic compounds produced by microalgae during the photosynthetic process saving the microalgae from contamination and supporting their growth (YIN; LI; HU; LI et al., 2022). Hence, microalgae cells are captured in fungal pellets or linked to fungal hyphae through opposite surface charges (YIN; LI; HU; LI et al., 2022). This new modality of immobilization with biological materials is non-toxic, efficient, low cost, and practicability when compared with traditional immobilization methods which are restricted in terms of high-scale production and have lowly biocompatible (YIN; LI; HU; LI et al., 2022). Under appropriate circumstances, fungi and microalgae cells can develop a spherical morphology which brings the advantages of great mechanical stability and improved mass transfer rate to accumulate biomass (YIN; LI; HU; LI et al., 2022).

Improving the immobilization of microalgae cells by biological materials by coating them with cationic polyelectrolyte (YIN; LI; HU; LI et al., 2022). The technique is used to prevent the cells from microalgae-fungal (MF) pellet leakage during the harvest (YIN; LI; HU; LI et al., 2022). This polyelectrolyte can be chitosan which is non-toxic and has the high capacity to form a membrane around the MF pellets reducing cell leakage and increasing their harvest (YIN; LI; HU; LI et al., 2022).

Together, synthetic polymeric coagulants and natural biocoagulants act through complementary mechanisms of charge neutralization, adsorption, bridging, and sweep coagulation, the efficiency of which depends on charge density, molecular weight, pH, ionic strength of the medium, and dosage. Although synthetic polymers, such as polyacrylamide, promote rapid sedimentation, limitations

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

associated with residual toxicity and restabilization by excess charge favor replacement by biocoagulants, such as chitosan, *Moringa oleifera*, and tannins, due to their greater environmental compatibility. Furthermore, strategies such as double coagulation/flocculation and biological immobilization increase the efficiency of the process, reinforcing the potential of these approaches for the development of more sustainable and economically viable microalgae harvesting systems.

2.2. Flotation

According to flotation can be viewed as inverted sedimentation, and the advantage is the tendency of microalgae to float instead of settle (LAAMANEN; ROSS; SCOTT, 2016). The flotation of particle suspensions in water can occur naturally or by external supply gas and high pressure. The autoflotation is the flotation naturally, while dissolved air flotation - DAF and dispersed air flotation - DiAF are electroflotation methods.

Flotation was originally used in the mineral industry; therefore this process may be used for microalgae bulk harvesting (WANG; YERKEBULAN; ABOMOHRA; EL-KHODARY et al., 2019). The small bubbles attach to destabilize particles, which is the same coagulation process; hence the bubbles cause the biomass to rise to the surface and concentrate upward rather than downward. Microalgae biomass is collected by simple mechanical scraping, through the air bubbles that carry the aggregates (cells) to the water surface, not to the bottom (WANG; YERKEBULAN; ABOMOHRA; EL-KHODARY et al., 2019).

Compared to centrifugation, flotation has the advantage of not subjecting cells to high shear forces, reducing the risk of structural damage (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). Flotation is an interesting process of harvesting microalgae cells with a tendency to self-flotation and low density through the use of air bubbles (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023; SILVA; SPERANZA; QUARTAROLI; MORUZZI et al., 2021). This process is rapid nor requires long spaces and has moderate operational costs. For some species of microalgae, adding a coagulant is necessary to improve flotation efficiency; the reason is the surface of air bubbles is also negatively charged like the cells. The challenge is overcome by using natural coagulants (natural polysaccharides). Inorganic coagulants contribute also to aggregate cells into large flakes that can be captured by the bubbles; nevertheless, there is a problem of contamination of the products (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023).

The autoflocculation and autoflotation are natural processes that come about in some microalgae species. In the firs process, the flocculation occurs spontaneously owing to prolonged cultivation which contributes to the limited photosynthetic CO2 supply and the increased pH (LEE; OH; KIM; KWON et al., 2011). The autoflocculation is known as alkaline flocculation induced by the pH increase. The high pH is a result of the formation of inorganic precipitates like by addition of alkalis or consumption of carbon resulted from the photosynthetic process of the microalgae (AJALA; ALEXANDER, 2020). In the second, the bubbles developed by the photosynthetic process are adhered or collided with the

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

cells/particles which are carried toward the surface of the liquid (FUAD; OMAR; KAMARUDIN; HARUN et al., 2018). The autoflotation or flotation can be induced by mechanisms : (i) agglutination of oxygen microbubbles on the cell surface resulting from the photosynthetic process; (ii) production of gas vacuoles intracellular; (iii) production of liquid vacuoles by replacing heavier ions with lighter (QI; WANG; HU; LEI et al., 2023). Effective microbubble adhesion is acquired when the electrostatic repulsion is overcome by a stronger hydrophobic attraction which is achieved with microalgae that have a highly hydrophobic surface (GUI; XU; LIU; ZHOU et al., 2022).

Dissolved air flotation - DAF and dispersed air flotation - DiAF are electroflotation methods used to form flakes from suspension particles in water or harvest microalgae. The two methods can combine chemical coagulants and electrodes. The coagulants are used to reduce the electrostatic repulsion between the microalgae cells. Both DAF and DiAF methods use air or gas bubbles and high pressure (MIN; KIM; KI; PACK, 2022). The bridging mechanism leads to big flake formation in the two methods (LEITE DE SOUZA; HOFFMANN; DANIEL, 2019). The difference between, DAF and DiAF methods, is that first, the bubbles of air or gas are dissolved in water and allow the flakes to float to the surface. The micro-bubbles are generated by high pressure. In the second method, the air or gas is injected on the top of the flotation column, so the bubbles are formed, mixed into the liquid, and pass through the spargers to harvest suspension particles or biomass (MIN; KIM; KI; PACK, 2022). The disadvantages of the two methods are the high consumption of energy, the cost of equipment and high pressure (MIN; KIM; KI; PACK, 2022).

Generally, flotation is carried out with air addition through a diffuser or dissolved air flotation (pressurization). When electrodes and coagulants are used in the system, the process is known as electro coagulation flotation (ECF). According to MIRANDA; PASSARINHO e GOUVEIA (2012), this process is compounded for some steps which are: (i) the coagulant is formed when the active anode is dissolved, (ii) the microalgae are destabilized into the suspension by interaction with these coagulants, (iii) the flakes are formed by the destabilized particles, (iv) gas bubbles formed at the electrodes adhere to the flakes which float at the surface. Commonly, aluminum or iron electrodes are dissolved in suspension to form the coagulants. Due to the current density, the bubbles are produced by the splitting of water molecules (LAAMANEN; ROSS; SCOTT, 2016). Quick flotation is got with a high current density.

In general, flotation and its variations, including autoflotation, DAF, DiAF, and electrocoagulation flotation, are efficient and versatile alternatives for microalgae harvesting, especially because they operate with lower shear forces and allow for rapid biomass recovery. However, limitations associated with energy consumption, the need for coagulants, equipment costs, and operational complexity still represent challenges for their large-scale application. Thus, the development of integrated strategies, the use of natural coagulants, and the optimization of operating conditions are fundamental to expanding the technical, economic, and environmental viability of these processes.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

2.7. Centrifugation

Centrifugation is used to separate liquids with different densities, solids from suspension, or microalgae biomass from water. This method is commonly used in laboratory-scale production; due to the high energy consumption it is common the combination coagulation and flocculation with centrifugation or filtration with centrifugation to reduce the costs (MIN; KIM; KI; PACK, 2022).

Centrifugation is a current process spent to separate particles in suspension or two miscible particles by applying centrifugal forces. It is not necessary the add chemical coagulants, the centrifugal forces are functions of the size, shape, viscosity, and density of the particles (OGBONNA; NWOBA, 2021). This method can be also worn for harvesting almost all microalgae cells and dewatering microalgae biomass.

The harvest of microalgae by centrifugation is currently most often because it is rapid and flocculation efficiency reaches 100%. It is one of the most efficient methods to recover microalgae biomass. The autoflotation is characterized by high instability, which results in low biomass harvesting efficiencies, therefore, in the production of high-added value products with biomass microalgae, the harvest is commonly done by centrifugation (WANG; STILES; GUO; LIU, 2015).

Centrifugal force is used to create the pressure differential necessary for particle separation from the aqueous suspension. It is applied to the feed of 4,000 to 14000 times higher than gravitational force and therefore, it reduces separation time (KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022). Tubular and multi-chamber centrifuges are types of centrifuges that may have been used to harvest microalgae cells (KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022). Figure 4 is an example of a multi-chamber centrifuge. The disadvantage of this process of harvesting the microalgae cells is the shear stress from the centrifugal force that can cause the cells to damage in some microalgae species that do not have cell walls (UDAYAN; SIROHI; SREEKUMAR; SANG et al., 2022).

Despite its high efficiency, centrifugation has significant limitations, including high energy consumption and substantial operating costs. It is estimated that the process can require up to 8 kWh m^{-3} for harvesting microalgae biomass, which compromises its economic viability in large-scale industrial applications (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). For this reason, centrifugation is often combined with filtration, coagulation, or flocculation, aiming to increase biomass concentration and reduce overall process costs (MIN; KIM; KI; PACK, 2022; OGBONNA; NWOBA, 2021).

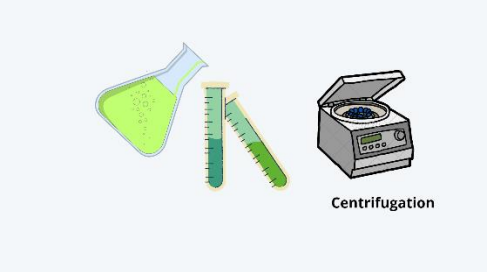

Figure 5: Centrifugation of microalgae medium

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

Flocculation and centrifugation have been widely combined for the treatment of wastewater and to recover the microalgae biomass; as well as, flocculation combined membrane filtration. However, flocculation combined gravity sedimentation does not reach 100% efficiency and demand time; which most of the time industry processes are not waiting for (OGBONNA; NWOBA, 2021).

In this context, centrifugation stands out as one of the most efficient and rapid methods for harvesting microalgae biomass, especially in applications that require high purity and near-complete recovery. However, its high energy consumption and high operating costs limit its large-scale application, making integration with coagulation, flocculation, or filtration steps necessary. Thus, centrifugation is more suitable as a complementary step in hybrid systems, in which the aim is to reconcile high separation efficiency with economic and operational viability.

2.8. Filtration

Filtration is a kind of separation method in which the pressure difference across the filter allows the fluid to pass through it, and solid particles stay retained (LEE; OH; KIM; KWON et al., 2011). A few filtration methods are classified according to their pore size, such as reverse osmosis, microfiltration, microfiltration, and ultrafiltration (LEE; OH; KIM; KWON et al., 2011). The flocculation process combined with centrifugation (low centrifugal force) or gravity filtration has high efficiency in removing stabled and sedimented flocs (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). Centrifugation and gravity filtration are also considered dewatering methods (DEMIR-YILMAZ; FTOUHI; BALAYSSAC; GUIRAUD et al., 2023). They can be applied as a step after the flocculation to harvest the microalgae flocs.

In the potentially concentrated microalgae biomass, membrane filtration is a proposal to retire the co-products from microalgae. Membrane filtration has advantages such as a long lifespan and low capacity to damage cells by shear stress (LEE; OH; KIM; KWON et al., 2011). Furthermore, it has a lower cost-effective than the centrifugation method. Therefore, the suspension can affect the permeation flux, consequently the cross-flow filtration (tangential flow filtration) allows the separation of shear fragile cells suspensions which contributes to completing the microalgae cells removal (LEE; OH; KIM; KWON et al., 2011).

The membrane filtration performance depends on the flux permeability and rejection. This means that the system must support the passage of the permeate through it with no or little fouling and to hold on the rejection of the retentate throughout the filtration process (OGBONNA; NWOBA, 2021). Fouling by organic matter into algal suspension is a serious problem to be overcome by the membrane filtration technology; hence the main challenge to reach the best results with membrane filtration among other methods is the appropriate membrane election of the porosity, charge, and hydrophilicity (LEE; OH; KIM; KWON et al., 2011).

The screening process included Microstrainer and Vibrating Screen Filters, two important microalgae harvesting devices. In essence, the suspension is

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

introduced through a pore-size screen appropriate for the kind of particles (MUSA; WOLF; STEPHENS; HANKAMER et al., 2020). Microstrainer presents rotating filters with thin mesh screen and backwash; the mechanism has simple construction, easy operation, low investment, and high filtration ratios (MUSA; WOLF; STEPHENS; HANKAMER et al., 2020). Vibrating Screen Filters retain the structure of the microalgae cells; in a vacuum, the filters recover relatively 89% biomass (MUSA; WOLF; STEPHENS; HANKAMER et al., 2020).

The integration between flocculation and membrane filtration has been widely explored, since the controlled formation of flocs — even under suboptimal dosage and sedimentation time conditions — can reduce coagulant consumption and increase overall harvesting efficiency (ZHAO; LI; MUYLAERT; VANKELECOM, 2020). Furthermore, the morphological characteristics of the flocs directly influence filtration performance, justifying the existence of different types of membranes and filtration systems. Membrane filtration, such as polyvinylidene fluoride (PVDF) can be combined with flocculation. According to ZHAO et al., (2020) the best efficiency is achieved after flocculation. Another important point that must be observed is the membrane flow, which can be determined by a filtration system and pressure. Equation 2 can be used to determine the membrane flux that means permeability (ZHAO; LI; MUYLAERT; VANKELECOM, 2020).

$$J = \frac{V}{AtP} \quad (2)$$

Where:
J - the membrane flux ($L.m^{-2}\ h^{-1}\ bar^{-1}$);
V - the volume of permeate (L);
A - the membrane active area (m^2);
t – flow time (h);
P - the transmembrane pressure (bar).

Membrane filtration techniques can be divided into microfiltration, macrofiltration, ultrafiltration, reverse osmosis, tangential flow filtration, dead-end filtration, vacuum filtration, and pressure filtration. The difference between which techniques is the pore size of the filters, i.e. the permeability. Downstream processing of microalgae is plenty used the macrofiltration combined with other techniques. Vacuum filtration commonly named rotary vacuum filters is also used for the recovery of large size flakes of microalgae. Tangential filtration is applied for dewatering suspended smaller algal cells; according to MATHIMANI AND MALLICK, (2018), this type of filtration is capable of concentrating 70–89% of microalgae cells. Before choosing the type of membrane filtration, it is important to available the fragile cells and their application for industries, which means, the end product (MATHIMANI; MALLICK, 2018). Additionally, permeance, rejection, and cost of membrane operation. The membrane must uphold its permeance during the operation without a considerable loss while sustaining the rejection (KHAN; NAUSHAD; IQBAL; BATHULA et al., 2022).

In summary, filtration, especially when integrated with flocculation, represents an efficient and versatile alternative for harvesting and concentrating microalgae biomass, combining high separation efficiency with less mechanical stress

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

compared to centrifugation. However, limitations associated with fouling, the appropriate choice of membranes, and operating costs make the careful selection of technology and operating conditions essential. Thus, hybrid flocculation-filtration systems emerge as promising strategies to optimize downstream microalgae processing, reconciling technical performance, economic viability, and preservation of biomass quality.

3. Research needs

Despite the wide range of technologies available for harvesting and concentrating microalgae, including coagulation, flocculation, centrifugation, flotation, and filtration, there is still no universal solution that is simultaneously efficient, economically viable, environmentally sustainable, and compatible with different species and industrial applications. Many established methods have significant limitations, such as high energy consumption, high operating costs, risk of cell damage, membrane fouling, the need for chemical coagulants, and potential contamination of the final product. Furthermore, most studies evaluate these technologies in isolation, leaving a gap regarding the optimization of hybrid systems and the use of natural coagulants, pretreatment strategies, and integrated operating conditions. Therefore, systematic investigation of combined and sustainable approaches that maximize harvesting efficiency, minimize environmental impacts, and reduce costs is necessary, aiming at enabling large-scale processing and integration with biorefinery concepts.

4. Conclusion

Harvesting microalgae involves technical challenges related to colloidal stability and low cell density, which limit simple methods such as gravity sedimentation. In this context, the integration of processes such as coagulation, flocculation, centrifugation, and filtration is essential to overcome efficiency and cost barriers. While synthetic polymers offer speed, their residual toxicity drives the search for environmentally compatible alternatives, such as natural biocoagulants. Hybrid strategies, which combine different solid-liquid separation techniques, emerge as promising solutions by reconciling technical performance, sustainability, and economic viability. Thus, advancing the understanding of coagulation/flocculation mechanisms and the careful selection of separation technologies constitutes a strategic path to optimize the large-scale harvesting of microalgae biomass, strengthening its potential as a renewable resource for industrial and environmental applications.

Acknowledgments: The authors gratefully acknowledge the support provided by our colleagues from Environmental Biotechnology Laboratory – LABAM. Special thanks to Prof. Dr. Roberto Rodrigues de Souza, the laboratory manager. They also acknowledgments CNPq, FAPESB, FAPITEC and CAPES for the financial support for carrying out the work.

Reference

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

ABOMOHRA, A. E.-F.; EL-HEFNAWY, M. E.; WANG, Q.; HUANG, J. et al. Sequential bioethanol and biogas production coupled with heavy metal removal using dry seaweeds: Towards enhanced economic feasibility. Journal of Cleaner Production, 316, p. 128341, 2021.

ABUHASHEESH, Y.; BANAT, F.; SHOW, P. L.; HASAN, S. W. Electro-assisted microalgae cultivation, harvesting, and recovery of high-value products: A review. Bioresource Technology, 438, p. 133269, 2025/12/01/ 2025.

AJALA, S. O.; ALEXANDER, M. L. Application of bio-based alkali to induce flocculation of microalgae biomass. Biomass and Bioenergy, 132, p. 105431, 2020.

ÁLVAREZ, X.; JIMÉNEZ, A.; CANCELA, Á.; VALERO, E. et al. Harvesting freshwater algae with tannins from the bark of forest species: Comparison of methods and pelletization of the biomass obtained. Chemosphere, 268, p. 129313, 2021.

ANP. Boletim da Produção de Petróleo e Gás Natural. Agencia Nacional de Petroleo 2021.

BHATT, A.; KHANCHANDANI, M.; RANA, M. S.; PRAJAPATI, S. K. Techno-economic analysis of microalgae cultivation for commercial sustainability: A state-of-the-art review. Journal of Cleaner Production, p. 133456, 2022.

BRANYIKOVA, I.; PROCHAZKOVA, G.; POTOCAR, T.; JEZKOVA, Z. et al. Harvesting of microalgae by flocculation. Fermentation, 4, n. 4, p. 93, 2018.

DANESHVAR, E.; ZARRINMEHR, M. J.; KOUSHA, M.; BHATNAGAR, A. Performance evaluation of different harvesting methods and cultivation media on the harvesting efficiency of microalga and their fatty acids profile. Fuel, 280, p. 118592, 2020.

DEEPA, P.; SOWNDHARARAJAN, K.; KIM, S. A review of the harvesting techniques of microalgae. Water, 15, n. 17, p. 3074, 2023.

DEMIR-YILMAZ, I.; FTOUHI, M. S.; BALAYSSAC, S.; GUIRAUD, P. et al. Bubble functionalization in flotation process improve microalgae harvesting. Chemical Engineering Journal, 452, p. 139349, 2023.

DIAS, A.; BORGES, A. C.; ROSA, A. P.; MARTINS, M. A. Green coagulants recovering Scenedesmus obliquus: An optimization study. Chemosphere, 262, p. 127881, 2021.

EL-TAWEEL, R. M.; MOHAMED, N.; ALREFAEY, K. A.; HUSIEN, S. et al. A review of coagulation explaining its definition, mechanism, coagulant types, and optimization models; RSM, and ANN. Current Research in Green and Sustainable Chemistry, p. 100358, 2023.

ESTEVES, A. F.; ALMEIDA, C. J.; GONÇALVES, A. L.; PIRES, J. C. Microalgae harvesting techniques. In: Handbook of microalgae-based processes and products: Elsevier, 2020. p. 225-281.

FERNANDES, I.; PINTO, R.; AGUIAR, R.; CORREIA, R. Perspective Application of the Circular Economy in the Blue Biotechnology: Microalgae as Sources of Health Promoting Compounds. Glob. J. Nutr. Food Sci, 3, 2020.

FERREIRA, A. F.; DIAS, A. P. S.; SILVA, C. M.; COSTA, M. Effect of low frequency ultrasound on microalgae solvent extraction: analysis of products, energy consumption and emissions. Algal Research, 14, p. 9-16, 2016.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

FUAD, N.; OMAR, R.; KAMARUDIN, S.; HARUN, R. et al. Mass harvesting of marine microalgae using different techniques. Food and Bioproducts Processing, 112, p. 169-184, 2018.

GHAZVINI, M.; KAVOSI, M.; SHARMA, R.; KIM, M. A review on mechanical-based microalgae harvesting methods for biofuel production. Biomass and Bioenergy, 158, p. 106348, 2022.

GOMES, N. F. P., G. M. P.; ALMEIDA, M. A.; SILVA, F. C.; MACIE, A. P.; MENDONÇA, C. J. S. . Produção de glicose e bioetanol a partir de Chlorella sp 2017, 57º CONGRESSO BRASILEIRO DE QUÍMICA57º CONGRESSO BRASILEIRO DE QUÍMICA. Disponível em: . http://www.abq.org.br/cbq/2017/trabalhos/9/11809-14605.htm.

GUI, L.; XU, L.; LIU, Z.-Y.; ZHOU, Z.-G. et al. Carotenoid-rich microalgae promote growth and health conditions of Artemia nauplii. Aquaculture, 546, p. 737289, 2022.

KHALATBARI, S.; TUPPURAINEN, V.; BELLO, A.; SOTANIEMI, V.-H. et al. Optimisation of chemical harvesting of microalgae from fish processing wastewater and economic assessment based on process modelling. Chemical Engineering Journal, 524, p. 169036, 2025/11/15/ 2025.

KHAN, S.; NAUSHAD, M.; IQBAL, J.; BATHULA, C. et al. Production and harvesting of microalgae and an efficient operational approach to biofuel production for a sustainable environment. Fuel, 311, p. 122543, 2022.

KHATIB, W. A.; AYARI, A.; YASIR, A. T.; TALHAMI, M. et al. Enhancing the electrocoagulation process for harvesting marine microalgae (Tetraselmis sp.) using interdigitated electrodes. Journal of Environmental Management, 292, p. 112761, 2021.

KIM, K. H.; CHOI, I. S.; KIM, H. M.; WI, S. G. et al. Bioethanol production from the nutrient stress-induced microalga Chlorella vulgaris by enzymatic hydrolysis and immobilized yeast fermentation. Bioresource Technology, 153, p. 47-54, 2014.

KOYANDE, A. K.; SHOW, P.-L.; GUO, R.; TANG, B. et al. Bio-processing of algal bio-refinery: a review on current advances and future perspectives. Bioengineered, 10, n. 1, p. 574-592, 2019.

KURNIAWAN, S. B.; AHMAD, A.; IMRON, M. F.; ABDULLAH, S. R. S. et al. Potential of microalgae cultivation using nutrient-rich wastewater and harvesting performance by biocoagulants/bioflocculants: Mechanism, multi-conversion of biomass into valuable products, and future challenges. Journal of Cleaner Production, p. 132806, 2022.

LAAMANEN, C. A.; ROSS, G. M.; SCOTT, J. A. Flotation harvesting of microalgae. Renewable and Sustainable Energy Reviews, 58, p. 75-86, 2016.

LABEEUW, L.; COMMAULT, A. S.; KUZHIUMPARAMBIL, U.; EMMERTON, B. et al. A comprehensive analysis of an effective flocculation method for high quality microalgal biomass harvesting. Science of The Total Environment, 752, p. 141708, 2021.

LEE, S.; OH, Y.; KIM, D.; KWON, D. et al. Converting carbohydrates extracted from marine algae into ethanol using various ethanolic Escherichia coli strains. Applied Biochemistry and Biotechnology, 164, p. 878-888, 2011.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

LEITE DE SOUZA, L.; HOFFMANN, M. T.; DANIEL, L. A. Coagulation and dissolved air flotation as a harvesting method for microalgae cultivated in wastewater. Journal of Water Process Engineering, 32, p. 100947, 2019.

LI, Y.; YIN, Z.; TIAN, L.; YANG, J. et al. Synergistic enhancement of chitosan-diatomite composite in microalgae flocculation: Mechanistic insights into extracellular polymeric substances-mediated harvesting. International Journal of Biological Macromolecules, 325, p. 147368, 2025/09/01/ 2025.

LV, J.; LIU, G.; FENG, J.; LIU, Q. et al. Harvesting biomass of an oil-rich microalga Parachlorella kessleri TY02 by ferric chloride: Effects on harvesting efficiency, lipid production and municipal wastewater treatment. Journal of Environmental Management, 273, p. 111128, 2020.

MAIA, J. L. D.; CARDOSO, J. S.; DA SILVEIRA MASTRANTONIO, D. J.; BIERHALS, C. K. et al. Microalgae starch: A promising raw material for the bioethanol production. International Journal of Biological Macromolecules, 165, p. 2739-2749, 2020.

MANEECHOTE, W.; CHEIRSILP, B.; ANGELIDAKI, I.; SUYOTHA, W. et al. Chitosan-coated oleaginous microalgae-fungal pellets for improved bioremediation of non-sterile secondary effluent and application in carbon dioxide sequestration in bubble column photobioreactors. Bioresour Technol, 372, p. 128675, Mar 2023.

MATHIMANI, T.; MALLICK, N. A comprehensive review on harvesting of microalgae for biodiesel–key challenges and future directions. Renewable and Sustainable Energy Reviews, 91, p. 1103-1120, 2018.

MIN, K. H.; KIM, D. H.; KI, M.-R.; PACK, S. P. Recent progress in flocculation, dewatering, and drying technologies for microalgae utilization: Scalable and low-cost harvesting process development. Bioresource Technology, 344, p. 126404, 2022.

MIRANDA, J.; PASSARINHO, P. C.; GOUVEIA, L. Pre-treatment optimization of Scenedesmus obliquus microalga for bioethanol production. Bioresource Technology, 104, p. 342-348, 2012.

MUSA, M.; WOLF, J.; STEPHENS, E.; HANKAMER, B. et al. Cationic polyacrylamide induced flocculation and turbulent dewatering of microalgae on a Britt Dynamic Drainage Jar. Separation and Purification Technology, 233, p. 116004, 2020.

NGUYEN, L. N.; LABEEUW, L.; COMMAULT, A. S.; EMMERTON, B. et al. Validation of a cationic polyacrylamide flocculant for the harvesting fresh and seawater microalgal biomass. Environmental Technology & Innovation, 16, p. 100466, 2019.

OGBONNA, C. N.; NWOBA, E. G. Bio-based flocculants for sustainable harvesting of microalgae for biofuel production. A review. Renewable and Sustainable Energy Reviews, 139, p. 110690, 2021.

PETRÓLEO, A. N. D. Gás Natural e Biocombustíveis (ANP). Boletim Mensal do Gás Natural, n. 29, 2011.

QI, S.; CHEN, J.; HU, Y.; HU, Z. et al. Low energy harvesting of hydrophobic microalgae (Tribonema sp.) by electro-flotation without coagulation. Science of The Total Environment, 838, p. 155866, 2022.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

QI, S.; WANG, Z.; HU, Y.; LEI, J. et al. Selective enrichment of auto-floating microalgae for wastewater bioremediation and biofuel/bioproduct production. Algal Research, 69, p. 102911, 2023.

RIVERA-SÁNCHEZ, E.; VILLARÓ-COS, S.; SALINAS-GARCÍA, M.; LAFARGA, T. Increasing the sustainability of photoautotrophic microalgae production by minimising freshwater requirements. New biotechnology, 2025.

RODRIGUES, J. R. D. S.; SANTOS, R. D. S.; MATOS, R. A.; PIRES, J. C. et al. Sustainable Microalgal Harvesting Process Applying Opuntia cochenillifera: Process Parameters Optimization. Applied Sciences, 13, n. 2, p. 1203, 2023.

RUGGERI, M. V. R.; GODOY, R. F. B.; ARROYO, P. A.; TREVISAN, E. Evaluation of natural flocculant efficiency in the harvest of microalgae Monoraphidium contortum. SN Applied Sciences, 3, n. 6, p. 627, 2021.

SILVA, D. F. S.; SPERANZA, L. G.; QUARTAROLI, L.; MORUZZI, R. B. et al. Separation of microalgae cultivated in anaerobically digested black water using Moringa Oleifera Lam seeds as coagulant. Journal of Water Process Engineering, 39, p. 101738, 2021.

TEIXEIRA, C. M. L. L.; KIRSTEN, F. V.; TEIXEIRA, P. C. N. Evaluation of Moringa oleifera seed flour as a flocculating agent for potential biodiesel producer microalgae. Journal of applied Phycology, 24, n. 3, p. 557-563, 2012.

THORÉ, E. S.; MUYLAERT, K.; BERTRAM, M. G.; BRODIN, T. Microalgae. Current Biology, 33, n. 3, p. R91-R95, 2023.

UDAYAN, A.; SIROHI, R.; SREEKUMAR, N.; SANG, B.-I. et al. Mass cultivation and harvesting of microalgal biomass: Current trends and future perspectives. Bioresource technology, 344, p. 126406, 2022.

VANDAMME, D.; MUYLAERT, K.; FRAEYE, I.; FOUBERT, I. Floc characteristics of Chlorella vulgaris: influence of flocculation mode and presence of organic matter. Bioresource Technology, 151, p. 383-387, 2014.

VU, H. P.; NGUYEN, L. N.; LESAGE, G.; NGHIEM, L. D. Synergistic effect of dual flocculation between inorganic salts and chitosan on harvesting microalgae Chlorella vulgaris. Environmental Technology & Innovation, 17, p. 100622, 2020.

WANG, Q.; OSHITA, K.; TAKAOKA, M. Flocculation properties of eight microalgae induced by aluminum chloride, chitosan, amphoteric polyacrylamide, and alkaline: Life-cycle assessment for screening species and harvesting methods. Algal Research, 54, p. 102226, 2021.

WANG, S.-K.; STILES, A. R.; GUO, C.; LIU, C.-Z. Harvesting microalgae by magnetic separation: A review. Algal Research, 9, p. 178-185, 2015.

WANG, S.; YERKEBULAN, M.; ABOMOHRA, A. E.-F.; EL-KHODARY, S. et al. Microalgae harvest influences the energy recovery: A case study on chemical flocculation of Scenedesmus obliquus for biodiesel and crude bio-oil production. Bioresource Technology, 286, p. 121371, 2019.

YIN, Z.; LI, S.; HU, D.; LI, Z. et al. Performance evaluation of different chitosan-clay composite materials for efficient harvesting of Chlorella vulgaris and impacts on downstream bioproduct processing and water reusability. Chemical Engineering Journal, 430, p. 132892, 2022.

REMUNOM
ISSN 2178-6925

Received: 26/01/2026 - **Accepted:** 25/02/2026
Vol: 02.03
DOI: 10.61164/7ck88f05
Pages: 1-25

ZHAO, Z.; LI, Y.; MUYLAERT, K.; VANKELECOM, I. F. Synergy between membrane filtration and flocculation for harvesting microalgae. Separation and Purification Technology, 240, p. 116603, 2020.Zhu, L., Pan, G., Xu, H., Kong, L., Guo, W., Yu, J., Mortimer, R.J.G., Shi, W., 2021. Enhanced chitosan flocculation for microalgae harvesting using electrolysis. Algal Res 55, 102268. https://doi.org/10.1016/J.ALGAL.2021.102268.