

Comparison of Microalgae Harvesting Methods: Technical Efficiency and Economic Feasibility for Scalable Biofuel Production

Andy Budiarto¹, Ari Hardianto², Abu Bakar Muhammad Ibnu Syihab³,
Saifa Aprilia Sidquni³, Lucy Adinisa⁴, Ivani Nurjannah⁴ and Toto Subroto^{2,*}

¹PT. Jawa Power, Jakarta 12190, Indonesia

²Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, West Java 45363, Indonesia

³PT. YTL Jawa Timur, East Java 67291, Indonesia

⁴Department of Biotechnology, Graduate School, Universitas Padjadjaran, West Java 40132, Indonesia

(*Corresponding author's e-mail: t.subroto@unpad.ac.id)

Received: 18 November 2025, Revised: 24 December 2025, Accepted: 31 December 2025, Published: 5 January 2026

Abstract

Global warming is a critical global challenge that has accelerated the development of carbon mitigation strategies. Microalgae-based systems have emerged as a promising carbon capture and utilization (CCU) approach, often referred to as BioCCU, due to their ability to convert captured carbon into valuable biomass. In the energy sector, algal biomass can be converted into diverse biofuels such as high-calorie biomass, biodiesel, bioethanol, and hydrogen. Despite this potential, large-scale deployment of microalgae-based CCU systems is still constrained by the harvesting stage, which remains one of the most energy- and cost-intensive processes. This review provides a comparative assessment of microalgae harvesting techniques such as centrifugation, filtration, and coagulation/flocculation, focusing on energy consumption, operational cost, biomass quality, and technical feasibility for BioCCU applications. The analysis is based on laboratory- and pilot-scale data obtained from BioCCU unit at Paiton Power Plant Units 5 & 6, Indonesia, complemented by relevant literature. The results show that centrifugation produces high-quality, contamination-free biomass but requires extremely high energy input, resulting in a low net energy ratio (NER) of 1.20 and a high operational cost of approximately USD 0.51/kg of dry biomass. Filtration shows improved energy performance (NER = 5.22) and low operational cost (USD 0.16/kg of dry biomass), but its application is limited by membrane fouling, operational complexity, and high moisture content of the harvested biomass. In contrast, coagulation–flocculation demonstrates the most favorable energy performance, achieving a high NER value of 21.34 with a relatively low operational cost of USD 0.21/kg of dry biomass, while offering simpler operation and more energy-efficient downstream drying. The main contribution of this review lies in quantifying the trade-offs among harvesting methods and identifying coagulation–flocculation as the most promising option for large-scale BioCCU systems targeting biofuel production, provided that future developments address the environmental impacts of chemical usage.

Keywords: Biofuel, BioCCU, Cost, Energy efficiency, Feasibility, Harvesting, Microalgae

Introduction

The intensification of the greenhouse effect due to anthropogenic greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂), has led to significant global warming and associated environmental impacts, including extreme weather events, sea-level rise, and

ecosystem disruption [1-4]. In response, international efforts such as the Paris Agreement have emphasized the need for effective carbon mitigation strategies to limit global temperature rise to well below 2 °C, with carbon capture technologies playing a key role [5].

Within this context, microalgae-based systems have emerged as a promising carbon capture and utilization (CCU) approach, owing to their high photosynthetic efficiency, rapid growth rates, and ability to directly assimilate CO₂ into valuable biomass. Compared to terrestrial plants, microalgae can fix CO₂ more efficiently and can be readily integrated with industrial point sources such as fossil fuel power plants through direct flue gas utilization [6]. In addition, microalgae biomass can be converted into a wide range of value-added products, particularly biofuels such as biodiesel and bioethanol, making microalgae-based CCU attractive for the energy sector [7].

Despite these advantages, the large-scale deployment of microalgae-based biofuel systems remains limited by the harvesting stage, which is among the most energy- and cost-intensive steps in the production chain. Harvesting can account for up to 30% of total production costs and directly affects biomass quality, energy balance, and downstream processing efficiency [8,9]. Common harvesting methods including centrifugation, filtration, and coagulation/flocculation are present distinct trade-offs in terms of energy demand, cost, operational complexity, and biomass purity [10,11].

In this review, we examine three microalgae harvesting methods (centrifugation, filtration, and coagulation/flocculation) for producing algal biomass as a feedstock for biofuel, with a particular emphasis on their potential contribution to reducing carbon emissions in the energy sector. The analysis considers harvesting efficiency alongside the technical and economic feasibility of large-scale applications. Since the choice of harvesting method directly influences biomass quality and its suitability for downstream processing, we also assess how different techniques affect the application of algal biomass for biofuel production. The

discussion integrates findings from laboratory-scale experiments and pilot-scale operations at the BioCCU pilot project in Paiton Power Plant Units 5 & 6, Indonesia, complemented by literature data.

Microalgae-based carbon capture and bioenergy applications

Microalgae are photosynthetic microorganisms capable of efficiently converting carbon dioxide (CO₂) into biomass through photosynthesis, making them a promising component of carbon capture and utilization (CCU) systems [12]. Naturally, microalgae contribute substantially to global CO₂ fixation and can assimilate inorganic carbon directly from aqueous environments in the form of dissolved CO₂ and bicarbonate. Their rapid growth rates, high photosynthetic efficiency, and ability to utilize industrial flue gas further support their integration with emission-intensive facilities such as power plants [13].

Microalgae biomass is a versatile feedstock with applications across pharmaceuticals, cosmetics, animal feed, chemicals, and bioenergy/biofuel. Their biomass predominantly consists of lipids (7 - 65%), proteins (5 - 74%), and carbohydrates (8 - 69%), along with pigments, vitamins, and other metabolites (1 - 14%) [14]. In the energy sector, microalgae biomass can be converted into various biofuels products through different conversion pathways, as summarized in **Table 1** or utilized directly as a solid fuel with high calorific value. Compared to terrestrial biomass, microalgae offer advantages such as higher productivity, flexible cultivation conditions, and reduced competition with arable land and freshwater resources [14,15]. In this context, microalgae have attracted considerable attention as a next-generation feedstock for biofuel production, including biodiesel, bioethanol, and hydrogen [16].

Table 1 Biofuels derived from microalgae biomass.

Type of biofuel	Utilised components	Conversion process	Application
High-calorie biomass	All biomass components	Biomass drying	Coal and biomass co-firing
Biodiesel	Lipids (free fatty acids, triacyl glycerols, diacyl glycerols, monoacyl glycerols)	Esterification & transesterification	Vehicle fuel, diesel engine fuel

Type of biofuel	Utilised components	Conversion process	Application
Bioethanol	Carbohydrates	Sugar fermentation	Vehicle fuel
Hydrogen	Acetate, lactate, and butyrate	Photo-fermentation	Hydrogen combustion, hydrogen fuel cell
	Glucose and other organic substrates	Dark-fermentation	
	All organic components (lipid, protein, carbohydrate, etc.)	Thermochemical (pyrolysis, gasification, steam reforming) and electrochemical	

Despite these advantages, the conversion of microalgae biomass into bioenergy products requires biomass with appropriate quality characteristics, particularly low moisture content and preserved biochemical composition. Since microalgae cultures typically contain more than 99% water [17], harvesting plays a critical role in concentrating biomass and determining its suitability for downstream bioenergy conversion. Inefficient harvesting can significantly increase energy demand and operational costs, thereby reducing the overall feasibility of microalgae-based CCU systems. Therefore, the selection of an effective microalgae harvesting method is essential not only for biomass recovery but also for ensuring energy-efficient and economically viable bioenergy production within microalgae-based CCU applications.

Technical review of microalgae harvesting methods

Microalgal biomass production consists of four main stages: Cultivation, harvesting, drying, and downstream processing. Among these, harvesting is one of the most expensive steps, accounting for approximately 20% - 30% of the total production cost. Harvesting is required to concentrate the biomass, as microalgal cells remain suspended in the culture medium at very low densities even after the growth phase [18]. This step is technically challenging due to several factors: The small size of many microalgae (< 30 μm), the low biomass concentration in culture media (< 1 g/L), and the highly electronegative surface of microalgal cells, which causes them to behave like stable colloids and resist sedimentation. These characteristics translate into high energy demands for separation. To address these challenges, a variety of harvesting strategies have been developed, including

centrifugation, filtration, coagulation–flocculation, flotation, electrocoagulation, or hybrid approaches. Each method presents distinct benefits and limitations. Consequently, the development of cost- and energy-efficient harvesting technologies remains critical to ensuring the sustainable production of high-quality microalgae biomass [7,19]. This review focuses on the technical and economic comparison of three widely applied harvesting techniques: Centrifugation, filtration, and coagulation–flocculation.

Centrifugation

Centrifugation is a well-established harvesting technique that concentrates microalgal suspensions to approximately 10% - 25% of dry weight by applying centrifugal force to separate cells from the culture medium based on density differences. Even highly diluted cultures can be effectively concentrated when operated at appropriate rotational speeds. Several types of centrifuges can be used to harvest microalgae, including disk stack centrifuges, perforated basket centrifuges, imperforated basket centrifuges, decanters, and hydrocyclones [10]. The performance of this method is influenced by several parameters, including cell sedimentation properties, cell size, the small density contrast between cells and water, and the residence time of the cell culture within the centrifuge [10,20].

The harvesting efficiency of centrifugation can reach 80% - 90% within just 2 - 5 min. Japar *et al.* [21] compared centrifugation efficiency across species of different cell sizes—*Chlorella sp.* UKM 2 (2 - 10 μm), *Coelastrrella sp.* UKM 4 (5 - 10 μm), and *Chlamydomonas sp.* UKM 6 (10 - 30 μm)—using rotational speeds of 3000, 5000, and 7000 rpm. At 7000 rpm, the recovery efficiencies (harvesting efficiencies) reached 98%, 96%, and 90%, respectively [21]. These

results highlight the strong influence of cell size: Larger cells are more difficult to recover and require higher speeds, which increases energy consumption.

The main advantage of centrifugation is that it does not require chemicals, thus producing high-quality biomass while preserving integrity during storage [22]. However, centrifugation is associated with high operational and energy costs, limiting its feasibility for large-scale biofuel production [20]. In addition, exposure to intense centrifugal and shear forces can damage cells, leading to the loss of sensitive compounds [9]. Despite these drawbacks, centrifugation is adaptable to a wide range of algal cell sizes. By adjusting rotational speed, operators can optimize harvesting efficiency according to the species being processed.

Filtration

Filtration is a physical separation technique that isolates solids from liquids using semipermeable membranes. It allows the culture medium to pass through while retaining microalgal cells, which are subsequently collected [19,23]. With appropriate membrane pore sizes, filtration can efficiently recover a wide range of species, including fragile microalgae that are susceptible to shear damage [9,24]. Two types of filtration systems, according to the flow of the filtration feed, are used for microalgae harvesting: Dead-end filtration and tangential flow filtration, both of which can operate under pressure or vacuum conditions [25].

The spherical shape and small size of microalgal cells make them difficult to harvest, while extracellular materials surrounding the cells can block membrane pores, leading to fouling and reduced filtration efficiency. Filtration systems are classified based on pore size: Macrofiltration ($> 10 \mu\text{m}$) for large particles, microfiltration ($0.1 - 10 \mu\text{m}$) for microalgae and large particulates, ultrafiltration ($0.01 - 0.1 \mu\text{m}$) for proteins and polymers, and nanofiltration ($0.001 - 0.01 \mu\text{m}$) for ions and small molecules [26]. The performance of a filtration system is also influenced by the physicochemical characteristics of the membrane surface. Membranes may possess positive, negative, or neutral surface charges and exhibit either hydrophobic or hydrophilic properties, both of which significantly affect permeate flux and fouling behavior. For instance, Rossignol *et al.* [27] reported that a polyacrylonitrile (PAN) membrane, which is neutral and hydrophilic,

demonstrated superior permeate flux compared to a polyethersulfone (PES) membrane, which is neutral and hydrophobic, under identical operating conditions.

Filtration can achieve recovery efficiencies approaching 100% and is relatively simple to operate for the main process [23]. However, membrane fouling and clogging remain major challenges, primarily caused by extracellular substances that block membrane pores, causing the need for additional, more complex cleaning systems. These issues necessitate frequent cleaning (backwashing) or membrane replacement, which slows down operations and increases operational costs [9]. Membrane cleaning typically involves not only backwashing with water but also the use of chemical agents to remove the fouling layer or “cake”. Excessive chemical cleaning, however, can degrade membrane materials and shorten their service life, leading to more frequent replacements [10]. To reduce cake resistance and facilitate backwashing, inactivation of microalgae cells before filtration is also important. Pretreatment of microalgal cultures with ozone, for example, has been shown to decrease cake resistance by 70% - 93% [28]. Another drawback of filtration is its limited flexibility: Membrane pore sizes are fixed and may not align with variations in algal cell size across different growth stages or species. Pores smaller than the cells increase the potential of clogging, while larger pores reduce cell recovery efficiency (RE) by allowing cells to escape through the membrane.

Coagulation-flocculation

Coagulation–flocculation is another widely applied technique that enhances particle size, thereby promoting sedimentation. The principle is similar to suspended solids removal in wastewater treatment. The process occurs in 2 steps: Coagulation, where coagulants destabilize cell suspensions to form microflocs, and flocculation, where flocculants bridge and bind microflocs into larger, visible macroflocs with improved settling properties (Feedwater, no date). This method is efficient and scalable for large-volume harvesting [23].

Because microalgal cell surfaces are negatively charged, they resist aggregation due to electrostatic repulsion between algae cells, acting as a stable colloid. Coagulants with positive charges neutralize this repulsion, allowing cells to aggregate into microflocs

[9,26]. Flocculants then strengthen and stabilize these aggregates, producing macroflocs with higher sedimentation rates.

There are various types of coagulant/flocculant agents, which can be inorganic or organic chemicals. For a microalgae harvesting system, the coagulant/flocculant agents used must be effective, non-toxic, economical, and easy to use. Inorganic coagulants such as aluminum sulfate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), and polyaluminum chloride (PAC) neutralize negative cell surface charges and initiate coagulation. Organic flocculants, including cationic, anionic, and nonionic polyelectrolytes such as polyacrylamide and polyethyleneimine, enhance floc formation. Cationic polyelectrolytes with high charge density are particularly effective because they both neutralize charges and physically bridge cells. Anionic and nonionic polymers, however, are generally ineffective due to electrostatic repulsion [10]. Alternatively, bioflocculants secreted by microorganisms such as fungi, algae, or bacteria produce extracellular polymeric substances that act as natural flocculants. These are increasingly favored as environmentally sustainable alternatives [29].

The coagulation–flocculation method offers high efficiency, low cost, operational simplicity, and scalability. However, the use of chemical coagulants can limit the reuse of the growth medium and harvested biomass. Although multivalent salts are inexpensive, they are non-biodegradable and may contribute to effluent pollution. For this reason, bioflocculants are recommended for sustainable harvesting [23]. The efficiency of this process depends strongly on dosage: Insufficient dosing results in weak flocs with poor settling, whereas overdosing can hinder floc formation [10].

Comparative analysis

Comparison of harvesting techniques

Two key parameters are commonly used to evaluate the effectiveness of microalgae harvesting processes: Recovery efficiency (RE) and the

concentration factor (CF). Recovery efficiency, also known as harvesting efficiency, represents the proportion of microalgal cells successfully separated from the culture medium relative to the initial number of cells present in the medium. In contrast, the concentration factor is defined as the ratio between the final concentration of microalgal biomass in the harvested product (biomass concentrate, see point C in **Figure 1**) and its initial concentration in the culture medium. Therefore, considering both RE and CF together provides a comprehensive assessment of a harvesting method's capability to separate and concentrate microalgal biomass from its growth medium [10]. These parameters are calculated as follows:

$$\text{Recovery efficiency (RE)} = \frac{AC_i - AC_f}{AC_i} \quad (1)$$

$$\text{Concentration factor (CF)} = \frac{A_f}{AC_i} \quad (2)$$

where:

AC_i (g/L) is the initial algae cell concentration in the culture medium (see point A in **Figure 1**)

AC_f (g/L) is the remaining algae cell concentration in the medium after harvesting (see point B in **Figure 1**)

A_f (g/L) is the concentration of microalgal biomass in the flocs obtained from harvesting (see point C in **Figure 1**)

The concentration of microalgae cells in the culture medium can be determined using several methods, including chlorophyll content analysis, direct cell counting, optical density (absorbance) measurement, and dry biomass determination [10]. Among these, optical density measurement is the most convenient and rapid technique, making it suitable for routine or qualitative assessments. However, this method does not provide information on the actual amount of biomass harvested. For accurate quantitative analysis, measurements based on dry biomass are required.

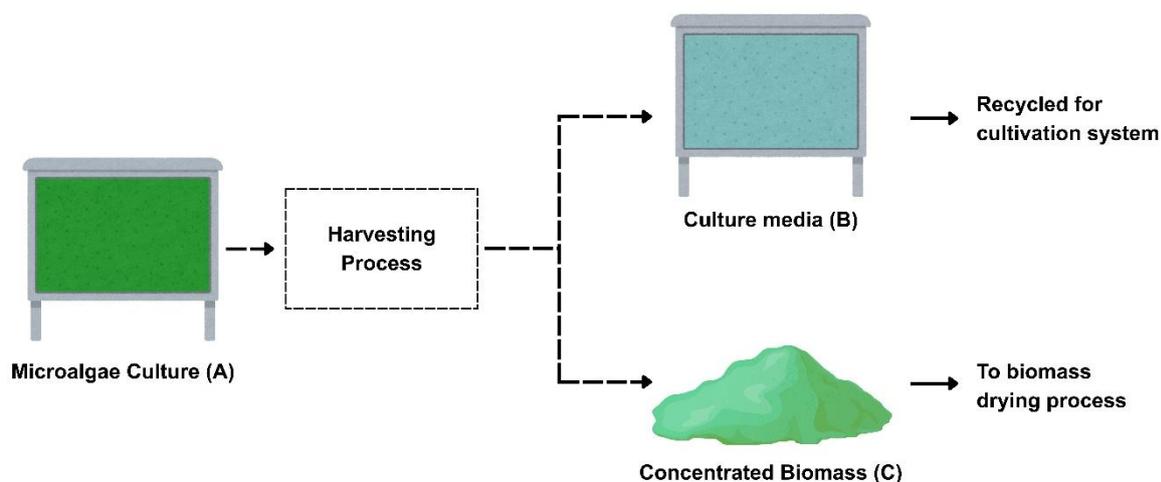


Figure 1 Schematic representation of the inputs and outputs of the microalgae harvesting process.

High RE and CF values indicate that a large proportion of algal cells or biomass has been successfully separated from the cultivation medium, leaving fewer cells behind in the residual water. However, in certain conditions, achieving excessively high RE or CF values is not always desirable. For instance, Dassey and Theegala (2013) reported that a continuous centrifugation system reduced energy consumption by up to 82% by reducing the processing time (increasing flow rate from around 1 L/min to 18 L/min), despite yielding a relatively low RE of only 28.5%. Nevertheless, when processing large volumes of algal cultures rapidly, such a trade-off can be highly advantageous. For applications in the biofuel industry to be both economically and environmentally feasible, low energy consumption is an essential requirement. Therefore, to balance low energy consumption with optimum output, the centrifugation method for microalgae harvesting requires optimizing the treatment time (flow rate) [30].

In the coagulation-flocculation method, to achieve a high RE value, a sufficient dose of coagulant and flocculant is required, which is typically slightly excessive. This excess dose of coagulant and flocculant chemicals will accumulate in the cultivation media, which will be detrimental to the process of recycling the cultivation media for use in the next cultivation cycle [20,31]. Increasing concentration of coagulant and flocculant chemicals in algae cultivation media will inhibit algae growth. In the harvesting process using the coagulation-flocculation method, where the cultivation

media are recycled repeatedly, and the concentration of coagulant-flocculant residue will continue to increase, and at a certain point, the media will no longer be usable for further cultivation. Therefore, targeting high RE value will reduce the number of recycling of the algae media, which will also have an impact on increasing water consumption for the cultivation process. Furthermore, coagulant and flocculant chemicals will also accumulate in the biomass product. Coagulants typically contain metals, which, when accumulated in biomass, increase the ash content of the biomass product. When used for biofuel production, high ash content in biomass can be detrimental to the combustion process and increase operational costs.

In filtration-based harvesting, a dead-end filtration system operated under low pressure or vacuum is effective and highly efficient for processing large microalgae cells that settle easily, such as *Spirulina*. This system typically achieves a very high RE value due to its simplicity and suitability for large-cell-size microalgae. However, because of its limited applicability to large cell species only, the dead-end filtration system will not be discussed in detail in this article. In contrast, the tangential flow filtration (TFF) or cross-flow filtration system, which operates under higher pressure, is particularly well-suited for harvesting small-cell microalgae such as *Chlorella* species, whose cultures behave like stable colloidal suspensions. TFF is advantageous for processing large culture volumes within a short period, though this often comes at the expense of slightly lower CF values. In a

TFF system, the microalgal culture flows tangentially across the membrane surface, allowing the solvent (water) to permeate through the membrane into the filtrate while retaining and concentrating the algal biomass in the retentate stream [10]. This system differs slightly from conventional filtration systems used in water or wastewater treatment, where the desired product is the permeate stream. In contrast, in this system, the target product—the biomass—is retained in the retentate stream. According to Danquah et al. (2009), TFF was able to concentrate *Tetraselmis suecica* microalgae cultures by a factor of 151, with an energy consumption of 2.15 kWh/m³ [32].

Similarly, Bhave *et al.* [33] reported that *Nannochloropsis oculata* cultures could be concentrated

up to 75 times using this technique, requiring only 0.3 - 0.7 kWh/m³ of energy and producing a biomass suspension with a concentration of 150 g/L. Targeting a too high CF value in this system may increase the rate of membrane blockage, necessitating more backwash and cleaning as well as a shorter membrane life. Although no chemicals need to be added during the main filtration stage, chemicals are still needed at certain routine periods for the periodic membrane cleaning process. If the membrane cleaning system for microalgae cell blockage on the membrane surface relies solely on backwashing with water without chemicals, this cleaning system will be ineffective, resulting in inefficient filtration process in the next cycles.

Table 2 Comparison of RE and CF values of several harvesting methods from previous researches.

Reference	System description	Microalgae type	System capacity	RE (%)	CF (%)
I. Centrifugation					
[34]	Conventional centrifugation	<i>Chlorella sorokiniana</i>	150 g L ⁻¹	99	58
[35]	Centrifugation	<i>Chlorella vulgaris</i>	NA	100	58
[34]	Conventional centrifugation	<i>Chlorella sorokiniana</i>	NA	99	58
II. Filtration					
[36]	Ultrafiltration	<i>Chlorella sp.</i> MUR 269	NA	78	10
[37]	Screw-press filtration	<i>Chlorella sp.</i> HS2	NA	93	8.4
[38]	Membrane filtration	<i>Chlorococcum sp.</i>	2.0 g L ⁻¹	98.7	-
III. Coagulation-flocculation					
Our research	Coagulation and flocculation using polyaluminium chloride and cationi-polymer (polyacrylamide-based)	<i>Chlorella vulgaris</i>	1000 l/batch	99.52	154
[39]	Autoflocculation	<i>Chlorella vulgaris</i>	NA	88.4	-
[40]	EPS Flocculation	<i>Chlorella sorokiniana</i>	NA	96.26	96
[34]	Tannin coagulant	<i>Chlorella sorokiniana</i>	NA	98	15-23

NA: Not available

For the next method comparison in this article, we chose one study result from each harvesting technique from other literatures and our own research utilizing *Chlorella* algae because of the species' high lipid and energy content, which makes it a popular raw material for the production of biofuel. Unfortunately, *Chlorella* species are challenging to harvest using simple filtering or other harvesting techniques due to their very small

cell size and behave like a stable colloid in water media. Therefore, comparing the technical aspects of several harvesting methods for small cells microalgae is appropriate to illustrate the effectiveness of each method.

Schematics of each harvesting scenario are shown in **Figure 2** below.

Table 3 Reference conditions for the next method comparison.

Reference	Method to be compared	System description
[20]	Centrifugation	<i>Chlorella sp.</i> harvesting using a Continuous Disc-stack centrifuge
[41,42]	Filtration	Harvesting <i>Coelastrrella</i> and <i>Desmodesmus</i> using a cross flow filtration system. The system is equipped with hollow fibre ultrafiltration membranes with total membrane surface area of 35 m ² with pore size of 0.03 µm, effective flux of 90 l/h/m ² and maximum of 1.25 bar of trans membrane pressure (TMP).
Our research (2025) at BioCCU pilot project at Paiton Power Plant Units 5 & 6, Jawa Timur, Indonesia.	Coagulation	Coagulation-flocculation method for <i>Chlorella vulgaris</i> harvesting using polyaluminium chloride (PAC) as coagulant and cationic polymer (polyacrylamide-based) as flocculants in a batch coagulation reactor. Reactor capacity: 500 l/batch with processing time of 30 minutes per batch (10 minutes for mixing and 20 minutes for settling). The optimum dose from this research is 50 ppm of PAC and 12.5 ppm of cationic polymer.

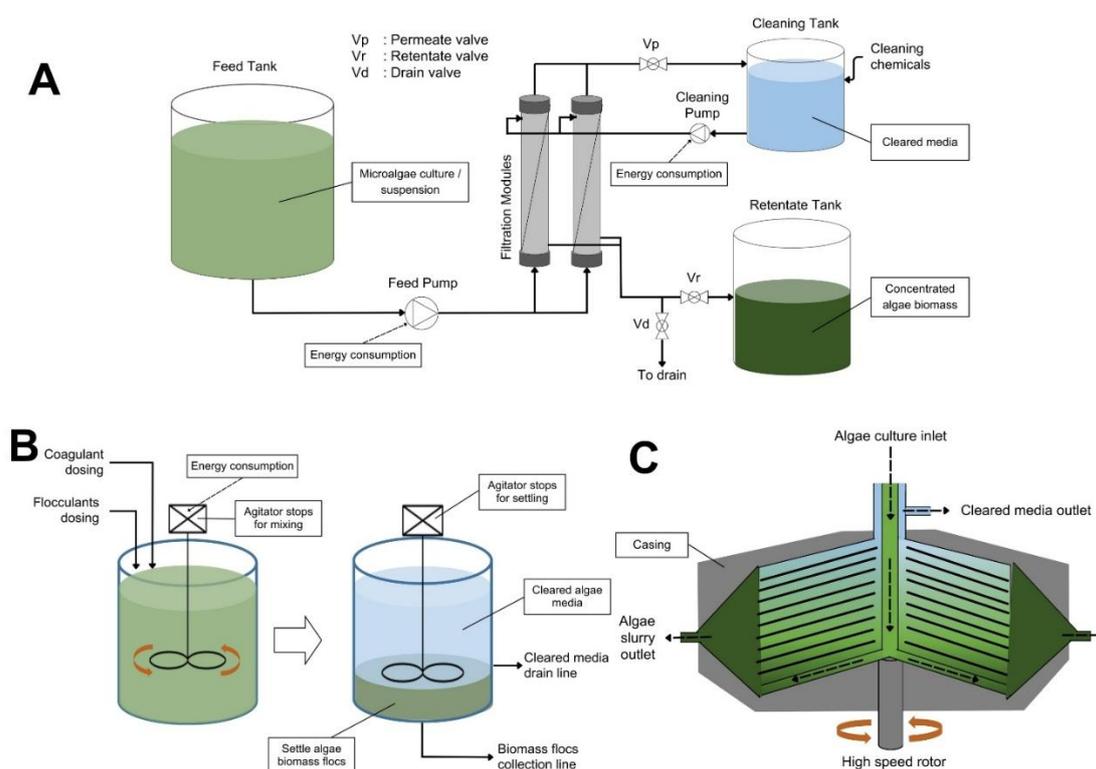


Figure 2 Schematic of the harvesting systems used for the method comparison in this article [41]. A) Microalgae harvesting using ultrafiltration system (adapted from Mora-Sánchez *et al.* [42] and Wang *et al.* [43]). B) Microalgae harvesting using coagulation-flocculation system (our research). C) Microalgae harvesting using continuous disc-stack centrifuge system (adapted from Liber *et al.* [25]).

Comparison of biomass quality

The quality of the biomass product will also be impacted by the harvesting method selection, which will have an impact on the downstream biomass processing. As presented in **Table 4**, each harvesting technique

produces a distinct biomass form and quality profile, influencing its efficiency for subsequent conversion processes such as drying, extraction, or biofuel production.

Table 4 Comparison of the biomass product characteristics.

Parameter	Centrifugation	Filtration	Coagulation/ flocculation
Form of the product	Biomass slurry with a biomass concentration of 15 - 20% [20].	Biomass slurry with a biomass concentration of 90 g/L [41].	Raw biomass floc with a water content of around 90%. Simple dewatering technique can be applied to reduce the water content to below 60% [44].
General characteristic	No chemical contamination. If the centrifugation speed is too fast, it can damage the algae cells.	No chemical contamination from the process. Algal cells can rupture and be damaged if filtration is performed at too high a pressure.	There is biomass contamination from the coagulant and flocculant chemicals used.

Parameter	Centrifugation	Filtration	Coagulation/ flocculation
Calorific value	Same as the calorific value of pure microalgae biomass. GCV = 5,303 kcal/kg [45].	Same as the calorific value of pure microalgae biomass. GCV = 5,303 kcal/kg [45].	Lower calorific value due to metal contamination from coagulant addition. GCV: 4,560.93 kcal/kg (dry basis) (our research).
Ash content	Low ash content.	Low ash content.	Higher ash content due to inorganic chemical contamination from coagulant (PAC). Ash content = 12.85% (PAC dosage during harvesting is 50 ppm) (our research).

The centrifugation method typically yields a biomass slurry with a biomass concentration of approximately 15 - 20% [20], characterized by its high purity and absence of chemical contaminants. This type of biomass retains its original calorific value, comparable to that of pure microalgal biomass, and exhibits low ash content, making it particularly suitable for thermochemical conversion processes such as combustion or pyrolysis. However, excessively high centrifugation speeds can cause mechanical stress and cellular disruption, potentially damaging the chemical structure of some cell components and reducing yields in biochemical extraction applications.

The filtration process generates a more concentrated biomass slurry, with a biomass concentration of approximately 90 g/L [41] or even less. The biomass concentration in the slurry resulting from filtration is usually limited to a certain value to maintain the membrane blockage velocity within normal limits, thereby reducing the amount of backwash and chemical cleaning and maximizing membrane lifetime. The slurry product from this process is relatively clean, though there remains a minor risk of chemical contamination from membrane cleaning residues. Such contamination can be minimized through appropriate membrane maintenance and cleaning protocols. Similar to centrifugation, excessively high filtration pressures may lead to cell rupture, potentially reducing the quality and value of the recovered biomass. Despite these challenges, the biomass obtained through filtration generally maintains its low ash content and original calorific value, making it suitable for both biochemical

and thermochemical processing pathways of biofuel production.

In contrast, the coagulation–flocculation method produces a raw biomass flocs with a water content of approximately 90 %. Even if the floc still has a relatively high water content (90%) if it has good floc qualities, it may be simply squeezed using a simple procedure to further reduce the water content, which will lessen the load on the drying process. The application of dewatering polymers can also be applied to help reduce the water content of flocs efficiently to below 60 % or lower [44]. Nevertheless, this approach introduces chemical contamination due to the use of coagulants and flocculants, such as polyaluminum chloride (PAC) and flocculant polymer, during the aggregation process. Based on the result of our research, the residual PAC in biomass increase the ash content to around 12.85% (at a PAC dosage of 50 ppm) and slightly alter the calorific value, recorded at 4,560.93 kcal/kg (dry basis). Although this energy value remains within an acceptable range, the increased inorganic fraction may reduce combustion efficiency and limit the suitability of the biomass for applications requiring high purity, such as food or pharmaceutical products.

Despite these limitations, the coagulation–flocculation method offers a distinct advantage in energy efficiency. The biomass slurry obtained from centrifugation and filtration generally contains a high water content, necessitating energy-intensive drying processes that significantly increase post-harvest energy demand and operational costs. Conversely, the dense biomass flocs produced via coagulation–flocculation are

easier to separate from the liquid phase and often require significantly lower energy demand for drying, thereby reducing the overall energy requirement for biomass preparation prior to downstream biofuel conversion process.

Comparison of energy consumption

Net Energy Ratio (NER) is an indicator used to assess the overall energy efficiency of a bioenergy system, which is calculated using the following formula [46]:

$$NER = \frac{E_{input}}{E_{output}} \tag{3}$$

where:

E_{output} = total energy produced by the system (e.g., energy content in the product),

E_{input} = total energy consumed during the entire process (including energy for aeration, pumping, mixing, drying, etc.).

An energetically feasible system produces more energy than it consumes, which is indicated by a NER value greater than 1. When the NER equals 1, the system’s energy output merely balances its input, rendering it impractical for biofuel applications due to no margin of energy from the system. Conversely, an NER value below 1 signifies an inefficient system, as the energy required for operation exceeds the energy produced. Therefore, to achieve both energy and economic viability, biofuel production systems must aim for the highest possible NER values.

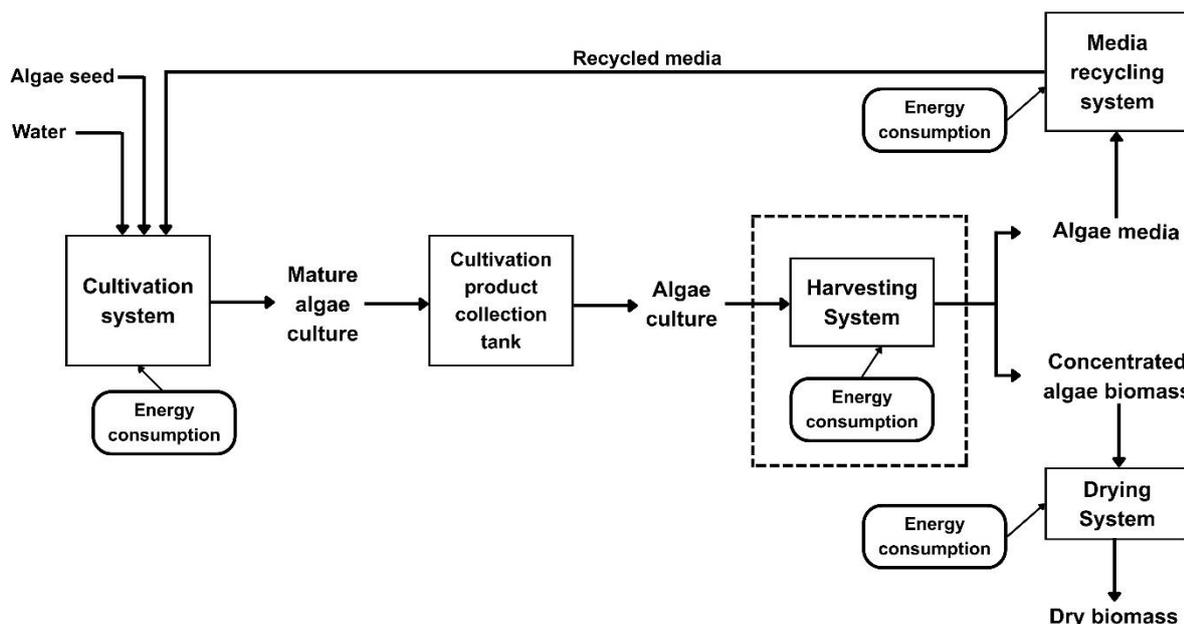


Figure 3 Schematic diagram showing the system boundary used for net energy ratio (NER) calculation in the microalgae-based biomass production process.

The NER value we computed in this study only includes energy consumption during the harvesting stage, as our sole focus is on comparing harvesting techniques (as shown in **Figure 3**). Therefore, an NER value greater than 1 in this study does not necessarily indicate a fully efficient system. If all sources of energy consumption were accounted for such as energy consumption for drying system, the recalculated NER

would likely decrease and fall below 1. Similarly, when the NER is initially less than 1, incorporating all energy inputs would further reduce the value, indicating an even less efficient system. Consequently, the observation of a substantially high NER in this study suggests that the system performs exceptionally well, providing a considerable energy margin that could accommodate additional energy demands from other

subsystems (cultivation system, gas supply system, water supply system, drying system, etc.) while still maintaining an NER value above 1.

Based on the NER calculations on **Table 5**, the centrifugation method yielded a low NER value of 1.2, indicating limited energy efficiency. In contrast, the coagulation method demonstrated a significantly higher NER value of 21.34, reflecting superior energy performance. Meanwhile, the filtration method exhibited a relatively high NER value of 5.22. It is important to note that the three NER values do not account for the energy consumption associated with the drying process. Both centrifugation and filtration methods produce biomass with high moisture content—

approximately 80% and 99%, respectively. This high water content significantly increases the energy required for drying, which would further reduce the overall NER values. In the case of filtration method, the very high moisture content (around 99%) is intentionally maintained to keep the membrane clogging rate within acceptable limits, thereby minimizing the frequency of backwashing and chemical cleaning. Attempting to achieve higher biomass concentration (i.e., lower water content) would accelerate membrane fouling, necessitating more frequent cleaning cycles and increasing operational costs. Moreover, excessive cleaning can shorten the membrane's lifespan, leading to even higher long-term operating expenses.

Table 5 NER value calculation.

Parameter	Centrifugation [20]	Filtration [41]	Coagulation- flocculation (Our research)
1. Energy consumption for the harvesting process			
Harvesting flow rate capacity	1 m ³ /h	1 m ³ /h	1 m ³ /h
Initial biomass concentration in the medium	0.65 g/L	0.65 g/L	0.65 g/L
Specific energy consumption for the harvesting process	3.3 kWh/m ³ or 3.3 kWh/h	0.76 kWh/m ³ or 0.76 kWh/h	0.18 kWh/m ³ or 0.18 kWh/h
RE and CF	RE = 100% CF = 308	RE = 100% CF = 15 - 27	RE = 99.52% CF = 615
Form of the harvesting process	Biomass slurry with 80% water content	Biomass slurry with algae biomass content of 9.7 g/L averagely	Biomass floc with 60% water content
2. Energy gained			
Dry biomass production rate (dry basis)	0.65 kg/h	0.65 kg/h	0.65 kg/h
Calorific value of the biomass (dry basis)	6.16 kWh/kg	6.16 kWh/kg	5.3 kWh/kg
Total energy gained from the product	4.01 kWh/h	4.01 kWh/h	3.76 kWh/h
3. Net Energy Ratio (NER)	1.20	5.22	21.34

Beyond energy consumption, a comprehensive technical comparison was also conducted considering other critical parameters that influence the overall performance and sustainability of each harvesting technique. These include energy efficiency, processing time, and product quality, applicability to different

microalgal species, technical hindrances, and environmental implications. A holistic summary of these aspects is presented in **Table 6**, providing an integrated evaluation of the advantages and limitations of each method for practical and sustainable microalgae harvesting applications.

Table 6 Overall technical comparison.

Parameter	Centrifugation	Filtration	Coagulation- flocculation
Energy efficiency	Unfeasible for biofuel production	Potentially feasible for biofuel production	Feasible for biofuel production
Processing time	Very fast (around 5 minutes/batch)	The processing time will depend on the membrane surface area. Fast processing time requires large membrane surface area that will increase investment cost.	Fast (around 30 min/batch)
Quality of the product	No contamination	No contamination	Contaminated by coagulant and flocculant chemicals
Applicability to all microalgae species	Adjustable to any microalgae species (by adjusting rotational speed)	Dead-end filtration only applicable to large cell microalgae species. TFF using specific membrane type only suitable to several microalgae species (depend on membrane pore size and microalgae cell size)	Applicable to any microalgae species (doesn't depend of microalgae cell size)
Hindrance	The difficulty of adjusting operating settings to achieve the most cost-effective RE value while achieving the lowest energy consumption conditions.	Membrane fouling can be accelerated by organic matter in the culture media, increasing more membrane cleaning activity and reduce membrane lifetime [10]	Most coagulants include metals, which accumulate in the harvested biomass. In biofuel applications, high metal content in biomass is undesirable because it produces ash when burned, reducing combustion efficiency and increasing management costs
Environmental aspect	In its core process, this method requires a large amount of energy, which means it also produces large indirect carbon emissions.	The energy requirements for the core process of this method are lower than those for centrifugation. However, it does produce wastewater from	This method produces low direct carbon emissions in its primary process due to its very low energy requirements. However, it tends to use an extensive amount of water and produces a large amount of

Parameter	Centrifugation	Filtration	Coagulation- flocculation
		backwashing and chemical membrane cleaning process.	wastewater because the accumulation of coagulant and flocculant chemicals in the algal medium decreases the time required to recycle the media.

Comparison of economic analysis

Economic assessment represents a fundamental component in evaluating the overall feasibility of microalgae harvesting technologies. While technical efficiency and energy performance determine the functional capability of a process, its economic viability ultimately dictates the scalability and long-term sustainability of biomass production systems [47]. The present analysis provides a comparative evaluation of the operational cost implications under operational conditions as shown in **Table 7**. Because microalgae harvesting techniques in bioCCU project are currently mostly in the pilot project stage, with designs that are still highly variable and equipment prices that vary from pilot project to pilot project, investment expenses—particularly equipment costs—are not included in this analysis.

Each harvesting technique was analyzed based on its energy (electricity) expenditure, and chemical consumption, assuming a uniform processing capacity of 1,000 liters per hour. As summarized in **Table 7**, centrifugation requires a centrifugation motor, which contributes to the highest energy cost per hour. Despite its superior separation efficiency and the absence of chemical requirements, the substantial power demand results in high operational expenses, reducing its suitability for large-scale applications. Because this process involves mechanical equipment that works continuously, maintenance costs will also be higher (not calculated in this study). From our calculation, electrical cost of this method is around 0.51 USD/kg of DBM produced.

The filtration process, which employs a filtration pump and membrane cleaning system, offers a lower electricity costs (0.12 USD/kg DBM) than centrifugation. However, operational challenges such as membrane fouling may increase maintenance cost over time. In order to maintain effective and efficient

filtration process, membrane cleaning systems must be performed on a regular basis (every few minutes). As a result, these systems routinely consume some chemicals, and the membranes condition degrades over time and need to be replaced every few years. Based on our recalculation membrane replacement cost of this system is around 0.04 USD/kg DBM (recalculated from Wang et al (2019) paper) where the total of electrical and chemical cost is around 0.13 USD/kg DBM giving the total operational cost of around 0.16 USD/kg of produced DBM [43].

In contrast, coagulation–flocculation utilizes an agitator along with chemical coagulants and flocculants, which substantially reduces energy consumption but introduces chemical-related operational costs. For biofuel production applications, it is essential to consider the effects of chemical additives, as excessive dosages can decrease the calorific value and increase the ash content of the resulting biomass. Therefore, optimizing the dosage of coagulants and flocculants is crucial to maintain biomass quality within the specifications required for biofuel conversion. In this study, the optimum dosages were determined to be 50 ppm of PAC as coagulant and 12.5 ppm of cationic-polymer as flocculants, producing biomass with a calorific value of 4,560.93 kcal/kg (dry basis) and an ash content of 12.85%, both of which fall within the acceptable range for biofuel conversion processes. The energy cost associated with the agitation stage during coagulation–flocculation was estimated at 0.03 USD/kg DBM, while the cost of chemical coagulants and flocculants was approximately 0.18 USD/kg. Maintenance costs of this method were minimal and thus considered negligible. The total cost of the coagulation–flocculation method is approximately USD 0.21 per kilogram of dry biomass (DBM), which is slightly higher than that of the filtration method. Nevertheless, this technique offers a major advantage,

as the resulting algal flocs contain relatively low moisture—around 90%, which can be further reduced to below 60% using simple dewatering techniques. When the energy demand and cost of the subsequent drying

stage are considered, the coagulation–flocculation method demonstrates clear economic superiority over both filtration and centrifugation approaches.

Table 7 Economic comparison of microalgae harvesting method.

Parameter	Centrifugation	Filtration	Coagulation/ flocculation
Required equipment	Centrifugation motor	Filtration pump Backwash pump	Agitator
Required materials	No additional materials needed	Water and chemicals for membrane cleaning	Coagulant (polyaluminium chloride) and flocculants (cationic-polymer)
Treatment capacity	1000 L of microalgae culture per hour		
Energy cost	0.51 USD/kg DBM ¹⁾	0.12 USD/kg DBM ¹⁾	0.03 USD/kg DBM ¹⁾
Chemical cost	-	0.01 USD/kg DBM	0.18 USD/kg DBM
Other cost	-	0.04 USD/kg DBM ²⁾	-
Total cost	0.51 USD/kg DBM	0.16 USD/kg DBM	0.21 USD/kg DBM
Important note	<ul style="list-style-type: none"> ● Exclude drying process ● Exclude investment cost and labour cost. ● Exclude mechanical maintenance cost. 	<ul style="list-style-type: none"> ● Include membrane replacement cost ● Exclude drying process ● Exclude investment cost, other maintenance cost and labour cost. 	<ul style="list-style-type: none"> ● Exclude drying process ● Exclude investment cost and labour cost. ● Maintenance cost of agitator and harvesting reactor is neglected due to insignificant.

DBM (dry biomass): Biomass product in dry basis.

¹⁾ Electricity price: 0.1 USD/kWh (electricity price in Indonesia).

²⁾ Membrane replacement cost (recalculation from Wang et al. (2019): (352,127 USD/year) / (9,834,563 kg DBM/year)) [43].

Future perspectives

The harvesting process in BioCCU projects remains one of the most critical and technically challenging steps in the overall microalgae-based CO₂ mitigation chain. Its effectiveness is strongly influenced by the morphological and physiological characteristics of the microalgal species used, particularly cell size, cell wall structure, and aggregation behavior. In general, species with smaller cell sizes and smooth cell surfaces pose significant challenges for efficient separation due

to their poor natural settling properties and the high energy required to concentrate it.

Conversely, filamentous or larger-celled species like *Spirulina platensis* are much easier to harvest through low-energy techniques such as filtration or sedimentation. However, their application in BioCCU systems, particularly those integrated with coal-fired power plant flue gas streams, remains limited due to sensitivity to fluctuating environmental parameters. These include high temperatures, intense irradiance during daytime exposure, and acidic conditions caused

by dissolved CO₂ and other acidic gas components (e.g., SO₂ and NO_x). Under such stressors, many filamentous species exhibit reduced growth rates and productivity, constraining their scalability under industrial flue gas conditions. In contrast, robust microalgae such as *Chlorella vulgaris* and other small-celled chlorophytes have demonstrated strong adaptability to harsh environmental and chemical conditions, including tolerance to high CO₂ concentrations, temperature fluctuations, and variable light intensities. These traits make them particularly promising candidates for large-scale BioCCU applications in tropical regions such as Indonesia. However, their small size and stable suspension in culture media make harvesting one of the most energy- and cost-intensive stages of the entire process chain.

Future research should therefore focus on the optimization and integration of harvesting strategies specifically designed for small-cell microalgae species. This includes the development of low-energy, hybrid separation systems that combine biological pre-concentration (e.g., bioflocculation or auto-flocculation) with physical methods such as membrane filtration or dissolved air flotation. Additionally, process intensification through system coupling, such as linking harvesting with nutrient recycling or biomass pre-treatment, could significantly reduce overall energy and resource demands. Moreover, the use of environmentally benign coagulants, magnetic-assisted separation, or smart materials with selective algal adsorption properties offers promising pathways for achieving high recovery efficiency with minimal chemical input. Economic modeling and life cycle assessment (LCA) should also accompany future technological developments to ensure that new harvesting solutions not only enhance performance but also meet sustainability and carbon-neutrality targets within the BioCCU framework.

Conclusions

Based on the comparison, centrifugation offers the advantage of preserving biomass quality without chemical contamination, which is beneficial for downstream processing. The simplicity of recycling the harvested algae media due to the lack of chemical contamination is another benefit of this process. However, its extremely high energy demand results in a

very low NER value of 1.20, making it unsuitable for biofuel production. The high NER value corresponds to an operational cost of approximately USD 0.51 per kilogram of dry biomass produced, rendering this method impractical for microalgae-based BioCCU applications aimed at biofuel production. Filtration, in contrast, provides high-quality biomass, a more favorable NER value of 5.22 and low operational cost of 0.16 USD/kg DBM. Even though it has low energy and chemical consumption cost, this method still has faces challenges related to operational complexity, filter clogging, and frequent maintenance, which raise costs and require the system optimization especial for efficient membrane cleaning system development to improve feasibility. Filtration products with a water content of 99% pose an additional challenge for this method, as they require considerable energy for drying, resulting in substantial extra operational costs.

Coagulation-flocculation method presents a more flexible alternative, as biomass quality can be tailored to downstream needs by adjusting coagulant and flocculant types and dosages. This method operates with a very low energy input, relatively fast processing, and a very high NER value of 21.34. The operational cost of this method is relatively low (USD 0.21 per kilogram of dry biomass), only slightly higher than that of the filtration method. However, it offers several advantages, including simpler operation, low maintenance requirements and the production of biomass with lower moisture content, which facilitates a more energy-efficient drying process. The main drawback lies in the substantial use of chemical additives, which can increase the carbon footprint and pose environmental concerns. Therefore, the future development of low-impact, highly effective coagulants and flocculants would make this method particularly promising for large-scale biofuel production within microalgae-based BioCCU projects.

Acknowledgements

This research was supported by Universitas Padjadjaran, PT. Jawa Power, Japan International Corporation Agency (JICA), and Japan Science and Technology Agency (JST) as part of the Science and Technology Research Partnership for Sustainable Development (SATREPS).

Declaration of generative AI in scientific writing

Since the writers of this work are not native English speakers, artificial intelligence was utilized to help improve the writing style.

CRedit author statement

Andy Budiarto: Conceptualization, Writing – original draft, Editing; **Ari Hardianto:** Conceptualization, Supervision, Writing – original draft, Validation; **Abu Bakar Muhammad Ibnu Syihab:** Conceptualization, Writing – original draft, Visualization; **Saifa Aprilia Sidquni:** Writing – original draft; **Lucy Adinisa:** Writing – original draft, Visualization, Editing; **Ivani Nurjannah:** Writing – original draft, Editing; **Toto Subroto:** Conceptualization, Supervision, Writing – original draft, Validation.

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