I J R B A T, Issue (XII) Vol (III) Sept 2024: 35-47

OPEN ACCESS

e-ISSN 2347 – 517X

A Double-Blind Peer Reviewed & Refereed Journal

Original Article

Reg. No. : MH-NGP/00018

INTERNATIONAL JOURNAL OF RESEARCHES IN BIOSCIENCES, AGRICULTURE AND TECHNOLOGY

© VMS RESEARCH FOUNDATION www.ijrbat.in

SUSTAINABLE APPROACHES IN MICROALGAL BIOMASS HARVESTING: CURRENT ADVANCES AND FUTURE PERSPECTIVES

Rahul Prasad Singh, Priya Yadav, Himani Sharma, and Rajan Kumar Gupta*

Laboratory of Algal Research, Department of Botany, Institute of Science, Banaras Hindu University, Varanasi-221005, India; (RPS-rah.singhbhu@gmail.com), (PY-priya02061995@gmail.com), (HS-himani.s1250@gmail.com

*Corresponding author Email: rajang.bot@bhu.ac.in

Communicated : 01.05.2024 | Revision : 19.05.2024 & 25.06.2024 Accepted : 22.07.2024 | Published : 30.09.2024

ABSTRACT:

Non-conventional biofuels derived from algae have significant potential to transform the energy sector. Unlike traditional biofuels from terrestrial crops, algal biofuels utilize the unique biochemical properties of microalgae, which can thrive in various environments, including saline and wastewater, and exhibit rapid growth rates for high biomass yields. However, advancing novel harvesting methods is crucial to fully realizing this potential, as efficient biomass harvesting is essential for commercial viability. This involves maximizing biomass production while minimizing costs, maintenance, and energy consumption. Selecting the appropriate harvesting methods tailored to specific end products is vital and must consider factors like cell size, density, integrity, salt concentration, and moisture content. Additionally, contamination-free harvesting and reusing the culture medium can enhance cost-effectiveness. This review provides an overview of microalgae harvesting techniques, including sedimentation, centrifugation, filtration, flotation, and bio-flocculation, discussing their principles, advantages, limitations, energy requirements, and scalability. Emerging technologies such as acoustic harvesting and electro-coagulation are also explored for their potential to improve efficiency while reducing energy consumption and environmental impact.

Keywords:- Microalgae harvesting; centrifugation; flocculation; magnetic separation; electrochemical technique; flotation.

INTRODUCTION :

Microalgae are photosynthetic organisms and possess the unique ability to convert solar energy into chemical energy. Their rich composition of essential nutrients, including proteins, carbohydrates, lipids, and pigments, positions them as promising candidates for various industries such as pharmaceuticals, cosmetics, biofuel, and food (Debowski et al., 2020). Notable commercially produced species like *Chlorella, Dunaliella, Haematococcus, Monoraphidium, Scenedesmus*, and *Spirulina* collectively contribute around 10 million tons of dry biomass annually (Muhammad et al., 2021). In comparison to traditional crops, microalgae offer significant economic and ecological benefits, including high photosynthetic efficiency, rapid growth, high oil yield, shorter generation time, simple to cultivate in-vitro condition, ability to cultivate in non-arable lands, and adapt to a variety of extreme environments (Udayan et al., 2022; Singh et al., 2023).

Microalgae harvesting techniques encompass a diverse array of methods designed to efficiently separate microalgal biomass from culture media. These techniques are crucial for various applications, including biofuel production, wastewater treatment, nutraceuticals, and pharmaceuticals. Several common and advanced microalgae harvesting techniques are available. Centrifugation is a widely used method for microalgal biomass harvesting due to its high efficiency in separating biomass from the culture medium. By applying centrifugal force, microalgae are separated based on their density, with denser biomass pelletized at the bottom of the centrifuge tube (Gultom and Hu,

http://doi.org/10.29369/ijrbat.2024.010.3.0007

2013). While centrifugation offers high harvesting efficiency, it comes with drawbacks such as high energy consumption and limited scalability for large-scale production. Further, filtration techniques involve the passage of microalgal culture through porous membranes, where biomass is retained while the culture medium passes through. Filtration can be effective for harvesting larger microalgal species and is relatively simple to implement. However, clogging issues can arise with fine microalgal species, and the efficiency of filtration may vary depending on the characteristics of the microalgae (Barros et al., 2015; Singh and Patidar; 2018). Furthermore, flocculation and sedimentation techniques rely on the aggregation of microalgal cells into larger flocs, which settle under gravity or are easily separated by filtration. Chemical additives are often used to induce flocculation, although bio-based flocculants are being explored as more sustainable alternatives. While flocculation/sedimentation can be cost-effective and applicable to a wide range of microalgae, challenges such as the variability in flocculation efficiency and the environmental impact of chemical additives remain (Yin et al., 2020; Taghavijeloudaret al., 2023). Additionally, electrocoagulation involves the destabilization of microalgal cells through the application of electrical current, leading to the formation of coagulated flocs that can be easily separated. Unlike chemical flocculants, electrocoagulation does not require the addition of external agents, making it a more environmentally friendly option (Visigalli et al., 2021). However, the requirement for electricity adds to operational costs, and maintenance of equipment and electrodes may be necessary. Bioflocculation harnesses the natural flocculating properties of microorganisms or bio-based agents to aggregate microalgal cells into larger flocs. This approach offers an environmentally friendly alternative to chemical flocculants and can be cost-effective for large-scale operations. However, the efficiency of bioflocculation may vary depending on the strain of microalgae and process conditions, necessitating optimization for consistent results. Traditional methods such as centrifugation and filtration are associated with high energy consumption, low throughput, and operational complexities. Magnetic separation presents a novel approach to overcome these limitations, offering high efficiency, scalability, and cost-effectiveness (Zhu et al., 2024). Magnetic separation exploits the intrinsic magnetic properties of microalgae or the introduction of magnetic nanoparticles to facilitate separation. The process involves three main steps: magnetic particle addition, aggregation of target cells, and separation using external magnetic fields (Kumar et al., 2022). Magnetic nanoparticles, typically coated with biocompatible materials, attach to the microalgae cells either via surface functionalization or physical adsorption. Upon application of a magnetic field, the magnetized cells form aggregates, enabling their easy separation from the culture medium. Microfiltration and ultrafiltration involve the passage of microalgal culture through membranes with specific pore sizes, retaining biomass while allowing the culture medium to pass through (Zhang et al., 2019). These techniques are effective for harvesting small microalgal species and can be integrated into continuous harvesting systems. However, membrane fouling is a significant challenge, requiring regular maintenance and potentially impacting operational efficiency (Zhang and Fu, 2018). Microalgal biomass harvesting techniques play a crucial role in the development of sustainable biotechnological processes for various applications. Advances in harvesting methods have improved efficiency, reduced costs, and enhanced scalability, paving

http://doi.org/10.29369/ijrbat.2024.010.3.0007

the way for the commercialization of microalgae-based products. However, challenges such as energy consumption, scalability, and environmental impact persist, highlighting the need for ongoing research and innovation in this field. By addressing these challenges, microalgae have the potential to become a valuable resource for the bioeconomy, contributing to a more sustainable future.

Types of microalgal harvesting methods:

For the successful commercialization of microalgal products, it is crucial to efficiently harvest microalgal biomass in a cost-effective manner. This efficiency relies on achieving high biomass production with minimal operational costs, maintenance, and energy requirements. Selection of specific harvesting methods should align with the desired end products and take into account factors such as cell size and density, potential cell damage, salt concentration, and moisture content. It is also important to consider the possibility of contamination and the potential for culture medium recycling. Current harvesting methods encompass chemical, biological, mechanical, and electrical technologies, often combining multiple approaches to reduce costs (Fig. 1). Downstream processing, particularly combining flocculation, sedimentation, and centrifugation, plays a pivotal role in cost reduction. Biological methods are also favored for their low operational costs, alongside various mechanical processes. Several techniques have been employed to efficiently separate microalgae biomass from the growth medium (Table 1).

EXPERIMENTAL : Centrifugation:

Centrifugation is a widely adopted process for separating biomass from suspensions, serving applications in both laboratory and commercial environments (Table 1). Its proficiency lies in effectively dehydrating thickened microalgal biomass, although it comes with the potential drawback of inducing cell damage, the extent of which varies based on the specific strain and operational conditions (Mathimani and Mallick, 2018; Kumar et al., 2023). This method is celebrated for its remarkable recovery rate, exceeding 95%, and its versatility across a wide range of microalgal species, enabling the concentration of recovered solids to range from 10% to 20% (Pragya et al., 2013; Cuevas-Castillo et al., 2020). However, despite its popularity in industrial harvesting, the energy-intensive nature of centrifugation significantly inflates overall process and operational costs. As a result, it is predominantly reserved for applications involving bioactive compounds, particularly in pharmaceuticals, where the demand justifies the associated expenses. The centrifugation process demands a substantial energy input, typically in the range of 50 to 75 kW, to recover 12% to 25% of the biomass (Najjar and Abu-Shamleh, 2020). Centrifugation systems can be categorized into two primary types: fixed wall systems, such as hydrocyclones, and rotary wall systems, encompassing centrifugal decanters, disc centrifuges, and tubular centrifuges (Najjar and Abu-Shamleh, 2020). For instance, hydrocyclones are cylindrical devices that introduce microalgal culture from the top at an angle, guiding cells in a cyclonic motion that culminates in the collection of larger and denser particles at the bottom outlet. In contrast, decanter centrifuges feature horizontally oriented conical tubes that rotate at high speeds, capitalizing on differences in the specific weights of particles to effect separation (Demoz, 2018). Biomass is directed towards the sides and subsequently gathered through a helical thread. Disc centrifuges consist of a vertical stack of slender conical metal discs, with the culture introduced at the central core of the stacked cylinder (Kordzadeh-Kermani et al., 2022; Udayan et al., 2022). The cylinder's

http://doi.org/10.29369/ijrbat.2024.010.3.0007

rotation causes biomass to move outward and then downward, while the culture liquid gravitates toward the center. Tubular centrifuges, primarily lacking a drainage system, find their typical application in laboratory research.

Flocculation:

Flocculation is a valuable method for biomass recovery, characterized by the aggregation of microalgae cells into larger flocs. This aggregation is achieved through the use of organic, inorganic, or bio flocculants, or by adjusting the systems pH (Lee et al., 2014; Abujazar et al., 2022). It involves bringing smaller particles together with the assistance of flocculating agents, resulting in the formation of substantial flocs that settle over time. Inorganic flocculants, including substances like aluminum sulfate or ferrous sulfate, are effective but tend to come at a higher cost (Abujazar et al., 2022). When applied in large doses, they can potentially compromise the quality of final products, a particularly significant concern when the intended use is for food and feed applications. While flocculation can achieve impressive biomass recoveries of up to 100%, the concentration of inorganic and organic flocculants, typically ranging from 50 to 600 mg/L, can have an impact on the quality of the end product (Mathimani et al., 2017; Zhang et al., 2023). Conversely, organic flocculants such as starch and chitosan demonstrate efficient recovery rates at relatively lower concentrations and have a reduced environmental impact on microalgae biomass (Yin et al., 2021). Nevertheless, addressing the removal of excess flocculants from the medium requires an additional separation step to mitigate any adverse effects on both biomass and products. An ongoing avenue of exploration involves the use of magnetic nanoparticles to optimize the flocculation process. In a broader context, the mechanisms of microalgae flocculation closely parallel those used in water treatment plants (Nitsos et al., 2020; Rossi et al., 2021). While inorganic metal salts can be employed for microalgae recovery, they are not the preferred choice, as reports suggest that the recovered biomass may retain a high concentration of metals from the salts, even after lipid and carotenoid extraction. Additionally, adjusting the pH of the system is often achieved using alkali, such as NaOH, further enhancing the effectiveness of flocculants (Teh et al., 2016; Li et al., 2020). Furthermore, combining flocculation with other conventional recovery methods, such as sedimentation or filtration, can enhance the overall efficiency of the recovery process.

Sedimentation:

Sedimentation is a widely used technique for the harvesting of microalgae, particularly in large-scale commercial applications. This method relies on the principle of gravity, allowing the microalgal biomass to settle at the bottom of a tank or vessel due to the differences in density between the cells and the surrounding medium (Yaakob et al., 2014). It is a relatively simple and cost-effective process that does not require complex equipment or energy-intensive procedures (Mayers et al., 2020; Yadav and Gogate, 2023). The effectiveness of sedimentation in microalgae harvesting is influenced by various factors, including the size and shape of the microalgal cells, the density of the culture, and the viscosity of the medium (Mathimani and Mallick, 2018; Roy and Mohanty, 2019). Larger and denser cells tend to settle more rapidly, facilitating the separation process. To enhance sedimentation efficiency, flocculation is often used in conjunction with this technique. Flocculation encourages the aggregation of microalgal cells into larger flocs, which settle faster and in a more concentrated manner (Suparmaniam et al., 2019; Chen et al.,

http://doi.org/10.29369/ijrbat.2024.010.3.0007

2024). One of the advantages of sedimentation is its versatility. It can be applied to a wide range of microalgal species, making it suitable for different applications in industries such as food, pharmaceuticals, biofuels, and cosmetics. Furthermore, the harvested microalgae obtained through sedimentation often have lower levels of contamination compared to some other harvesting methods, making them suitable for high-value products (Roy and Mohanty, 2019). While sedimentation is a relatively straightforward technique, it does have some limitations. It may not be as efficient for microalgal species with very small or buoyant cells that do not settle easily. Additionally, the time required for sedimentation can be relatively long, and the method may require larger settling tanks or clarifiers for effective biomass recovery in industrial-scale operations.

Filtration:

Filtration is a prominent technique employed in microalgae harvesting, offering a highly efficient and versatile method for separating microalgal biomass from the culture medium (Mathimani and Mallick, 2018). This process relies on the use of various types of filters, such as depth filters, membrane filters, or centrifugal filters, depending on the specific requirements of the application. Depth filters, also known as granular filters, typically consist of a porous medium like sand or diatomaceous earth (Michen et al., 2012). The microalgal culture is passed through these porous materials, where the biomass is retained. Depth filters are particularly effective for large-scale operations and can handle high flow rates. They are relatively cost-effective and can achieve high biomass recovery rates. Membrane filters, on the other hand, employ specialized membranes with defined pore sizes to separate microalgae from the liquid medium (Ennaceri et al., 2022). These filters offer precise control over the separation process, allowing for the selection of specific pore sizes to retain microalgal cells while allowing the passage of liquid (Mathimani and Mallick, 2018). Membrane filtration can achieve high levels of separation efficiency and is well-suited for applications requiring stringent product quality control. However, they may be more susceptible to fouling, requiring regular maintenance. To illustrate, consider the case of *Chlorella vulgaris*, a well-known microalgal species with a high potential for biofuel production (Ru et al., 2020). The biomass concentration achieved after filtration plays a pivotal role in the overall yield of biofuels. Researchers have explored various filter types and sizes to optimize the harvesting process for *Chlorella vulgaris*. Membrane filters with specific pore sizes have been found to effectively capture *Chlorella* cells, producing a concentrated biomass that can be further processed for biofuel extraction (Ghazvini et al., 2022). This precision in separation ensures that valuable lipids for biofuel production are retained while minimizing the loss of algal biomass. This method is particularly effective for concentrating microalgal biomass and can achieve high recovery rates. However, it is energy-intensive and may not be the most cost-effective option for large-scale applications. Filtration methods can be further enhanced by combining them with other harvesting techniques, such as flocculation or sedimentation.

Magnetic separation:

Magnetic separation is an innovative and promising technique that offers a non-invasive, efficient, and scalable approach for harvesting microalgae (Arenas et al., 2017). This method capitalizes on the unique properties of microalgal cells to enable their separation using magnetic forces. Magnetic separation exploits the paramagnetic or superparamagnetic properties of microalgal cells (Sincak et al., 2023). When exposed to a magnetic field, these cells become magnetized, allowing them to be

http://doi.org/10.29369/ijrbat.2024.010.3.0007

attracted and separated from a liquid medium. The principle underlying this technique is relatively straightforward. Microalgal cells are first introduced to a magnetic solution, often containing magnetic nanoparticles, which can be tailored to have an affinity for specific cell types (Li et al., 2021). Under the influence of a magnetic field, the magnetic nanoparticles attached to the microalgal cells create a magnetic moment, resulting in their attraction to a magnet or magnetic filter. As a result, microalgal cells cluster around the magnetic source, enabling efficient separation and extraction.

Dissolved air flotation:

Dissolved Air Flotation (DAF), originally designed for wastewater treatment, is now catalyzing a green revolution in microalgae cultivation (McGinn et al., 2011). This innovative approach offers a highly efficient and environmentally sustainable method for harvesting microalgae, with the potential to reshape the landscape of biotechnology (Torres ET AL., 2017). DAF operates on the principle of bubble-microalgae attachment, capitalizing on the remarkable buoyancy created when tiny air bubbles adhere to microalgal cells (Kligerman and Bouwer, 2015). This process involves three key steps: saturation, flocculation, and separation. In the saturation phase, air is pressurized and dissolved in water before being released into a flotation tank, where a sudden pressure drop causes the air to form microbubbles. In the flocculation step, coagulants or flocculants are introduced to aggregate microalgae cells into larger flocs, making them more readily attach to the microbubbles. Finally, in the separation phase, the buoyant microbubbles, along with the attached microalgae flocs, rise to the surface, creating a froth layer that can be easily skimmed off, leaving behind clarified water. The adoption of DAF in microalgae cultivation introduces a range of advantages. Notably, DAF is highly efficient, effectively separating microalgae from the culture medium (Ometto et al., 2014; Show, 2022). The formation of a buoyant froth significantly expedites the harvesting process, making it faster and more resource-efficient than traditional methods. Additionally, DAF systems are scalable, allowing for application across various production scales, from small-scale research to large-scale industrial settings. Scalability is a key asset for the growing microalgae industry, where production needs vary widely.

Electrochemical technologies:

Traditional coagulation and flocculation methods serve as the foundation for charge neutralization or the creation of networks, often in response to pH adjustments or the introduction of polyvalent metal ions. In contrast, electrochemical technologies introduce a modern approach to harvesting microalgal biomass, with a central focus on the principles of electrocoagulation, electroflocculation, and electrofloatation (Jeevanandam et al., 2020). When compared to alternative methods that demand intricate operational parameters and the use of costly chemicals, electrochemical technologies stand out for their recognized cost-effectiveness, innovation, and efficiency in the extraction of biomass from microalgae (Udayan et al., 2022). Electrocoagulation (EC) is rooted in the generation of metal ions through the oxidation of metal electrodes, resulting in the destabilization of colloid suspensions and subsequent coagulation of microalgal biomass (Visigalli et al., 2021). The EC process can be implemented using either direct current (DC) or low-frequency alternating current (AC), initiating anodic oxidation and commencing the electrocoagulation procedure. However, a notable limitation associated with EC relates to electrode depletion, which necessitates periodic replacements. This challenge could potentially be mitigated by substituting conventional

http://doi.org/10.29369/ijrbat.2024.010.3.0007

electrodes with cost-effective materials, such as non-sacrificial carbon electrodes (Udayan et al., 2022). Additionally, another drawback of this method is the possibility of contaminating the harvested microalgae due to the leaching of metals from the electrodes, ultimately impacting the overall cost-efficiency. To address this concern and ensure protection against any decrease in market value, alternative dewatering methods that exclude the use of trace metals can be explored and put into practice.

CONCLUSION:

Advancing microalgae harvesting technologies is critical to unlocking the full potential of algal biofuels. By addressing the challenges associated with efficient biomass harvesting and leveraging both established and emerging techniques, it is possible to enhance the commercial viability and sustainability of algal biofuels, contributing significantly to the transformation of the energy sector. Continued research and innovation in this area will be key to overcoming existing limitations and achieving a sustainable and economically viable biofuel production process.

Acknowledgments:

The author would like to thank Department of Botany, IoE, Banaras Hindu University, Varanasi, India, for providing the infrastructure and necessary facilities.

Author contributions:

Rahul Prasad Singh: Conceptualization, Investigation, Writing Original Draft, Visualization; **Priya Yadav:** Validation, Investigation, Resources; **Himani Sharma**: Investigation, Writing- Review & editing; **Rajan Kumar Gupta:** Conceptualization, Validation, Resources, Writing-Review & editing, Visualization, Supervision. All authors have read and agreed to the published version of the manuscript.

REFERENCES:

Abujazar, M.S.S., Karaağaç, S.U., Amr, S.S.A., Alazaiza, M.Y. and Bashir, M.J., (2022). Recent advancement in the application of hybrid coagulants in coagulation-flocculation of wastewater: A review. Journal of Cleaner Production, 345, p.131133.

Arenas, E.G., Rodriguez Palacio, M.C., Juantorena, A.U., Fernando, S.E.L. and Sebastian, P.J., (2017). Microalgae as a potential source for biodiesel production: techniques, methods, and other challenges. International Journal of Energy Research, 41(6), pp.761-789.

Barros, A.I., Gonçalves, A.L., Simões, M. and Pires, J.C., (2015). Harvesting techniques applied to microalgae: a review. Renewable and sustainable energy reviews, 41, pp.1489-1500.

Chen, C.Y., Yeh, K.L., Aisyah, R., Lee, D.J. and Chang, J.S., (2011). Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: a critical review. Bioresource technology, 102(1), pp.71-81.

Chen, X., Li, C., Zhang, Y., Cao, P., Wang, C., Zhang, X., Lin, Z. and Zhang, H., (2024). Mechanism of rapid settling algal flocs formation in a novel fluidized bed flocculator. Algal Research, p.103605.

Christenson, L. and Sims, R., (2011). Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnology advances, 29(6), pp.686-702.

Cuevas-Castillo, G.A., Navarro-Pineda, F.S., Rodríguez, S.A.B. and Rivero, J.C.S., (2020). Advances on the processing of microalgal biomass for energy-driven biorefineries. Renewable and

http://doi.org/10.29369/ijrbat.2024.010.3.0007

Sustainable Energy Reviews, 125, p.109606.

Dębowski, M., Zieliński, M., Kazimierowicz, J., Kujawska, N. and Talbierz, S., (2020). Microalgae cultivation technologies as an opportunity for bioenergetic system development—advantages and limitations. Sustainability, 12(23), p.9980.

Demoz, A., (2018). Impact of preflocculation on scroll decanter centrifuge separation performance. The Canadian Journal of Chemical Engineering, 96(1), pp.265-273.

Ennaceri, H., Fischer, K., Schulze, A. and Moheimani, N.R., (2022). Membrane fouling control for sustainable microalgal biodiesel production: A review. Renewable and Sustainable Energy Reviews, 161, p.112335.

Ghazvini, M., Kavosi, M., Sharma, R. and Kim, M., (2022). A review on mechanical-based microalgae harvesting methods for biofuel production. Biomass and Bioenergy, 158, p.106348.

Gong, M. and Bassi, A., (2016). Carotenoids from microalgae: A review of recent developments. Biotechnology advances, 34(8), pp.1396-1412.

Gultom, S.O. and Hu, B., (2013). Review of microalgae harvesting via co-pelletization with filamentous fungus. Energies, 6(11), pp.5921-5939.

Jeevanandam, J., Harun, M.R., Lau, S.Y., Sewu, D.D. and Danquah, M.K., (2020). Microalgal biomass generation via electroflotation: a cost-effective dewatering technology. Applied Sciences, 10(24), p.9053.

Kligerman, D.C. and Bouwer, E.J., (2015). Prospects for biodiesel production from algae-based wastewater treatment in Brazil: A review. Renewable and Sustainable Energy Reviews, 52, pp.1834-1846.

Kordzadeh-Kermani, V., Madadelahi, M., Ashrafizadeh, S.N., Kulinsky, L., Martinez-Chapa, S.O. and Madou, M.J., (2022). Electrified lab on disc systems: A comprehensive review on electrokinetic applications. Biosensors and Bioelectronics, 214, p.114381.

Kumar, L., Anand, R., Shah, M.P. and Bharadvaja, N., (2022). Microalgae biodiesel: a sustainable source of energy, unit operations, technological challenges, and solutions. Journal of Hazardous Materials Advances, 8, p.100145.

Kumar, N., Banerjee, C., Negi, S. and Shukla, P., (2023). Microalgae harvesting techniques: updates and recent technological interventions. Critical Reviews in Biotechnology, 43(3), pp.342-368.

Lee, C.S., Robinson, J. and Chong, M.F., (2014). A review on application of flocculants in wastewater treatment. Process safety and environmental protection, 92(6), pp.489-508.

Li, S., Hu, T., Xu, Y., Wang, J., Chu, R., Yin, Z., Mo, F. and Zhu, L., (2020). A review on flocculation as an efficient method to harvest energy microalgae: mechanisms, performances, influencing factors and perspectives. Renewable and Sustainable Energy Reviews, 131, p.110005.

Li, X., Liu, B., Lao, Y., Wan, P., Mao, X. and Chen, F., (2021). Efficient magnetic harvesting of microalgae enabled by surface-initiated formation of iron nanoparticles. Chemical Engineering Journal, 408, p.127252.

Mathimani, T. and Mallick, N., (2018). A comprehensive review on harvesting of

http://doi.org/10.29369/ijrbat.2024.010.3.0007

microalgae for biodiesel–key challenges and future directions. Renewable and Sustainable Energy Reviews, 91, pp.1103-1120.

Mathimani, T. and Mallick, N., (2018). A comprehensive review on harvesting of microalgae for biodiesel–key challenges and future directions. Renewable and Sustainable Energy Reviews, 91, pp.1103-1120.

Mathimani, T., Bhumathi, D., Ahamed, T.S., Dineshbabu, G., Deviram, G., Uma, L. and Prabaharan, D., (2017). Semicontinuous outdoor cultivation and efficient harvesting of marine *Chlorella vulgaris* BDUG 91771 with minimum solid co-precipitation and high floc recovery for biodiesel. Energy Conversion and Management, 149, pp.13-25.

Mayers, J.J., Landels, A.R., Allen, M.J. and Albers, E., (2020). An energy and resource efficient alkaline flocculation and sedimentation process for harvesting of *Chromochloris zofingiensis* biomass. Bioresource Technology Reports, 9, p.100358.

McGinn, P.J., Dickinson, K.E., Bhatti, S., Frigon, J.C., Guiot, S.R. and O'Leary, S.J., (2011). Integration of microalgae cultivation with industrial waste remediation for biofuel and bioenergy production: opportunities and limitations. Photosynthesis research, 109, pp.231-247.

Michen, B., Meder, F., Rust, A., Fritsch, J., Aneziris, C. and Graule, T., (2012). Virus removal in ceramic depth filters based on diatomaceous earth. Environmental science & technology, 46(2), pp.1170-1177.

Milledge, J.J. and Heaven, S., (2013). A review of the harvesting of micro-algae for biofuel production. Reviews in Environmental Science and Bio/Technology, 12, pp.165-178.

Muhammad, G., Alam, M.A., Mofijur, M., Jahirul, M.I., Lv, Y., Xiong, W., Ong, H.C. and Xu, J., (2021). Modern developmental aspects in the field of economical harvesting and biodiesel production from microalgae biomass. Renewable and Sustainable Energy Reviews, 135, p.110209.

Najjar, Y.S. and Abu-Shamleh, A., (2020). Harvesting of microalgae by centrifugation for biodiesel production: a review. Algal Research, 51, p.102046.

Nitsos, C., Filali, R., Taidi, B. and Lemaire, J., (2020). Current and novel approaches to downstream processing of microalgae: A review. Biotechnology Advances, 45, p.107650.

Ometto, F., Pozza, C., Whitton, R., Smyth, B., Torres, A.G., Henderson, R.K., Jarvis, P., Jefferson, B. and Villa, R., (2014). The impacts of replacing air bubbles with microspheres for the clarification of algae from low cell-density culture. Water research, 53, pp.168-179.

Pittman, J.K., Dean, A.P. and Osundeko, O., (2011). The potential of sustainable algal biofuel production using wastewater resources. Bioresource technology, 102(1), pp.17-25.

Pragya, N., Pandey, K.K. and Sahoo, P.K., (2013). A review on harvesting, oil extraction and biofuels production technologies from microalgae. Renewable and sustainable energy reviews, 24, pp.159-171.

Rakesh, S., Tharunkumar, J., Sri, B., Jothibasu, K. and Karthikeyan, S., (2020). Sustainable cost-effective microalgae harvesting strategies for the

http://doi.org/10.29369/ijrbat.2024.010.3.0007

production of biofuel and oleochemicals. Highlights in bioscience, 3(July), pp.1-8.

Rashid, N., Rehman, M.S.U., Sadiq, M., Mahmood, T. and Han, J.I., (2014). Current status, issues and developments in microalgae derived biodiesel production. Renewable and Sustainable Energy Reviews, 40, pp.760-778.

Rossi, S., Visigalli, S., Cascino, F.C., Mantovani, M., Mezzanotte, V., Parati, K., Canziani, R., Turolla, A. and Ficara, E., (2021). Metal-based flocculation to harvest microalgae: a look beyond separation efficiency. Science of the Total Environment, 799, p.149395.

Roy, M. and Mohanty, K., (2019). A comprehensive review on microalgal harvesting strategies: Current status and future prospects. Algal Research, 44, p.101683.

Ru, I.T.K., Sung, Y.Y., Jusoh, M., Wahid, M.E.A. and Nagappan, T., (2020). *Chlorella vulgaris*: A perspective on its potential for combining high biomass with high value bioproducts. Applied Phycology, 1(1), pp.2-11.

Show, P.L., (2022). Global market and economic analysis of microalgae technology: Status and perspectives. Bioresource Technology, 357, p.127329.

Sincak, M., Luptakova, A., Matusikova, I., Jandacka, P. and Sedlakova-Kadukova, J., (2023). Application of a magnetic field to enhance the environmental sustainability and efficiency of microbial and plant biotechnological processes. Sustainability, 15(19), p.14459.

Singh, G. and Patidar, S.K., (2018). Microalgae harvesting techniques: A review. Journal of environmental management, 217, pp.499-508.

Singh, R.P., Yadav, P., Kumar, I., Solanki, M.K., Roychowdhury, R., Kumar, A. and Gupta, R.K., (2023). Advancement of abiotic stresses for microalgal lipid production and its bioprospecting into sustainable biofuels. Sustainability, 15(18), p.13678.

Suparmaniam, U., Lam, M.K., Uemura, Y., Lim, J.W., Lee, K.T. and Shuit, S.H., (2019). Insights into the microalgae cultivation technology and harvesting process for biofuel production: A review. Renewable and Sustainable Energy Reviews, 115, p.109361.

Taghavijeloudar, M., Yaqoubnejad, P., Ahangar, A.K. and Rezania, S., (2023). A rapid, efficient and eco-friendly approach for simultaneous biomass harvesting and bioproducts extraction from microalgae: Dual flocculation between cationic surfactants and bio-polymer. Science of The Total Environment, 854, p.158717.

Teh, C.Y., Budiman, P.M., Shak, K.P.Y. and Wu, T.Y., (2016). Recent advancement of coagulation–flocculation and its application in wastewater treatment. Industrial & Engineering Chemistry Research, 55(16), pp.4363-4389.

Torres, D.M., Araújo, A.L.C., de Oliveira, R. and de Brito, A.C., (2017). Dissolved air flotation (DAF) for biomass recovery from algal ponds. Water Practice and Technology, 12(3), pp.534-540.

Udayan, A., Sirohi, R., Sreekumar, N., Sang, B.I. and Sim, S.J., (2022). Mass cultivation and harvesting of microalgal biomass: Current trends and future perspectives. Bioresource technology, 344, p.126406.

http://doi.org/10.29369/ijrbat.2024.010.3.0007

Visigalli, S., Barberis, M.G., Turolla, A., Canziani, R., Zrimec, M.B., Reinhardt, R. and Ficara, E., (2021). Electrocoagulation–flotation (ECF) for microalgae harvesting–A review. Separation and Purification Technology, 271, p.118684.

Yaakob, Z., Kamarudin, K.F., Rajkumar, R., Takriff, M.S. and Badar, S.N., (2014). The current methods for the biomass production of the microalgae from wastewaters: An overview. World Applied Sciences Journal, 31(10), pp.1744-1758.

Yadav, P. and Gogate, P.R., (2023). Process intensification approaches applied to the downstream processing of microalgae production. Microalgae-Based Systems: Process Integration and Process Intensification Approaches, p.241.

Yin, Z., Chu, R., Zhu, L., Li, S., Mo, F., Hu, D. and Liu, C., (2021). Application of chitosan-based flocculants to harvest microalgal biomass for biofuel production: A review. Renewable and Sustainable Energy Reviews, 145, p.111159.

Zhang, B., Peng, C., Zhang, S., Zhang, M., Li, D., Wang, X. and Mao, B., (2023). Comprehensive analysis of the combined flocculation and filtration process for microalgae harvesting at various operating parameters. Science of The Total Environment, 857, p.159658.

Zhang, J. and Hu, B., (2012). A novel method to harvest microalgae via co-culture of filamentous fungi to form cell pellets. Bioresource technology, 114, pp.529-535.

Zhang, M., Yao, L., Maleki, E., Liao, B.Q. and Lin, H., (2019). Membrane technologies for microalgal cultivation and dewatering: Recent progress and challenges. Algal Research, 44, p.101686.

Zhang, X., Wang, L., Sommerfeld, M. and Hu, Q., (2016). Harvesting microalgal biomass using magnesium coagulation-dissolved air flotation. Biomass and Bioenergy, 93, pp.43-49.

Zhang, Y. and Fu, Q., (2018). Algal fouling of microfiltration and ultrafiltration membranes and control strategies: A review. Separation and Purification Technology, 203, pp.193-208.

Zhu, J., Wakisaka, M., Omura, T., Yang, Z., Yin, Y. and Fang, W., (2024). Advances in industrial harvesting techniques for edible microalgae: Recent insights into sustainable, efficient methods and future directions. Journal of Cleaner Production, p.140626.

http://doi.org/10.29369/ijrbat.2024.010.3.0007

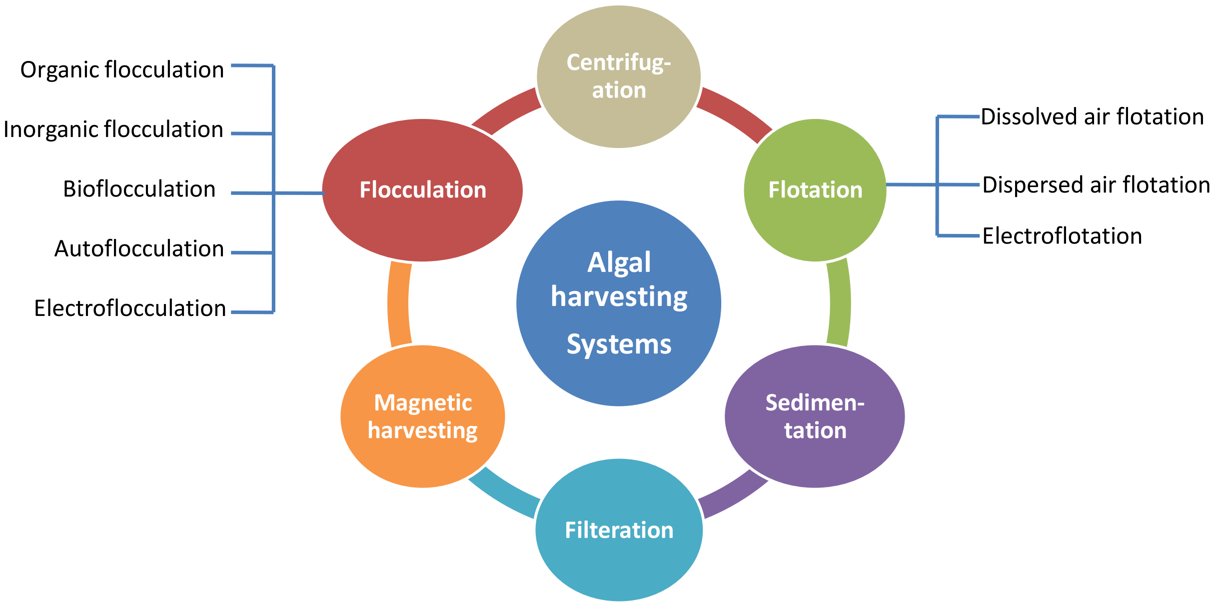

Fig.1. Different types of microalgal harvesting and dewatering techniques

Table 1. Principle, advantages, and disadvantages various of microalgal harvesting techniques

Harvesting techniques	**Principle**	**Advantages**	**Disadvantages**	**References**
Centrifugation	Centrifugation employs centrifugal force to separate microalgae from the culture medium based on differences in density.	Rapid and efficient separation, high biomass recovery, suitable for large-scale operations.	Energy-intensive, costly equipment, potential damage to fragile microalgae cells.	Chen et al., 2011; Gong and Bassi, 2016
Filtration	Filtration involves passing the microalgae culture through a porous medium, where the algae are retained while the liquid passes through.	Relatively simple and cost-effective, gentle on microalgae cells, suitable for continuous operation.	Clogging of filters, limited by the size and density of microalgae, may require pre-treatment to improve efficiency.	Christenson, and Sims, 2011; Barros et al., 2015
Flocculation	Flocculation induces aggregation of microalgae cells into larger clusters, facilitating separation from the culture medium.	Compatible with various microalgae types, low energy requirement, potential for combination with other techniques.	Chemical additives may be necessary, effectiveness depends on flocculant and conditions, residual flocculants may require further treatment.	Pittman et al., 2011; Kligermanand Bouwer, 2015
Sedimentation	Sedimentation relies on gravity to settle microalgae cells to the bottom of a container, allowing for separation from the liquid phase.	Simple and low-cost method, suitable for large-scale operations, minimal energy requirement.	Slow process, may require additional post-treatment for higher purity, efficiency affected by cell size and density.	Milledge and Heaven, 2013
Flotation	Flotation is a separation method based on the	Effective for harvesting microalgae with low	Selectivity issues may arise leading to the	Pragya et al., 2013; Rashid

http://doi.org/10.29369/ijrbat.2024.010.3.0007

	attachment of microalgae cells to air bubbles. In this process, microalgae cells are introduced into a flotation chamber where air bubbles are injected. The hydrophobic surfaces of the microalgae cells attach to the air bubbles, causing them to rise to the surface and form a froth layer. The froth layer containing the microalgae cells can then be collected and separated from the culture medium.	density or buoyancy, can be used for both freshwater and marine microalgae, allows for continuous processing in large-scale operations, and minimal energy requirement compared to other harvesting methods.	flotation of unwanted particles, efficiency can be influenced by factors such as cell size, shape, and surface properties, chemical additives may be required to enhance flotation efficiency, potentially increasing costs, and maintenance of equipment and froth removal can be labor-intensive.	et al., 2014
Electrochemical techniques	Electrochemical separation involves the application of an electric field to induce the migration of microalgae cells towards oppositely charged electrodes. Microalgae cells typically carry a net negative charge, which can be manipulated using electrodes to facilitate their separation from the culture medium.	High selectivity, allowing for precise control over the separation process, minimal use of chemicals, reducing the risk of contamination, can be integrated into automated systems for continuous processing, and suitable for harvesting microalgae with a wide range of sizes and densities	Initial investment in equipment and infrastructure can be substantial, optimization of electric field parameters and electrode configuration is required for different microalgae species, energy-intensive process, particularly for large-scale applications, electrode fouling and degradation may occur, and requiring regular maintenance.	Zhang and Hu, 2012; Kligermanand Bouwer, 2015
Magnetic separation	Magnetic separation relies on the use of magnetic particles or ferromagnetic materials to selectively capture microalgae cells from the culture medium. Magnetic particles are introduced into the microalgae culture, where they attach to the cells through specific interactions. An external magnetic field is then applied to separate the magnetically labeled microalgae cells from the bulk solution.	High selectivity and efficiency in capturing target microalgae cells, minimal risk of contamination, as no chemical additives are required, can be integrated into continuous processing systems, suitable for large-scale applications and automation.	Initial investment in magnetic separation equipment and magnetic particles may be considerable, optimization of magnetic particle size and surface properties is necessary for efficient cell capture, magnetic field strength and gradient may need to be adjusted for different microalgae species, and agnetic separation may not be suitable for microalgae species with low magnetic susceptibility.	Rakesh et al., 2020; Zhang et al., 2016

http://doi.org/10.29369/ijrbat.2024.010.3.0007