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A comprehensive review on harvesting of microalgae for biodiesel – Key challenges and future directions

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ABSTRACT

Economically viable microalgal biodiesel production is unrealistic and unsustainable owing to expensive harvesting or dewatering techniques. Hence, immense and meticulous exploration of harvesting process is essential to identify knowledge leads by which suitable harvesting technique could be ascertained for lucrative biodiesel production. With this in view, this review aims to collate and highlight the spectrum of harvesting techniques applied to microalgae, i.e., conventional – modern, high cost- inexpensiveness, energy efficient- energy consuming process. At the outset, global energy outlook and demand had been critically addressed, and the scientific ways to tackle or satiate the fuel demand had also been highlighted in this reveiw. This review manuscript has thrown widespread light on the physical harvesting methods namely centrifugation, sedimentation, filtration, flotation and technical advantages thereof. Due to the energy-intensive and cost barrier of physical harvesting techniques, chemical methods entailing organic, inorganic, and electroflocculation have come to limelight and in this regard, microalgae used, floc recovery and the dose of flocculants have been compared and presented in detail. Further, state of the art harvesting techniques viz., bioflocculation by microalgae/bacteria, flocculation by pH adjustment, and magnetic nanocomposite based microalgal harvesting had been critically articulated. Besides discussing the several methods, this paper has summarized the key challenges in conventional and advanced harvesting techniques and also provided the scope thereof. Hence, the key suggestions and findings given in this manuscript would positively offer a well-defined roadmap in choosing foreseeable harvesting technology for cost-effective microalgal biofuel development.

1. Introduction

Globally, energy is the prime commodity for the development of any nation, and till date, the majority of energy necessities are satiated through fossil fuels namely petroleum, coal and natural gas [1,2]. Fossil fuel poses dual threats to the society, i.e., fuel demand and climatic change. Due to the depletion of fossil fuels, energy consumption is predicted to rise from 550 EJ (Exajoule) to 865 EJ by 2040 [3]. In this regard, India featured to 7th place in energy production, accounting 2.49% of the world's annual energy production and in parallel, ranked as world's 5th energy consumer by utilizing 4% world's total energy consumption [4]. Further, India has imported 163 million metric tonnes of crude oil during 2010–2011 by spending $100 billion due to prompt urbanization and oil demand [4]. On the other hand, the current CO_2 level is 394.5 ppmv (parts per million volume), and it is projected to reach 500 ppmv in 2050 if emissions remain unrestricted [5]. In a view to culminate the hazardous diesel usage, in-depth R & D initiatives have been unleashed in wide dimension for exploring the renewable fuel sources to encounter energy thirst. As a decisive consequence, biofuel (first generation) came to limelight along with certain shades of negative criticism of uprooting the food market by food vs fuel debate. In fast-developing economies like India, China, Thailand and South Africa, increasing requirement for food and fuel has initiated an augmented race for already limited water resources [6].

Biofuel is a renewable and alternate fuel produced from the organic (biological) feedstocks which can readily be fueled to the existing transportation infrastructure without engine modification [7–10]. Many countries realized the importance of biofuel, and thus, they geared up for producing biofuel and blending it with current transportation fuel to reduce the dependency on fossil fuel. The order of top biofuel producing countries is the United States > Brazil > Germany > China > Argentina [11]. Indonesia set a probable target of replacing 15% gasoline by ethanol and 20% diesel by biodiesel in 2025, and in Thailand, twelve bioethanol plants are being constructed that will produce 2.6 million L ethanol per day [12].

Brazil set a 5% and 20% biodiesel blending target by 2013 and 2020

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respectively and to achieve above goals, 2000 and 12,000 ML/year biodiesel is likely to be produced respectively [13]. With reference to biofuel policy of India, National Biodiesel Mission (NBM) was launched in 2003, and concurrently National policy on biofuels was enacted to regulate the biofuel usage and blending. The blending target set by India was initially 5% by 2012 and then, 10% by 2017 and 20% after 2017 [14]. In 2007, an amendment in blending mandate indicated 5% ethanol blending with petrol throughout India, except the North Eastern States, Jammu and Kashmir, and other Island territories [15]. Recent times, certain countries set 7% or less than 7% biofuel blending target. In Japan, bioethanol and biodiesel blending has been limited to 3% and 5% respectively to ensure safety and avert the degradation of engine components [16]. However, increasing the blending beyond 7% (B7) poses substantially two major concerns between light and heavy-duty vehicles i.e., rapid lubricant deterioration during post injection and presence of undesired compounds or impurities in the blends and notably in heavy-duty trucks, 30% biodiesel-diesel blend can safely run 80% of heavy-duty trucks [17]. In a very recent policy draft, oil ministry of India has set a lower blending of 5% biodiesel in diesel by 2030 [18]. Besides the difficulty in speculating the rapid implementation of blending, National biofuel policy enacted by Malaysian government in 2006 stated 5% blending target nationwide and also it had considered the implementation of 7% biodiesel blend [19], and recently, Malaysian government decided to blend 7% B100 biodiesel in conventional diesel to ensure the availability of 7% biodiesel-diesel blend (B7) in 2018 [20]. Though biofuel blending target of 7% is set by various countries, certain countries like Brazil, European Union, and the United States of America set a target of 20%, 10%, and 25% biofuel blending respectively by 2020 [21]. In a line of above blending, 10% blend is considered to be technically feasible for spark-ignited gasoline engines [16]. As reported by Kampman [17], in European Union, all diesel locomotives are compatible with 7% biodiesel blend in diesel, and therefore, 12.8 Mtoe of fatty acid methyl ester (biodiesel) is predicted to be brought on the energy market for road transportation by 2020 considering 7% blend. Low biofuel blending with transportation fuel is quite desirable since the fueling of certain automotive engines by high biofuel blends demand technical modification [16]. In this regard, increasing the blending target from 7% to 10% or 15% might not be problematic considering the availability of suitable technologies [17].

It is interesting to note that, overproduction and oversupply of biodiesel were witnessed in two major biodiesel producing companies, which gives 8.5 million L day^{-1}, and this caused issues with domestic producers since production competition was tightened up with more companies in terms of biodiesel production. Global Green Chemicals Plc and PTG Energy are producing B100 biodiesel and simultaneously using it for their own supply [20]. In fact, Thai Biodiesel Producers Association stated that 13 industries are currently producing 100% biodiesel (B100) at about 6.6–7 million L day^{-1}, but present national demand is ~ 3.3–3.5 million L day^{-1} [20]. The present oversupply of biodiesel in Thailand affected the profit of numerous domestic biodiesel producing companies at < 50% of capacity and cutting the cost below 20 baht L^{-1}. However, biodiesels stated above are produced from vegetable oil like corn, maize, palm or other sources, and microalgal biodiesel has not yet been commercialized. It is stated that, cultivation of corn, soybeans, and other edible crops for biofuel or bioethanol taking a substantial toll on the environment and also affecting the food market through elevated food prices [22].

In addition to energy and environmental benefits, biofuel industries play a key role in providing socioeconomic services to the rural peoples such as infrastructure development, poverty reduction by creating job opportunities, opening schools, hospitals especially in the countries Brazil, India, China. In Brazil, ethanol industry provides occupation to ~ 12% of the rural population either directly or indirectly and adding to that; sugarcane employs one million workers in Brazil at different levels [14]. Further, biodiesel can also be used a lubricant, which is 66% more competent than diesel [23]. However, the major limitations in biofuel include (i) imperiling food security due to tradeoff between food vs fuel through resource allocation, (ii) surplus land requirement and agricultural inputs, (iii) high capital cost and uncompetitive retail prices, (iv) low net energy returns, (v) higher claims over gaseous emission reductions (v) low productivity over seasons [10,24,25]. Among the biofuel feedstocks, algae (microalgae, cyanobacteria, diatoms) have secured rampant attention as a next-generation sustainable substitute to diesel fuel [26,27], in the burgeoning energy enterprises over the past decades as it holds dual potentials to abate climatic disaster, and to safeguard energy security. Algae are prokaryotic (cyanobacteria) or eukaryotic (green algae and diatoms) photoautotrophs, which may be either unicellular or multicellular or heterocystous or colonial in morphology [28], and algae are being explored as potential crops for biodiesel whose ancestral relationships is broader than terrestrial plants and rich in genetic diversity [26]. Utilizing algae for biodiesel application offer several pros as microalgae, do not compete with edible crops, do not affect food security, do not emit high gaseous pollutants, do not demand surplus fertile land and fertilizer supplements, do have high biomass density and sustainable lipid productivity over terrestrial crops [29–31], and can grow in various habitats like freshwater, seawater, wastewater, and brackish water [32]. Preferably, Microalga was able to produce 58,700 L oil $hectare^{-1}$, which is two magnitudes higher compared to other bioenergy feedstock [33].

Although microalgae are considered as a viable alternate to offset fossil fuel, there are numerous obstacles need to be overcome for lucrative biofuel production. Using current production process, a barrel of algal biofuel cost is estimated to be US$300–2600, which is much higher than a barrel of petrol $40–80 [26]. To substitute petrol with microalgal biofuel cost-effectively, algal oil costing ~ US$ 1.619 L^{-1} is preferable [11]. US invested $800 million through American Recovery and Renewal Act for R & D on economic algal biofuel production [34]. Albeit many economical biodiesel production strategies are underway, it is yet in primitive stage demanding financial viability, and however, *hitherto* findings have portrayed microalgae as a positive candidate for biodiesel [28]. The bottlenecks or need of the hour in biodiesel production are resilient strain isolation, mass cultivation using low-cost nutrient inputs, ideal harvesting techniques, pertinent lipid extraction method, fuel production, coproduct development, residual biomass utilization [26]. In concern with strain selection, a microalgal monoculture that resistant to pathogens (algal pond sustainability) and capable accumulating high lipid content is a prerequisite for biodiesel since algal cells could be invaded by pests and pathogens [26,33]. Acclimatization of microalgae to an unconducive open environment, resistant to contamination and high biomass productivity in a low-cost medium is the favorable features in strain selection and outdoor cultivation. In low-cost medium formulation, inexpensive urea can be used for *Chlorella* sp., and *Spirulina platensis* culturing instead of expensive chemical nutrients to reduce the cost [35]. In this connection, marine or halophilic strain could be used as a potential feedstock since it requires only seawater with few nutrient supplements during large-scale cultivation. Another bottleneck in biodiesel production is lipid extraction, which is most commonly carried out by oil expeller, solvent extraction, and supercritical extraction [30]. These methods are expensive concerning energy consumption and device investment; however, are amenable to engineering improvements [26]. It is reported that drying of microalgal biomass and oil extraction occupies ~90% of overall biodiesel economy [36,37]. Among the challenges in microalgal biodiesel, the most pressing challenge lies in the harvesting [38], because harvesting costs individually occupy nearly 30% of the total capital investment for biodiesel [39,40]. Harvesting is an economical key for commercial biodiesel production and therefore, choosing a pertinent harvesting technique, which is able to dewater high voluminous culture medium inexpensively is essential to increase the scale of biomass yield and decrease the overall harvesting cost concurrently [41,42].

Considering the above issues, this review contextualizes various harvesting methods and their limitations and scope as listed below to