Key Issues in Pilot Scale Production, Harvesting and Processing of Algal Biomass for Biofuels

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1 Introduction

It has now become a well-established fact that global dependence on natural petroleum reserves must decline and alternate energy sources must be identified and migrated to. This is due to two critical factors: (a) the remaining petroleum

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reserves are continuously getting depleted and, with current rate of extraction and use, may hardly sustain global energy demands for ~50–60 more years, and (b) the associated carbon emissions with their extraction and application contribute heavily towards the global warming. Lot of efforts are already in place to identify feasible alternate and renewable energy sources and include focus on solar cell, wind energy, geothermal and biofuels among others. Out of these, biofuels have garnered increasing attention as a direct replacement of petroleum products with the use of existing technology.

1.1 Biofuels

Biofuel or more specifically biodiesel is currently derived from organic biomass including plants and animal oils. Short-chain alcohol triglycerides or free fatty acids are transesterified to produce monoalkyl esters or biodiesel (Du et al. 2008). Common sources to produce biodiesel include soybeans, jatropha oil, waste cooking oil, animal fat, palm oil, corn oil and canola oil among others (Chisti 2007). Biodiesel have been observed to be less toxic, contribute less gaseous pollutants and effectively contain no CO_2 or sulphur in comparison with petro-diesel (Rawat et al. 2013). These factors significantly contribute towards acceptance of biodiesel as an alternative for conventional petro-diesel. Another important aspect is their suitability to be used with existing engines without (or minor) modification and ability to fit into existing infrastructure of distribution (Du et al. 2008). However, a major limitation in the commercial applicability of these biodiesels has been their low yield and unrealistically high arable land requirement (even for high yield palm oil) for meeting the demand for transport fuel (Chisti 2007).

1.2 Suitability of Algal Biofuels for Commercial Applications

The third-generation biodiesel derived from algal biomass, in general, addresses the limitations of other biodiesels. The high lipid content and biomass productivity essentially translate to reduced and achievable requirements of non-arable land and feasible commercial applicability. Hence, biodiesel from microalgae is increasingly being perceived as the only viable alternative of petro-diesel (Chisti 2007). In addition to biodiesel, other biofuels can also be generated from microalgal biomass, e.g. hydrogen, methane, etc. (Sivakumar et al. 2012). Commercial suitability of algal biofuels is due to the following factors (Brennan and Owende 2010):

1. The production of algal biomass with high lipid contents can be continued throughout the year on non-arable lands, thus avoiding the debate of food vs fuel.

2. Though the microalgae are aquatic species, the overall water requirement is very less in comparison to crop-based biofuel production and thus substantially lowers the dependence on freshwater resources.
3. Photosynthesis during autotrophic growth of algae is capable of biofixing the atmospheric CO_2.
4. The biomass growth can effectively be obtained using nutrients present in wastewater, thus also acting as a means of tertiary treatment.
5. In addition to biofuels, algal biomass is also a source of other useful products, viz. protein, pigments and many compounds of pharmaceutical nature, etc.
6. The chemical and physical properties of algae-derived biodiesel, viz. viscosity, density, flash point, heating value, solidifying point, cold filter plugging point, etc., have been found to be similar to those of petro-diesel (Xu et al. 2006). Most of these parameters for algal biodiesel also meet the international limits of biodiesel for automotive sector (Ahmad et al. 2011).

1.3 Techno-Economic Concerns with Algal Biofuels

Despite being perceived as the possible alternative for petroleum fuels, algal biofuels (and algal biodiesels) have yet to achieve techno-economic sustainability. The algal biomass production for primary objective of algal biofuel is at present economically unsustainable (Lundquist et al. 2010). Two approaches have been advocated by researchers for achieving the favourable economics: (a) to utilize the algal biomass as a byproduct for producing algal biofuel with a primary objective of wastewater treatment (e.g. nutrient removal) (Lundquist et al. 2010) and (b) adopting biorefinery concept in which a range of useful products (viz. protein, carbohydrate, pigments, etc.) are extracted with lipids from produced biomass in order to maximize the value recovery (Subhadra and Grinson 2011). In addition, the biomass production at pilot scale still faces many technical issues before the lipid production could be optimized. Such issues remain at three distinct stages of biomass production, harvesting, and processing for lipid and biofuel production and are discussed in detail in subsequent sections of this chapter.

1.4 Environmental Concern with Algal Biofuels

The rapid exploitation of natural reserves of fossil fuels and environmental concerns with the burning of fossil fuels lead the path of the development of carbon neutral biofuels. However, the environmental sustainability aspects of renewable biofuels are of prime concerns. The first-generation biofuels which were obtained from the energy crops and oilseed were phased out due the debate over food vs fuels. The second-generation biofuels were based on biomass. However, the use of the water and arable land resources for the production of biomass was again of the major environmental concerns. The production of lignocellulosic biomass requires substantial amount of water resources and arable lands. In the past few decades, numerous studies evaluated the extensive requirement of water for second-generation biofuels (Varis 2007; Hoekstra and Chapagain 2008; De Fraiture et al. 2008). Therefore, the production of such biofuels was much needed which should be free from environmental concerns. In this regard, the microalgae seem to be the potential contender for the production of third-generation biofuels. The microalgal biomass has been recognized as a versatile feedstock for biofuel purposes which fulfil all the basic prerequisites of environmental sustainability. Numerous studies have demonstrated the excellent use of microalgal biomass for the production of various types of algal biofuels at small scales. However, the pilot scale production of liquid algal biofuels such as algal biodiesel, ethanol, etc. as well as the gaseous fuels such as algal biohydrogen or biogas is still in infancy stages. The major environmental and economic concerns are the high production cost and high energy demands in the production as well as conversion of the algal biomass to biofuels. The energy demands for the harvesting and dewatering of microalgal biomass and oil extraction from algal biomass through the conventional processes as well as its conversion require substantial energy which is carbon intensive.

The carbon and water footprints are generally used to major the environmental sustainability of various commodities including biofuels. The major concern with the production of biofuels is the water footprint, as huge amount of water is required in production of both the algal and lignocellulosic biomass. As per estimates, almost 86 % of the global water is used in the agriculture alone (Singh et al. 2015). Therefore, the additional demand of water, which is already a scarce resource, for the production of algal biofuels may worsen the scenario. Numerous studies have shown environmental concerns due to extensive water used for biomass energy production. Berndes (2002) estimated almost double water loss in large-scale biofuel production through the evapotranspiration by 2100. Gerbens-Leenes et al. in 2012 reported 70–700 times larger water footprint for the biomass-based biofuels compared to the fossil fuels. Approximately tenfold increase in the water footprint is expected only for the biofuels used in transport in ten largest biofuel-consuming countries. Therefore, the requirement of the huge water could be a limiting factor for algal biofuels. The water and land use patterns, type of the feedstock, its productivity, climatic condition, geographical locations, etc. also regulates the carbon and water footprint for any biofuels (De Fraiture and Berndes 2009).

Similar to the water footprints, Johnson and Tschudi in 2012 recommended the measurement of CF of the biofuels. The carbon footprint of the biofuels were approximately 0.248 billion global hectares in 2010, and as per estimates, it will be increased by twofold by 2020. Fahd et al. (2012) reported that in 1 g of algal biodiesel production, around 1.72 g CO_2 is emitted which is substantially high compared to the biofuel production from the oilseeds. The environmental sustainability of algal biofuel depends on several other factors as well. However, the water and carbon footprint can be reduced by applying advanced tools and techniques. Substantial reduction in WF and CF is possible by use of flue gases as well as use of wastewater for culturing and production of algal biomass, selection of high oil-yielding algal species, etc. Similarly, the energy production from algal biomass in a biorefinery concept is one of the best environmentally sustainable option.

2 Issues with Algal Biomass Production

The commercial production of lipid-rich algal biomass is a complex process depending on many factors. The key concerns during the pilot scale biomass production are summarized in this section.

2.1 Selection of Suitable Algal Strain

Griffiths and Harrison (2009) summarized some suitable characteristics of algal strain for mass production as listed in Table 1.

One of the primary aspects for successful pilot scale algal production is the selection of suitable strain which can (a) have higher lipid productivity and (b) counter the culture contamination and environmental variability invariably occurring in such application. Bioprospecting for suitable cultures having these characteristics is one of the most important and challenging issue for pilot scale algae production (Mutanda et al. 2011). Indigenous cultures from native locations are considered better for such large-scale production since these are already adapted to the environmental conditions. Further investigations in selecting species having higher lipid productivity depend on both the biomass productivity and lipid content (Griffiths and Harrison 2009). These two objectives are often counteracting to each other, since conditions for higher biomass productivity are

Table 1 Suitable traits in algae for mass production (Griffiths and Harrison 2009)

Characteristic	Benefit
High growth rate	• Less area requirement • Outcompeting the contaminants
High lipid content	High value product suitable for further processing
Growth in extreme condition	Reduced probability of competition and contaminants
Large cell size, filamentous or colony formation	Easy harvesting at lower cost
High tolerance to variation in environmental conditions	Reduced effort on maintaining growth conditions
Tolerance to various contaminants (viz. NO_x, SO_x, etc.)	Applicability to contaminated wastewater

known to suppress the lipid content and vice versa. Hence, selection of culture with high lipid productivity becomes challenging in nature. Another factor that controls the selection of the strain is suitability of produced lipids for further processing (Mutanda et al. 2011).

The ability of algae to sustain the environmental stresses and variability becomes important during their large-scale production. Also, the possibilities of establishing symbiosis with existing bacteria increase the chances of successful application of these algal strains. In addition, the ability to grow in conditions hostile to other contaminants may help in identifying suitable operating conditions and hence tackling the issue of contamination in these systems.

2.2 Growth Media and Reactors

Once the proper algae culture is selected, the growth media for such large-scale production becomes important. Though artificial growth media have been utilized for low-scale biomass production, any effort for pilot scale production can only be sustainable with wastewater rich in nutrients, i.e. domestic sewage. However, utilization of wastewater presents some unique challenges during the biomass production. First are the variability of nutrient levels and the ability of selected algae to cope with it without any negative impacts (Shriwastav et al. 2014). Second, the presence of high organic substrates in this sewage may either pose additional stress to algae culture (Gupta et al. 2016) or promote bacterial growth. Both of these impacts require careful investigation for their ultimate impact on quantity and quality of the produced lipids.

Another important factor remains the mode of biomass growth, i.e. open systems or photobioreactors. Historically, open systems such as aerobic oxidation ponds have been used for algal growth. However, inefficient mixing and light distribution results in suboptimal growth and hence lipid productivity (Arceivala and Asolekar 2007). The development of high-rate algal ponds (HRAP) with paddles resulted in better growth conditions for microalgae. These systems (HRAPs) are widely utilized for large-scale biomass production. However, dependence of growth on direct sunlight and prevalent environmental conditions (e.g. temperature) result in variable growth. Also, these open systems are prone to contamination and hence require careful operation. To address these issues of open systems, closed systems as photobioreactors have also been investigated. However, only tubular photobioreactors are deemed suitable for large-scale biomass production (Chisti 2007). Although costlier than open systems, these photobioreactors provide higher biomass productivity and fewer contamination issues. The choice of open or closed systems depends on multiple factors and requires careful selection.

2.3 Effects of External Factors

Major concern during pilot scale production of algal biomass is the effect of various external factors. The variable nature of sunlight and the intensity critically govern the growth characteristics in open systems, and because of inefficient light utilization, they have low productivity than closed systems. The application of artificial illumination is yet to be investigated at such large-scale production, though it has been deemed suitable at low scale. Also, the temperature affects the growth of algal culture. Hence, selecting proper strain having optimal temperature within the prevailing conditions would invariably result in better performance. In addition, evaporative losses with open system are directly dependent on temperature. The issue of contamination by protozoa and other algae in open systems is a serious concern which could eventually lead to system failure. This can be dealt with by providing highly selective growth conditions at additional cost. However, this strategy limits the choice of suitable algal strain considerably (Rawat et al. 2013).

3 Issues with Biomass Harvesting

The harvesting of produced algal biomass proves to be a highly complex process due to many inherent factors and may account for significant fraction of the total production cost (Chisti, 2007).

3.1 Key Parameters and Available Technology

Major difficulties in devising efficient harvesting processes arise from low culture density in open systems, and small cell size (Li et al. 2008). Since closed systems such as tubular photobioreactors are more efficient in biomass production, cell density may be up to 30 times higher in them than open systems. This leads to easier harvesting (Chisti 2007).

Over the years, different technologies have been applied for biomass harvesting. These include flocculation, flotation, sedimentation (gravity or centrifugal) and filtration among others. Detailed description and critical comparison of these processes are available (Chen et al. 2011; Rawat et al. 2013). Table 2 lists few of their traits. Since these processes are dependent on different characteristics of algal culture, a proper selection of algal strain and a suitable harvesting process are critical (Rawat et al. 2013).

In general, harvesting is a two-stage process. Bulk harvesting is the first step towards efficient biomass recovery, where 2–7% solid concentrations are achieved from the bulk broth depending on the initial levels and the process adopted. Then

Table 2 Some aspects of the harvesting processes in practice (Rawat et al. 2013)

Process	Advantage	Disadvantage
Filtration	Low cost	Slow, membrane fouling, cell damage
Centrifugation	Fast, efficient	Highly energy intensive
Gravity sedimentation	Low cost, low energy requirement	Slow, applicable only with high cell density
Chemical flocculation	Low cost, low cell damage	Risk of degrading the biomass quality and yield
Dissolved air floatation	Low cost, easy upgrade to pilot scale	Energy intensive, may degrade product quality
Bio-flocculation	High efficiency	High energy requirement than other flocculants
Electrolytic flocculation	High efficiency	High energy requirement, electrode fouling, high system temperature
Submerged membrane filtration	Low cost, less shear to the cells	Membrane fouling

this slurry is further thickened using more energy-intensive processes, viz. centrifugation and filtration for use during downstream processing (Brennan and Owende 2010).

Not all methods are efficient for biomass harvesting, and their application is governed by many other factors such as cost and energy requirement. For example, gravity sedimentation is only efficient for harvesting algae which inherently have good settling characteristics. However, this provides with one of the cheapest and very low energy-intensive techniques available. Hence, processes such as these are suitable with biomass production in HRAPs, where algae with better settling are favoured. Similarly an informed decision for a suitable method should be based on relative urgency between efficiency, cost and input energy in each case.

3.2 Major Precautions and Concerns

Since harvesting is dominantly a physical process, concerns of damage to biomass and the lipid quality are very real. Addition of chemical agents for flocculation may have an impact on the acceptability of harvested biomass for downstream processing and hence requires serious care during their selection. One of the major factors during various harvesting processes is the requirement of skilled or semi-skilled personnel to sustain the operation. Also, desired solid concentrations in the thickened slurry govern the selection and overall cost of harvesting and hence must be optimized. Main precautions and concerns for selecting and implementing a harvesting process are listed below:

- Suitability of the harvesting process with the algal strain is important for optimal recovery. However, maintaining a single species (of desired qualities) in these large-scale systems (especially open systems) is very difficult, and more often than not, a population of diverse species is obtained whose dominance is governed by prevailing conditions. Hence, the selection of a harvesting protocol should also account for changing dynamics of these species during the operation.

- Though many of the harvesting processes can achieve very high recovery efficiencies (viz. microfiltration and centrifugation), their applicability is finally governed by the economics of the whole process. A proper analysis between recovery efficiency and the operation cost should help in selecting suitable processes.
- Also, as discussed earlier, the impact of harvesting on the quality of biomass and lipids decides acceptance of that process. Further investigations are necessary if other products are to be extracted in addition to lipids.

4 Issues with Processing of Algal Biomass

Once the algal biomass is produced and recovered, it requires further processing for lipid extraction that is finally utilized for biodiesel production. The processing of algal biomass for these objectives is highly complex and poses some serious concerns for product quality. In addition to the quality of extracted lipids, the overall extraction cost also plays an important role for feasibility of this approach.

4.1 Suitability of Harvested Algae and the Extraction Process

As the thick biomass slurry is obtained, various downstream processes are utilized for converting it to biofuels. However, the nature of the biofuel (lipids, biogas, etc.) inherently depends on the biomass quality after harvesting. Although, algae cultures are selected for production based on their suitable lipid profile and productivity, the mechanical and/or chemical processing during various upstream processes may either denature the accumulated lipids within the cells or altogether destroy cells leading to lipid loss. Both of these cases render the recovered biomass unsuitable for downstream extraction.

Once thickened slurry of suitable biomass is recovered, further drying is often practised to increase its viability. Many ways to achieve this have been investigated and include sun drying, low-pressure shelf drying, spray drying, drum drying, freeze drying and fluidized bed drying among others (Brennan and Owende 2010). Many of these are highly energy intensive in nature and considerably add to the cost of production. Hence, recent focus is on developing processes, where wet algal biomass can directly be utilized for lipid extraction (Patil et al. 2011; Sathish and Sims 2012).

Further, cell disruption is needed before lipids can be extracted using solvents. This is achieved by processes, viz. microwave digestion, ultrasonication, autoclaving or osmotic shock among others (Ansari et al. 2015). However, the efficiency and cost of individual process vary. The liberated lipids are then extracted using solvents such as mixture of methanol and chloroform. The choice of solvents also plays an important role for acceptability of the lipid as well as reuse of remaining biomass.

4.2 End Use of the Biomass: Single or Multiple Product Extraction

The final justification of using microalgae for biofuel can only be achieved with favourable economics. Conventional approach has been to extract the lipids only. This simplifies the operational details considerably, and process optimization is needed only for lipids. Use of the residual biomass for animal feed may be undertaken depending on the residual toxicity of extracting solvents. However, such an approach has not been able to achieve favourable economics so far. Hence, recent investigations are directed towards extracting plethora of useful compounds from algal biomass in addition to lipids and thus maximize the benefit. This approach is fairly reasonable since algae host many valuable compounds, viz. proteins, carbohydrates, pigments, medicinal compounds, etc. (Pulz and Gross 2004). Efforts towards this follow the algal biorefinery approach, where cumulative value extraction is optimized (Subhadra 2010). However, simultaneous extraction of multiple compounds poses unique challenges. The effect of extraction of one compound on the yield and quality of other metabolites needs careful investigation. This requires proper selection of extraction processes for all targeted compounds as well as their sequence of extraction (Ansari et al. 2015). Hence, the current focus of the community is towards developing greener extraction protocols for target compounds with minimal effect on yield and quality of other products.

5 Summary and Conclusions

The importance of algal biofuels as a feasible alternative of petroleum products has resulted in ever-increasing attention towards developing technologies for their large-scale production. However, such an undertaking is highly complex and faces multiple issues during each intermediate steps. These issues are discussed in detail in this chapter and are also summarized in Fig. 1. Achieving sustainability in this requires tremendous efforts. Though the large-scale production for algal biofuel is technically feasible, it is yet to achieve the economic sustainability. The efforts to achieve are focussed on two distinct themes, (a) to develop better processes at each step to maximize the biomass productivity and minimize the operational cost and (b) to maximize the value extraction once the biomass is harvested by developing more efficient and greener technologies for each

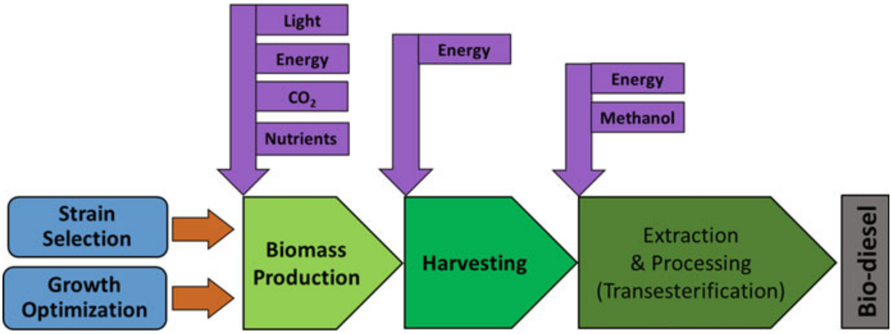

Fig. 1 Summary of the key processes and involved issues during algal biodiesel production, modified from Scott et al. (2010)

compound with algal biorefinery approach. This again highlights the importance of further research towards achieving the overall objective of feasible and commercially viable production of algal biofuels.

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