Chapter 15
Biofuels from Diatoms: Potential and Challenges

Jyoti Verma, Akriti, Hemlata Pant, and Ambrina Sardar Khan

Abstract Biofuel is the hope of this planet to ensure safe and sustainable use amid increasing rate of pollution and global warming. The term biofuel may be misleading for some that it is only substitute of fossil fuels, which is not true. Biofuel is a broad term including bio-oil, biodiesel, bioethanol, biogas, etc. finding its use in transportation, cosmetics, cooking, nutrient supplements, etc. The generation of biofuel from diatoms is third-generation biofuel production. Either the lipid from diatoms is extracted as bio-oil or the whole biomass of diatoms is used as biocrude. Apart from the mainstream uses of biofuel, the diatom culture produces many by-products which find their use in multiple fields. The public authority of India reported Biofuels Policy in 2008 to advance its production and utilization. The main obstacle on the way is economic production of biofuel from diatoms, to make it worth choosing over other options. Diatoms grow fast but they produce lipids slow, and the process of extraction is even more tedious. However, with the use of recent technologies, proper management and planning, this method proves to be the most efficient and environment friendly way of biofuel production. Diatoms don’t have a large number of cells in the body to support, they use carbon dioxide and other nutrients from waste, or eutrophied water bodies produce biofuel and clean their nearby environment in return. It is high time we develop this method to make it feasible for greater good.

Keywords Biofuels · Diatoms · Microalgae · Hydrocracking · Sustainable energy

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15.1 Introduction

Biofuel is a kind of fuel (liquid or gaseous), produced over a short time span from the biotic component of our environment rather than very slow natural processes involved in the formation of fossil fuels. It could be derived from plant, algae material or animal waste. These materials could be replenished readily, making biofuel a source of renewable energy. The word fuel associated with biofuel could lead to assumptions, that it could be used only for transportation purposes. Biofuel's advantage is not limited to one field only but also extended to energy generation, heat production, charging electronics, clean oil spills and grease, lubrication, removal of paint and adhesive, as cooking oil and there are many yet to be discovered to utilize their full potential.

15.1.1 Diatoms

Diatoms, a significant component of phytoplankton, are microalgae. They contain silica-based tiny shell walls. The lineage is traditionally divided into two orders: radially symmetrical centric diatoms, or centrales, and bilaterally symmetrical pennate diatoms, or pennales. The first order is further classified into polar and non-polar centrics, whilst the latter order comprises the classes Bacillariophyceae and Fragilariophyceae based on the presence or absence of a raphe; each group emerged and developed progressively over the Mesozoic era when CO_2 levels decreased. Diatoms displaced a substantial amount of other algae (mostly cynobacteria and few green algae) in the ocean throughout the Mesozoic era, according to the fossil record (Hildebrand et al. 2014). They evolved around the Jurassic Period. They have the ability to biosynthesize a variety of commercially valuable chemicals.

Each year, living diatoms generate 20% to 50% of the oxygen produced on the Earth, absorb about 6.7 billion metric tons of silicon from the waters in which they dwell and account for nearly half of the organic material present in the seas (Treguer 1995). Diatoms are natural nanotechnology factories that have been discovered in the fossil record for over 100 million years. Diatoms are less sensitive to turbulence in the ocean than any other phytoplankton (Wyatt 2014).

Diatoms also produce other useful items such as semiconductors, health foods (glucosamine) and chitin fibres. These incredible microscopic algae will be able to absorb some of the cheapest, most abundant elements on Earth—like silicon and nitrates—and make a steady stream of affordable products with nothing more than sunlight, practically any sort of water and carbon dioxide (Rorrer 2012).

15.1.2 Biofuel from Diatoms

During the vegetative period of growth, diatoms create oil drops that are kept intracellularly as a reserve material, with percentages ranging from less than 23% to greater than 45% of dry cell weight. Membrane-bound polar lipids, triglycerides and free fatty acids are a variety of lipids found in diatoms. Other substances discovered include sterols, waxes and acyl lipids. The concentration varies by species, depending on the availability of nutrients and other growth requirements. Lipid fractions can range from 70% to 85% in some species, whilst 15% to 25% is more common. Diatoms are particularly promising for biofuel production because of (a) their widespread prevalence and competitive advantage over other microalgae, (b) their rapid growth, doubling their biomass every few hours, (c) their growth could be controlled by availability of silicates and (d) almost all of their biomass could find profitable use (Wang and Seibert 2017).

Bio-oil is a type of oil derived from diatom lipids that can be enhanced by transesterification and other methods. **Biocrude** is natural crude, such as oil, that has been thermochemically transformed from diatom biomass (Wang and Seibert 2017) (Fig. 15.1).

Diatoms are a good contender for a ‘drop-in’ fuel replacement. There are two ways to obtain biofuels from diatoms or any other microalga: (1) direct lipid extraction followed by biofuel processing (which is a common practice) and (2) thermochemical conversion of the entire biomass portion into a biocrude (this is not straightforward but is advantageous over the first one) (Wang and Seibert 2017).

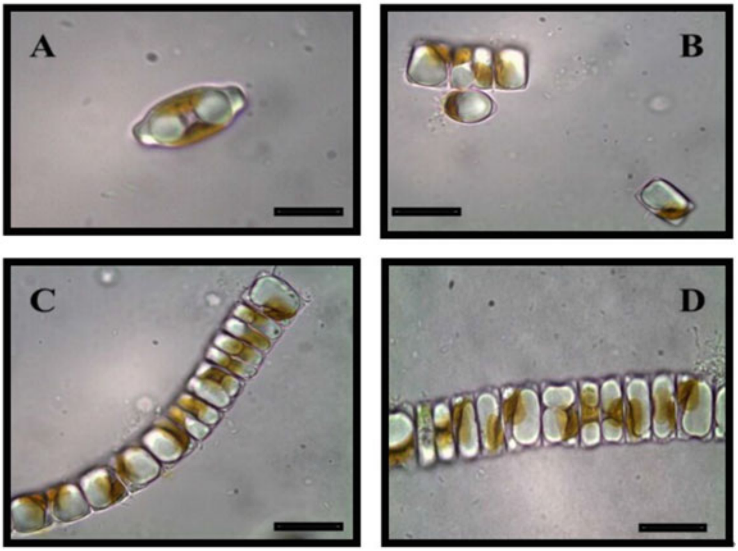

Fig. 15.1 *Diadesmis confervaceae* in solitary and chain forms observed under 100× (oil immersion in III). (Source: Mar. Drugs 2015, 13, 2629–2665; doi: 10.3390/md13052629)

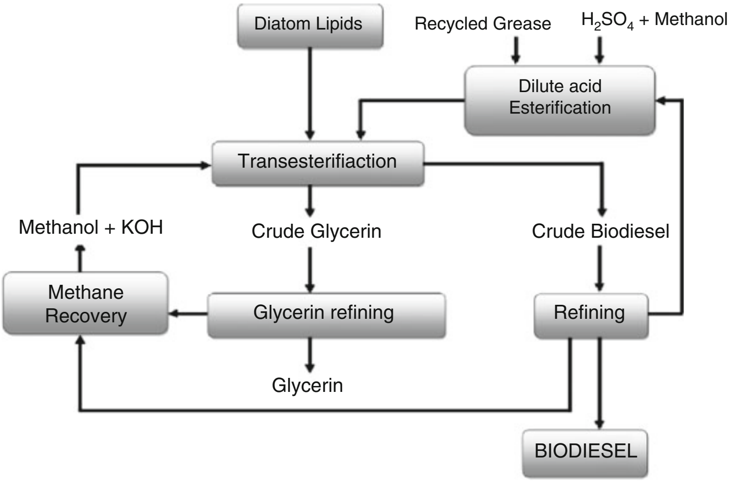

Fig. 15.2 Flow chart showing different fate of diatom lipid. (Source: Ramachandra et al. (2009) 3: 764 ; doi: 10.1021/IE900044J)

Hydrothermal liquefaction (HTL) can utilize all the biomass as a feedstock, regardless of lipid content, and can process wet feedstock directly (without the need for a time-consuming drying procedure). Carbon in various types of biomasses, including carbohydrates and proteins, can be used by HTL. The goal of HTL techniques is to convert carbon to oil rather than extracting existing oil from microalgae (Wang and Seibert 2017) (Fig. 15.2).

15.2 History

Until recently, it was widely assumed that the cost of creating algal biomass was higher than that of producing biodiesel crops. For research purposes, *Phaeodactylum tricornutum* is designated as a model diatom (Graham et al. 2012). Its lipid content is stated to be between 21% and 26% of dry weight, and its doubling time (Td) is 25 h. Cerón-García et al. (2013) evaluated *P. tricornutum's* mixotrophic growth on several carbon sources. Although all diatoms synthesize and store lipids as food reserves, marine diatom species have been examined for lipid content in relation to biofuels (Fig. 15.3).

Weyer et al. (2010) of the Jawkai Bioengineering R & D Center in Shenzhen, China, has achieved sustainable diatom yields of over 120 MT dry weight per hectare per year. The HTL process can convert one-third of the dry weight of diatoms to biocrude which is more than 36,000 L of biocrude per hectare.

A version published by New Zealand's prominent biochemist Chisti (2007) presents algae as an oil producer that is 130 times more productive than soybeans.

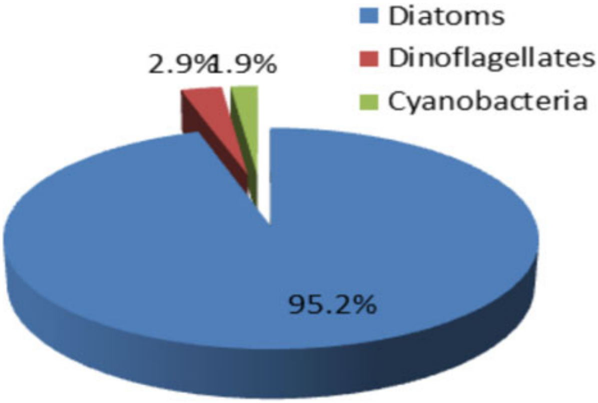

Fig. 15.3 Pie chart showing contribution of different microalgae in biofuel production. (Source: Beetul et al./Biofuel Research Journal 2 (2014) 58–64)

15.3 Methodology

15.3.1 Harvesting

Traditional methods such as **centrifugation**, **filtration** and **flocculation** are very popular as the energy concentrated, not easy to perform, and involve high chemical induction for harvesting process. Natural existing surfactants (as in the case of *Chaetoceros*) produced by the microalgae themselves may deliver a partial result. Similar surfactants will allow the use of froth separation to concentrate diatoms. Csordas and Wang (2004) have shown that froth separation can remove up to 90 of *Chaetoceros* from its culture medium (after diatom discarding, the medium can be reused with applicable treatment).

15.3.2 Breaking the Cell Wall

The approach of producing lipids from diatoms and converting them to bio-oil involves: (a) harvesting cells after the growth period and application of stress conditions to amplify lipid production, (b) destroying cells to extract lipids and then (c) altering lipids configuration to biodiesel by transesterification. Rossignol et al. (1999) stated that the cell breakage is due to the sudden and a rapid transmission of diatoms from a state of extreme elevated pressure (30–270 MPa) to one of low pressure (0.1 MPa). This sudden change is very damaging for diatoms. Their experiments showed significant splintering of *Haslea ostrearia* cells occurred at 30 MPa. Kelemen and Sharpe (1979) in their studies have defined and stated that there is a certain threshold of a pressure that triggers the destruction of 50% of the various microbial cell populations. They have shown that cells do not rupture at a defined pressure; instead, a critical pressure must first be applied before the cells begin to rupture. **High-pressure rapid release (HPQR)** cell destruction methods have been shown to be effective in recovering intracellular metabolites (nucleic acids, enzymes, proteins, pigments, etc.) from diatoms. This technology complements or competes with traditional laboratory-scale technologies such as **sonication or shear-based system** previously used for the extraction of **marennine**, a blue pigmentation that is exhibited by the marine diatom *Haslea ostrearia Simonsen*. Additional methodology of destruction is **to use the application of one or more powerful but very quick and rapid electric field shock to diatoms** suspended in a moderate aqueous solution for facilitating electrical conductivity. If the field is strong enough, many temporary aqueous pores will be created. If there are high concentrations of dissolved ions and molecules in the internal space of diatoms, an osmotic pressure difference will occur. Water from external media would enter the cells and increase the pressure in the diatom's lipid bilayer, the membrane-protected area. The pressure difference must be large enough to destroy the diatoms. The average lifespan of pores is controversial, probably more than a second, so multiple pulses may be required. The temperature rise is generally small (Weaver 2010).

15.3.3 Hydrothermal Liquefaction of Diatoms

This methodology eliminates the necessity for the breaking of cell unit and is considered to be more economical and viable approach for the reduction in the production cost of a biocrude yield process. The dry weight of wet diatom is mostly 80%–90% water because of their large water content, and relatively with low heat capacity, before using in heat, power generation or other biofuel production operations, it should be pretreated. Hydrothermal liquefaction (HTL) equipment functions under subcritical water conditions and is thus well suited to transform wet biomass into liquid energy (Zhou 2015). The innovation is like the regular geographical cycles that prompted the development of unrefined petroleum; however, this happens in minutes rather than a long period of time. HTL involves water as the transporter under sub-basic circumstances to deteriorate the biomass and structure of more important and more limited chain atoms. The immediate treatment of wet biomass by HTL maintains a strategic distance from the need for drying, which ought to fundamentally work on the proficiency of the overall thermal process. Goudriaan et al. (2000) asserted that the biomass thermal processing effectiveness during hydrothermal treatment (HTU) in a 10-kg (dry weight) *h*—1 pilot workshop establishment can be as high as 75. Biocrude is the main produce of the procedure, counting for about 45 of the feedstocks on an ash-free, dry weight base. Biocrude had an advanced heating value of 30–35 MJ/kg, which might be additionally upgraded if desired. Bohlmann et al. (1999) elaborated a similar procedure applying a novel high-pressure microwave oven reactor to reduce the energy consumption of algal biofuel yield. Brown et al. (2010) drew the transfiguration of the oceanic microalga, *Nannochloropsis* sp . into biocrude plus a gaseous produce harnessing hydrothermal processing from 200 °C to 500 °C and a set holding time of 60 min. Similar study by Minowa et al. (1995) recounted a 37% oil production from

Dunaliella tertiolecta (moisture content, 78.4 wt% and carbon content), applying direct HTL at around 300 °C and 10 MPa. To have more understanding of these techniques' efficacy, Aresta et al. (2005) evaluated and compared these various transformation procedures, namely, pyrolysis, supercritical CO $_2$, hydrothermal and organic solvent extraction, for diatom biodiesel production. HTL was found to be a better and efficient technology than any other known technologies for harnessing biofuel out of diatoms.

The studies reported that by the conversion of fatty acids in biocrude into alkanes, the property and quality of the fuel enhances due to the reduction of the oxygen content of the bioproducts. Previous records stated that the biocrude obtained with direct conversion without utilizing the catalyst was not of good quality and have low commercial values as its properties completely changes. Levine et al. (2011) in an inert setting experimented that all their sampled liquefaction catalysts delivered higher productions of biocrude in *Nannochloropsis* sp .; still, the heating value of the biocrude (ca. 38 MJ/kg) and its essential composition weren't reactive to the catalyst applied, for most of the duration. Nevertheless, in the case of a backed Ni catalyst, the biocrude obtained had untraceable sulfur content. The desulfurization process was, however, exceptional in the case of Ni catalyst. Reports stated that the increased protein and lipid contents in algal dry weight increased the production of biocrude. However, the nitrogen content is completely dependent on the feedstock utilized to extract biocrude. Zhang et al. (2010) found that diatoms, which are N-containing hetero-aromatic compounds and are used for biocrude, managed to increase in intensity with rising resulting temperature and are characterized with 10% of the total known peak area. These substances may be considered as unsuitable outputs as they are structurally stable and are dangerous for the biocrude production at large scale.

15.4 Indian Scenario

The public authority of India reported Biofuels Policy in the year 2008 to advance the creation and the utilization of biodiesel to accomplish an objective of mixing 20% biodiesel with diesel by 2017. Biodiesel can be delivered from palatable, non-eatable oils and fats. The biodiesel creation from eatable oils is unrealistic because of its utilization for consumable purposes and 80% of palatable oils are imported. Non-palatable sources are Jatropha, Pongamia, Neem, Sal and so forth. Microalgae can possibly deliver 1,36,900 L, whilst Jatropha can create 1892 L of oil for every section of land. Microalgae have the most elevated biofuel creation potential, i.e. 15 to multiple times more than earthbound oil seed crops on an area premise (Alam et al., 2012) (Fig. 15.4).

Important factors to be thought about for choosing appropriate microalgae species are cell biomass, macromolecule content, macromolecule quality, rate of growth, response to conditions like lightweight, temperature and nutrient input, and growth medium. Production of microalgal strain and improvement of its growth is the most

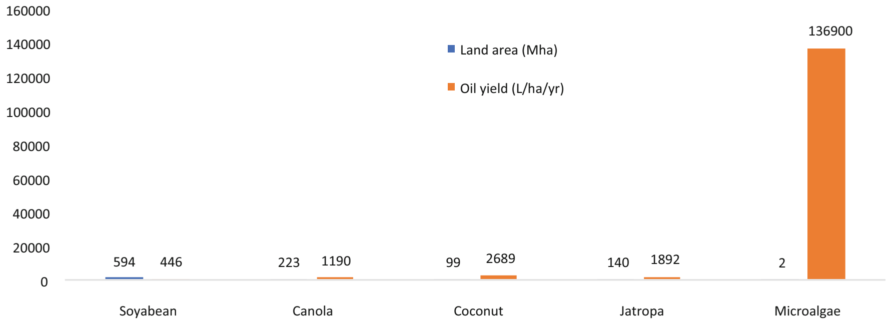

Fig. 15.4 Land required and oil productivities from different feedstocks. (Source: J Integr Sci Technol, 2014, 2(2), 72–75)

significant in determining the political economy of biofuel production. Sudhakar et al. (2012) reported that if microalgae are farmed on 0.06% of the overall expanse, 75 g/m ^{2}/day of protoctist biomass and 35 mL/m ^{2}/day of microalgal oil will be made. Bajpai et al. (2014) also reported that if microalgae are cultivated in <2%–3% of the total expanse, it will fulfil the nation's liquid fuel demand. Robles-Medina et al. (2009) urged that the Sundarbans delta ground of 100 islands (Bay of Bengal) will be used for protoctist cultivation and extraction of biodiesel. Compared to edible and non-edible oil-based biodiesel, the soundness of biodiesel from microalgae is the intercalary advantage, which suggests that the biodiesel remains unchanged in fuel quality for an extended amount of time.

In India, broad work has been done on the use of microalgae for food and drug applications; however, very little work has been done on development, reaping, oil creation, biodiesel change and its use as motor fills. Lately, microalgae have been found to deliver 19,000–57,000 L contrasted with 2000–2500 L of biodiesel per section of land from eatable and non-consumable oils (Kumar and Sharma 2014). Saranya et al. (2018) researched on diatom consortia across diverse lentic and lotic habitats of the Aghanashini estuary with varied levels of nutrients primarily influenced by distribution of flora and fauna to understand the role of environmental parameters and nutrient levels in species composition and community structure. This effort was an essential prelude to phyco-prospecting potential candidates for third-generation biofuel production. Hierarchical cluster revealed highly productive clusters that are capable of accumulating higher lipids under certain environmental conditions over other species. **Regression modeling** was performed to understand the probable lipid productivity potential by integrating physicochemical and nutrient parameter which provided an empirical equation relating lipid and other critical factors affecting lipid content of diatoms. This empirical modeling is capable of providing lipid content details right at the sampling stage without cultivating diatoms under laboratory conditions. Rajaram et al. (2018) considered exploring the impacts of CO_2 on biomass, unsaturated fats, carbon-hydrogen and biochemical gathering of the marine diatom *Amphora coffeaeformis* RR03. The outcome showed that *A. coffeaeformis* RR03 contained high biomass efficiency and biochemical creation in various development conditions. *A. coffeaeformis* RR03 showed the most extreme development of 5.2 × 106/mL on the 21st day of development under CO_2 supply. The bio-unrefined petroleum creation from *A. coffeaeformis* RR03was 36.19 megajoule (MJ). Marella et al. (2017) concentrated on metropolitan wastewater from eutrophic Hussain Sagar Lake to develop a diatom cultivating consortium, and the impacts of silica and the following metal advancement on development, supplement evacuation and lipid creation were assessed; results exhibit the possibility to deliver feedstock for inexhaustible biodiesel creation.

15.5 Potential

Diatoms can ingest CO_2 (alongside certain contaminations all the whilst) and can be exceptionally helpful in advantageous power age/diatom creation, oil refining/diatom creation, or brewery/diatom creation connections. They can eliminate natural NOx from burning gases. At the point when utilized in fluid, fuel creation will leave almost no waste material (toxins) behind. The leftover development medium can be reused. Proteins created (with non-warm handling) are good for animal feed (Fig. 15.5).

The frustules from diatoms (which are covered with nanosized openings), which endure the HTL interaction, are possibly great material for the adsorption of major contaminants from wastewaters coming from mills, industries, textiles, etc., particularly heavy metal; up to 99.9% of the copper can be eliminated from wastewater by

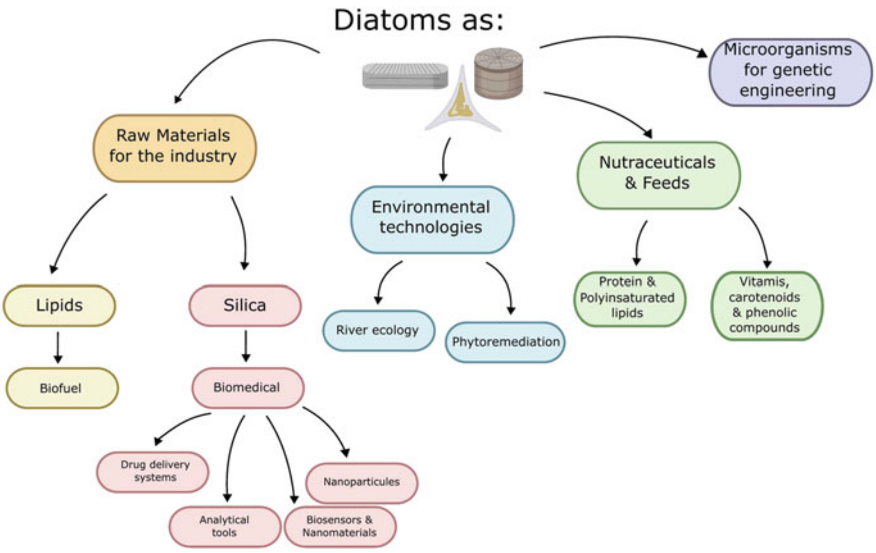

Fig. 15.5 Potential of diatoms in different fields other than biofuel. (Source: Article in Frontiers in Marine Science. February 2021. doi: 10.3389/fmars.2021.636613)

separating the water through diatom frustules according to the study reported by Wang (2015).

Assuming we are to utilize untreated or even treated wastewater to substitute composts, we can save the expense of the manure, and by cleaning up of the wastewater, we ought to likewise acquire another income stream to counterbalance the expense of the biocrude. The capacity to eliminate supplements can likewise be utilized to advantage in the treatment of wastewater. On the off chance that creation productivity, for example, yield per unit region per unit time, is anything but a genuine concern, and if we can match the constituent or the composition of the supplements in the treatment lakes or ponds to that expected by the diatoms, we can diminish the supplement load in the wastewater to near nothing (Wang and Seibert 2017).

This may be used as environmentally friendly fillers for polymers, thus widely employed in our everyday activities, or may be even as materials for composites or metal additive producing. Several potential coproducts embody specific organics like food-grade carotene, prescription drugs and pigments, also as compounds like polysaccharides, carbohydrates, surfactants and different polymers. The alga *Phaeodactylum tricornutum* is cultivated in out-of-door photobioreactors for the assembly of long-chain unsaturated fatty acids that can be used as food supplements (Graham et al. 2012).

Oil (lipids) from diatoms can likewise be utilized to deliver cooking oil in applications where HTL isn't utilized. The top notch of the lipids created will bring about good quality oil for human utilization, and expansive future accessibility ought to assist with the lack of cooking oil, which is a crisis and a serious issue in the coming time. The utilization of food crops for biodiesel creation prompts contest between the utilization of farming area for food creation and its utilization for fuel creation with a subsequent expansion in food expenses and possible environment and biodiversity misfortunes. Diatoms can deliver as much as multiple times the volume of oil per unit of land region, contrasted with business oilseed crops. There are other energy fuel sources; yet sadly, there is not a viable alternative for cooking oils from natural sources (Wang and Seibert 2017).

Diatomaceous earth is a mineral material consisting chiefly of the siliceous fragments of various species of fossilized remains of diatoms. In cosmetics and personal care products, diatomaceous earth may be used in the formulation of bath products, soaps, detergents, cleansing products, face powders, foundations and skin care preparations (https://www.cosmeticsinfo.org/ingredients/diatomaceous-earth).

15.6 Challenges

The extraction of lipids from diatoms is a very tedious process and requires a large amount of labor and attention; apart from this it also requires surplus amount of financial aid (Fig. 15.6).

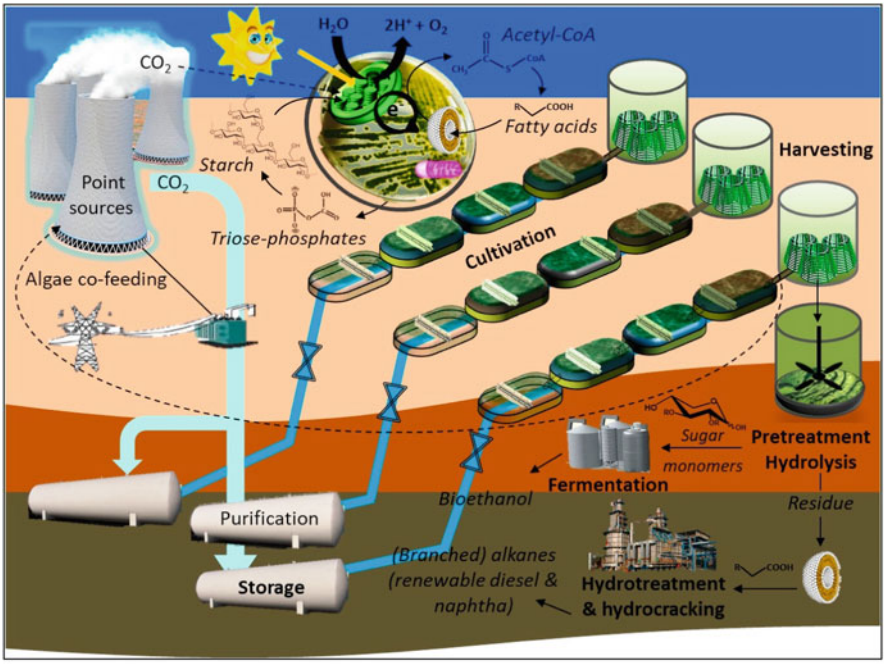

Fig. 15.6 Complex process of biofuel production from algae (diatom). (Source: A review on sustainable microalgae based biofuel and bioenergy production: Recent developments; https://doi.org/10.1016/j.jclepro.2018.01.125)

Even after its numerous benefits over other biofuel substitutes, the economic cultivation and production of biofuel from diatoms have not gained popularity because of the following reasons:

(a) The asexual division in diatoms make them smaller in size.
(b) Grow quick, however, production of oil is slow in them.
(c) Wild alga quickly displaces the alga being cultivated.
(d) Initial capital prices, the necessity to get rid of heat and the critical issue and high price of maintenance activities.
(e) The method of getting careful lipid profiles for microalgae is slow and exhausting.
(f) The major prices of alga production, not reckoning facility investments, square measure fertilizers (including silicate), dioxide and electricity make the method terribly pricey and nearly not possible for industrial production.

15.7 Solutions

The surplus water in the lake will give it a time to reduce the organic load by itself. The excessive water enhances the decomposition of organic content by aerobic decomposition. Further, the city water shall be treated utilizing the diatoms as it enters the aquatic bodies via city wastewater plants. Hence, eliminating supplements and contaminants from the wastewater at the source ought to be a viable and a suitable methodology. This is important since even an efficiently designed wastewater treatment plant eliminates minimal inorganic supplements from city wastewater. It for the most conversion happens from organic into inorganic ones, so cleaning the water would become a significant specialty for diatoms (Wang and Seibert 2017) (Figs. 15.7 and 15.8).

(a) Limited but however continuous replacement of the native algae species underneath culture with the leading economical diatoms from the wild guarantees constant economical production.
(b) When we economically harness algae for biocrude, we are really keen on fixing carbon content and not to harness oil essentially. The entire notion is ought to be intended to produce natural carbon from inorganic carbon. Whether the natural carbon is as oil or sugar or whatever else, HTL can generate the products that we need.

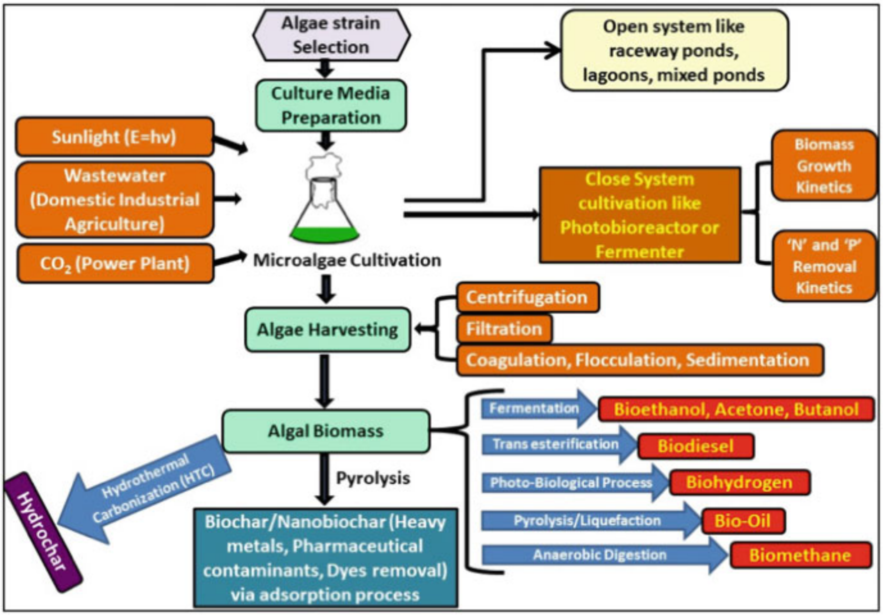

Fig. 15.7 Process and products of an algal (diatom) culture. (Source: Ajay Kumar (2021);249–275 (2021). https://doi.org/10.1007/s42250-020-00221-9)

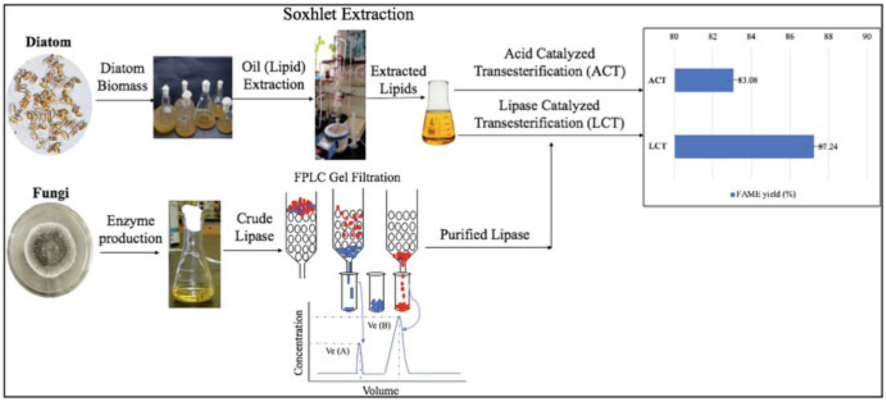

Fig. 15.8 Catalytic upgrade of lipids extracted from diatom. (Source: https://doi.org/10.1016/j.renene.2020.02.053)

(c) Using domestically isolated strains, we tend to additionally avoid the issues that may come back from introducing foreign (invasive) species into native waters.

(d) If the diatom can be maintained in an open system, growing at log phase by limiting, among various contents like the concentration of salt, nutrients, silica, etc., then it will outgrow non-diatom species and thereby retain its dominant position within the production system (*Chaetoceros* sp . a marine phytoplankton has been unendingly cultivated with success in an exceedingly industrial, open-production system in Hawaii, exploitation using the similar technique). The management of aquatic animals that kill diatoms has conjointly been achieved during this system by repeatedly applying stresses (e.g. pH stress), and also the impact of predators will be reduced.

(e) A new technique was reported for the direct, quantitative determination of lipid profiles on living microalgal cells by single-cell laser-trapping Raman spectroscopy. Lipid profiles were reported for single living cells of *Botryococcus braunii, Chlamydomonas reinhardtii* and *Neochloris oleoabundans*, with the time to obtain spectra for fatty acids less than 10 s. **Raman spectroscopy** should make rapid monitoring of mass cultures of microalgae possible for the determination of optimal harvest time (Wu, 2014).

(f) Denitrogenation by catalytic upgrading will help in matching the level of algal biocrude transportation fuel.

(g) To lessen the expense of power (one of the expense issues referenced above), environmentally friendly power, for example, sun based, or wind power could be utilized where fitting.

(h) The modification of a collective or joined heat and power (CHP) plant or an internal heat exchanger network would assist in executing the immediate handling of wet biomass.

15.8 Discussion

Recent engineering life cycle comparisons, however, indicate that linking algal production to wastewater cultivation has the potential to offset many of the environmental burdens of algae biomass production for biofuel feedstocks and outperform terrestrial crops. Wastewater-linked algae cultivation also offers the prospect of effluent bioremediation, with the sale of algal feedstock potentially offsetting increased costs associated with new N and P reduction mandates. The creation of diatoms under subtropical circumstances is significantly more impacted by variation in accessible sun-powered illumination than the changes in temperature, as long as the temperature stays under 36 °C or more 25 °C. Subsequently, they can be delivered in desert regions, where saline water is accessible, and in the mild zone at low temperatures. Diatoms, coincidentally, have been found in the desert and high-altitude lakes. Even in cold temperate climates, algal biomass production can outperform soybean-based biodiesel production if the algal production is carried out in a photobioreactor within a greenhouse warmed by waste heat from an adjacent powerplant (Wang and Seibert 2017).

They are adapted to the high nutrient conditions of hypereutrophic lakes, for wastewater-linked biofuel feedstock production. If diatoms or other algae are to be grown in wastewater effluents as a potential source of biomass feedstock for biofuels and as a cost-effective means of reducing nutrient pollution to natural waters, then the diatoms must be grown to the maximum biomass permitted by the levels of phosphorus and nitrogen in the wastewater effluent. In that event, the diatoms will reduce phosphorus and nitrogen in the effluent before discharge to levels that would not cause eutrophication. A discharge level of less than 50 μg P/l of effluent would be in the mesotrophic range for natural waters and one of <10–15 μg P/l would be in the oligotrophic range for natural freshwaters. The cultures grown at the lower silicon levels showed a decline in lipid content as the time in stationary phase increased. It would be useful to determine the optimal time in stationary phase to produce the maximum lipid. In addition to these growth parameters, diatoms sink out of culture readily in the absence of stirring. All non-motile algal cells tend to sink in freshwater in the absence of mixing because their cytoplasm tends to be slightly denser than water. Diatoms sink more rapidly than many other groups of algae because their silicon impregnated cell walls are extremely dense (2600 kg/m ^{3}). The capacity of diatoms to sediment rapidly should be useful in harvesting their biomass for lipids. In diatom lipid production, shape matters, and it may be possible to use diatom cell shape as an indication of the potential to accumulate significant amounts of lipids for commercial application. Ways to deal with creating diatoms in the sea would have various benefits, including defeating the heat intensity challenge and a significant issue in close production frameworks. A close creation framework drifting on the water can scatter heat at almost no expense. As of late, NASA has examined the specialized plausibility of an interesting floating algal growth development and culture system for the coming time. (http://www.nasa.gov/centers/ames/research/OMEGA/). The study has exhibited that their OMEGA framework is

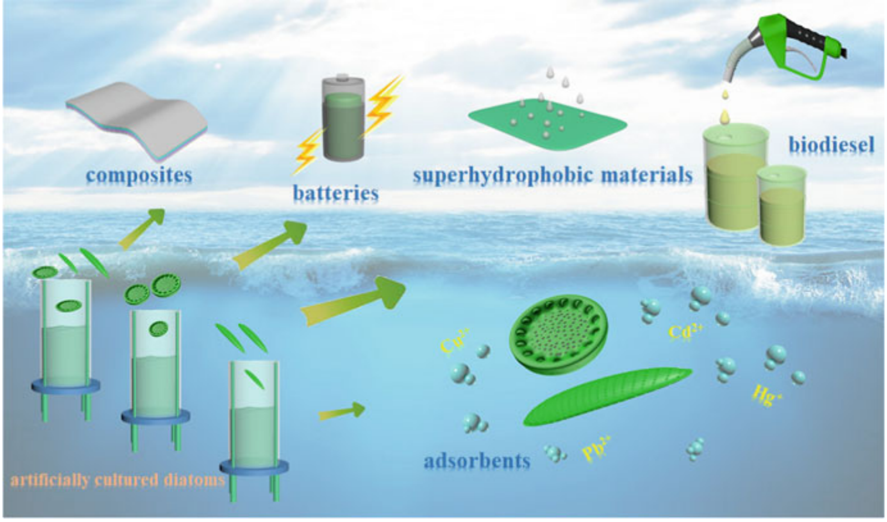

Fig. 15.9 Applications of artificially cultured diatoms. (Source: ES Energy & Environment 2020, 8, 3–4, https://doi.org/10.30919/esee8c486)

powerful in developing microalgae and treating wastewater on a limited scale; however, the monetary plausibility of this plan still needs to be shown (Wang and Seibert 2017).

To be successful, the microalgal growth model should be more like agriculture. Some of the suggestions for higher yield of diatoms are as follows: (a) semicontinuous harvesting (once a day), leading to highest quality light absorption at some stage in the year; (b) most useful strains must be grown during the two (the altering dominant strain have to be acquired, which need to be consistently seed to examine bioreactors; thus, one will be capable to use the most prolific resident strain for the local environments at all instances throughout the time); (c) substantial rheostat of invasive species or strain; (d) acceptable management of aquatic species that forage on diatoms; (e) optimum control or regulated temperature at all times; (f) optimum dietary supplementation have to be there throughout; and (g) diatoms normally in the log segment of their life cycle over prolonged durations of time (Wang and Seibert 2017) (Fig. 15.9).

15.9 Conclusion

The capacity to deliver biocrude, with the consumption of carbon dioxide and utilizing just wastewater or water sources that are undesirable for human utilization and watering system, as well as utilizing barren and waste land, offers nations genuine resource and expectations to produce biocrude in the future for

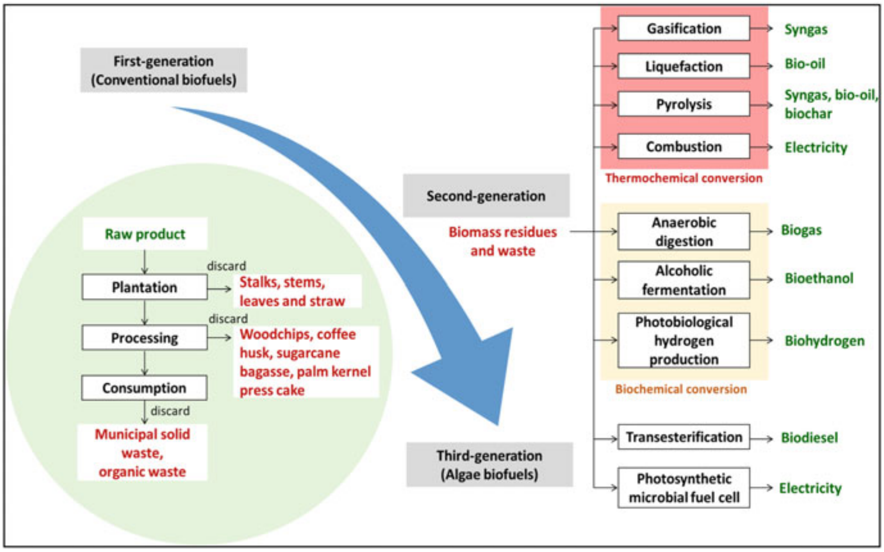

Fig. 15.10 Generation of biofuel using waste as resources. (Source: https://pubs.rsc.org/en/journals/journal/ra)

accomplishing, to some extent, an independence in maintainable fluid biofuel creation (Fig. 15.10).

We should know that the actual significance is of discovering the candy spot between maximizing organic carbon manufacturing and minimizing the conversion costs. This potential that booms price enhancements and organic carbon ought to outweigh oil content in the choice of a diatom species, assuming profitable HTL processing for biocrude production. This has genuine ramifications for strain determination and genetic designing work in all microalgae and bio-oil creation control. Diatoms don't have to help a variety of non-photosynthetic cells as in plants. Besides, on the grounds that they fill in a fluid climate, they are intrinsically more proficient at getting to water, utilizing CO_2 (utilizing a carbon-concentrating component), and breaking down dissolved nutrients. Utilizing CO_2 from substance or power plants, exploiting wind- and sun-oriented power and co-creating a variety of important substances and biofuels, we really want to contemplate on the business creation of diatoms for biofuel age. It is currently time to look again at these well-established issues and attempt back to foster new innovation that can be utilized at a suitable chance to increase diatom industry with authentic probability of success and progression (Wang and Seibert 2017).

References

Alam F, Date A, Rasjidin R, Mobin S, Moria H, Baqui A (2012) Biofuel from algae-Is it a viable alternative? Procedia Eng 49:221–227

Aresta M, Dibenedetto A, Carone M, Colonna T, Fragale C (2005) Production of biodiesel from macroalgae by supercritical CO2 extraction and thermochemical liquefaction. Environ Chem Lett 3(3):136–139

Bajpai R, Zappi M, Dufreche S, Subramaniam R, Prokop A (2014) Status of algae as vehicles for commercial production of fuels and chemicals. In: Algal biorefineries: volume 1: cultivation of cells and products, pp 3–24

Bohlmann J, Phillips M, Ramachandiran V, Katoh S, Croteau R (1999) cDNA cloning, characterization, and functional expression of four new monoterpene synthase members of the Tpsd gene family from grand fir (Abies grandis). Arch Biochem Biophys 368(2):232–243. https://doi.org/10.1006/abbi.1999.1332

Brown TM, Duan PG, Savage PE (2010) Hydrothermal liquefaction and gasification of Nannochloropsis sp. Energy Fuel 24:3639–3646

Cerón-García MC, Fernández-Sevilla JM, Sánchez-Mirón A, García-Camacho F, Contreras-Gómez A, Molina-Grima E (2013) Mixotrophic growth of Phaeodactylum tricornutum on fructose and glycerol in fed-batch and semi-continuous modes. Bioresour Technol 147:569–576

Chisti Y (2007) Biodiesel from microalgae. Biotechnol Adv 25(3):294–306

Csordas A, Wang JK (2004) An integrated photobioreactor and foam fractionation unit for the growth and harvest of Chaetoceros spp. in open systems. Aquac Eng 30(1–2):15–30

Goudriaan F, Naber JA, Van De Beld B, Boerefijn FR, Van Der Wal S, Bos GM, Zeevalkink JA (2000) Thermal efficiency of the HTU process for biomass liquefaction

Graham JM, Graham LE, Shahrizim B, Zulkifly Brian F, Pfleger SW, Hoover JY (2012) Freshwater diatoms as a source of lipids for biofuels. J Ind Microbiol Biotechnol 39:419–428. https://doi.org/10.1007/s10295-011-1041-5

Hildebrand M, Davis AK, Smith SR, Traller JC, Abbriano R (2014) The place of diatoms in the biofuels industry. Biofuels 3:221–240. https://doi.org/10.4155/bfs.11.157

Kelemen MV, Sharpe JE (1979) Controlled cell disruption: a comparison of the forces required to disrupt different microorganisms. J Cell Sci 35(1):431–441

Kumar M, Sharma MP (2014) Status of biofuel production from microalgae in India. J Integr Sci Technol 2(2):72–75

Levine RB, Costanza-Robinson MS, Spatafora GA (2011) Neochloris oleoabundans grown on anaerobically digested dairy manure for concomitant nutrient removal and biodiesel feedstock production. Biomass Bioenergy 35(1):40–49. https://doi.org/10.1016/j.biombioe.2010.08.035

Marella TK, Parine NR, Tiwari A (2017) Potential of diatom consortium developed by nutrient enrichment for biodiesel production and simultaneous nutrient removal from wastewater. Saudi J Biol Sci 25:704–709

Minowa T, Murakami M, Dote Y, Ogi T, Yokoyama SY (1995) Oil production from garbage by thermochemical liquefaction. Biomass Bioenergy 8(2):117–120

Rajaram MG, Nagaraj S, Manjunath M, Boopathy AB, Kurinjimalar C, RamasamyRengasamy TJ, Sheu J-R, Li J-Y (2018) Biofuel and biochemical analysis of *Amphora coffeaeformis* RR03, a novel marine diatom, cultivated in an open raceway pond. Energies 11:1341–1352

Ramachandra TV, Mahapatra DM, Gordon R (2009) Milking diatoms for sustainable energy: biochemical engineering versus gasoline-secreting diatom solar panels. Ind Eng Chem Res 48 (19):8769–8788

Robles-Medina A, González-Moreno PA, Esteban-Cerdán L, Molina-Grima E (2009) Biocatalysis: towards ever greener biodiesel production. Biotechnol Adv 27(4):398–408. https://doi.org/10.1016/j.biotechadv.2008.10.008

Rorrer G (2012) Ancient diatoms could make biofuels, electronics, and health food – at the same time. http://www.eurekalert.org/pub_releases/2012-09/osu-adc091712.php

Rossignol N, Vandanjon L, Jaouen P, Quemeneur F (1999) Membrane technology for the continuous separation microalgae/culture medium: compared performances of cross-flow microfiltration and ultrafiltration. Aquac Eng 20(3):191–208

Saranya G, Subashchandran MD, Mesta P, Ramachandra TV (2018) Prioritization of prospective third-generation biofuel diatom strains. Energy Ecol Environ 3:338. https://doi.org/10.1007/s40974-018-0105-z

Sudhakar K, Rajesh M, Premalatha M (2012) A mathematical model to assess the potential of algal bio-fuels in India. Energy Sources Part A: Recover Util Environ Eff 34(12):1114–1120. https://doi.org/10.1080/15567036.2011.645121

Treguer P, Nelson DM, van Bennekom AJ et al (1995) The silica balance in the world ocean: a reestimate. Science 268:375–379

Wang J-K (2015) An absorbent and method of application for the treatment of heavy metal wastewater. Chinene Patent:201410072325

Wang J-K, Seibert M (2017) Prospects for commercial production of diatoms. Biotechnol Biofuels 10:16. https://doi.org/10.1186/s13068-017-0699-y

Weaver JC (2010) MIT personal communication

Weyer KM, Bush DR, Darzins A, Willson BD (2010) Theoretical maximum algal oil production. Bioenergy Res 3:204–213

Wu Y-H, Hong-Ying H, Yin Y, Zhang T-Y, Zhu S-F, Zhuang L-L, Zhang X, Yun L (2014) Microalgal species for sustainable biomass/lipid production using wastewater as resource: a review. Renew Sust Energ Rev 33:675–688

Wyatt T (2014) Margalef's mandala and phytoplankton bloom strategies. Deep-Sea Res 2014(101): 32–49

Zhang Y (2010) Hydrothermal liquefaction to convert biomass into crude oil. In: Blaschek Hans P, Ezeji Thaddeus C, Scheffran J (eds) Biofuels from agricultural wastes and by-products. Wiley-Blackwell, Oxford, pp 201–232

Zhou Y, Schideman L, Zheng M, Martin-Ryals A, Li P, Tommaso G, Zhang Y (2015) Anaerobic digestion of posthydrothermal liquefaction wastewater for improved energy efficiency of hydrothermal bioenergy processes. Water Sci Technol 72:2139–2147