Chapter 16
Potential Industrial Application of Diatoms for a Greener Future

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Abstract The advantage of the complicated, microscopic, and industrially imperative diatoms is not a secret now and has recently astounded the scientific society with their miscellaneous potentiality. It attracts considerable attention due to their success in diverse environmental conditions. Diatoms are highly attractive for industrial applications due to their richness in natural lipids and carotenoids, especially in the field of biofuel, metabolites, and nutraceutical production. The possibility to utilize a diatom cell for industrial application has increased considerably accompanied with the advanced knowledge of microscopy, metabolic pathways, and genetic tools. Commercially it is feasible to perform the harvesting, primary culturing, and further downstream processing of diatom culture. Diatoms with their unique frustule structure, micro- to nanoscale properties, good thermal steadiness, proper surface area, surface functionalization procedures, and eco-friendliness have obtained a huge attention for their application in diverse topics of biotechnology and nanotechnology. In this chapter, an effort has been made to assemble the important development of diatoms in various industrial applications such as metabolite, feed, nutraceuticals, biofuel, pharmaceutical products, and nanostructure production.

Keywords Diatoms · Industrial application · Biofuel · Nanostructure · Metabolite

16.1 Introduction

The biggest challenge of today's world has paced up the scientific community's attention toward the arising issues related to resource limitations. The prime challenges of the world include, but are not limited to, clean water, energy, access to

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P. Srivastava et al. (eds.), *Insights into the World of Diatoms: From Essentials to Applications*, Plant Life and Environment Dynamics,
https://doi.org/10.1007/978-981-19-5920-2_16

affordable medicines, and healthy food. Recently, the International Conference on Key Engineering Materials 2020 researchers addressed the likely challenges in context to material science before the scientists from different areas of research. It was pointed out that innovations are required that rely on biomimetic to find a sustainable way for the production of structural and functional materials. The arguments pertaining to the economic meltdown, global health issues, and current environmental scenario favored the utilization of eco-friendly, renewable, and local resources. Optimistically, the forum promoted the idea that to counter the changing scenario of disrupted global demand and supply chain, such use of resources is inevitable (Kalyaev et al. 2020).

In this context, diatoms by the virtue of their worldwide distribution, a significant role in silicon and carbon recycling, a major share in the ocean's photosynthetic productivity is presumed to be a suitable alternative for today's crisis (Huang and Daboussi 2017; Yi et al. 2017). But conversely, diatoms are the least explored organisms for their utility, although average annual diatomaceous resource availability accounts for 132 MT dry diatoms/ha within approximately 5 years (Wang and Seibert 2017). Alongside, it is noteworthy that diatoms' share in the annual production of oxygen and organic carbon is approximately 20% and 40%, respectively (Treguer et al. 1995; Falkowski et al. 1998; Afgan et al. 2016). Diatoms constitute the rich diversity and dominating phytoplankton community possessing silica-built cell walls called frustules. Since the nineteenth century, this inherent capacity of silicon acquisition marked diatoms as an appealing microbial community (Sharma et al. 2021).

The electron microscopy and advanced genetic tools facilitated the research on frustule structure and confirmed the biochemical processes that constitute acquisition, transfer, and polymerization of silicon (Knight et al. 2016; Zulu et al. 2018). Moreover, this knowledge advancement in metabolic processes and elucidation of frustule structure could be a sustainable key to fabricating a vast range of commercial products, like biofuels, nutrient supplements, ecological tools, optoelectronics, etc. (Marella et al. 2020). Also, diatoms are capable to capture carbon and nitrogen released from different sources. This property could be utilized in waste management and the biofuel industries to generate fuels without carbon (Singh et al. 2017).

In the nutraceutical and pharma industries, diatoms can be explored to produce plant-based proteins, omega, and other important fatty acids (Wen and Chen 2001a, b). The industrial dependence for omega oils on the fishery sector could be reduced by replacing omega fatty acid diatoms. This will also decrease the issue pertaining to the biochemical composition of fish oil, which was arising due to the oceanic contamination and seasonal changes (Martins et al. 2013). The diatoms could also ease the commercial production of fucoxanthin and some other carotenoids, strong antioxidant pigments (Xia et al. 2013). Likewise, this multifaceted applicability of diatoms allows a colossal opportunity for sustainable development that could help to achieve carbon neutrality.

The structure of diatom frustules has provided enormous potential to build up various techniques and tools in biomedical industries (Mishra et al. 2017). The nanomaterials developed from diatom biosilica have major applications in the

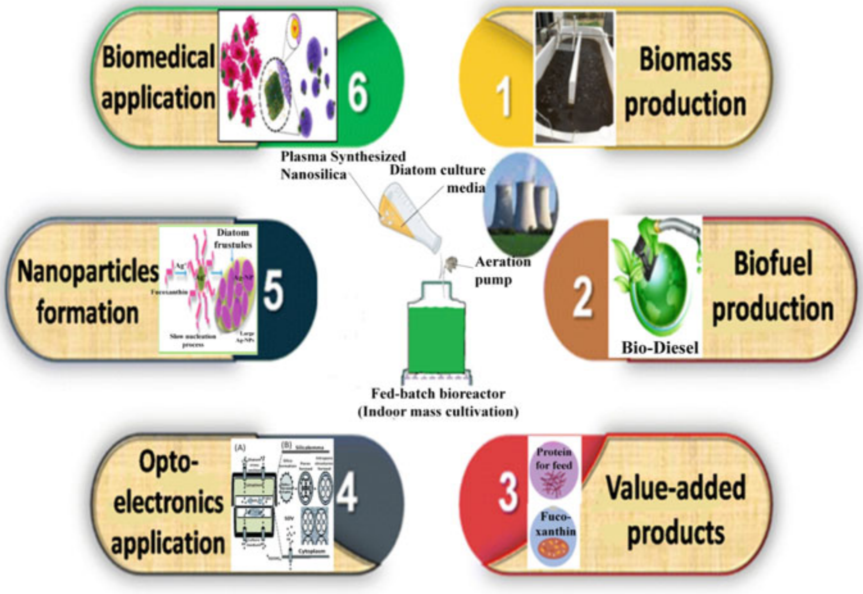

Fig. 16.1 Industrial applications of diatoms. (Modified after Hildebrand et al. 2012; Jayakumar et al. 2021; Popovich et al. 2020; Rabiee et al. 2021; Saxena et al. 2021)

recognition of highly sensitive compounds of biological origin by advanced optical and electronic techniques (Dolatabadi et al. 2011). In a new approach to diatom, metabarcoding has widened its applicability in exploring environmental issues such as algal blooms, acidification, and changing climate (Nanjappa et al. 2014).

In this context, this chapter intends to serve recent development in the potential use of diatoms in the industrial sector (Fig. 16.1). Herein, we attempted to produce inclusive knowledge on a diverse array of diatom applications for sustainable development. Indeed, the exploration of diatom's potential will significantly improve the steps progressing toward sustainable development. This will strengthen the economy along with decrease reliance on nonrenewable resources. Therefore, the need of the hour is to sustainably procure benefits and services from diatoms.

16.2 Industrial Applications

16.2.1 Biofuel Production

The advances in science and technology have created an era of industrialization and globalization. Although it has affected the environment largely, this is now an inevitable part of the human race. Industrialization is dependent on the transportation sector that runs approximately almost completely on nonrenewable energy sources (Rodrigue and Notteboom 2013). In this scenario, finding a sustainable carbon-neutral energy solution is the need of the hour. This will not only reduce the utilization of natural oils but will also shoulder the monitory development along with living in tune with nature. Consequently, in this context, biofuel generation via diatoms will serve as an optimistic solution due to its copious occurrence, cheap processing methods, and fast and handy growth (Wang and Seibert 2017). Diatoms in their vegetative growth phase produce oil food reserve till the arrival of a favorable condition. These oil contents of the oil glands produce more oil than many other oil seeds (Mishra et al. 2017). In comparison, oil yield in corn is 15 times less than that in diatoms; conversely, corn and maize occupy 66 times more land than diatom (Brocks et al. 2003). Also, it was reported that under stress condition diatom yields more oil (Ramachandra et al. 2009). They developed a modified diatom that secrete oil for daily oil extraction rather than oil storage and genetically modified diatom secretes gasoline without extra processing. Consecutively, substation of natural oil by diatom fuel may reduce greenhouse gases.

The cultures of diatom *Thalassiosira weissflogii* and *Cyclotella cryptic* under nitrogen starve condition enhance the lipid yield. Nitrogen deficiency works by affecting the de novo triacylglycerol synthesis and lipid remodeling. In *T. weissflogii* and *C. cryptic*, out of the total glycerolipids, approximately 82% and 88% are triacylglycerols, respectively. This accounts for suitability of diatoms for the large-scale production of biofuels (d'Ippolito et al. 2015), while diatom *Fragilaria capucina*'s ability to accumulate lipids to high level along with different temperature tolerance outstands its potential for biofuel production. Conversely, large industrial scale production is limited by the need for more optimized and improved protocols (Chaffin et al. 2012).

Additionally, high production of biodiesel could be achieved by transesterification of oil obtained from diatom *Nitzschia punctata*. This catalytic process is carried out by an enzyme lipase obtained from fungi *Cladosporium tenuissimum* (Saranya and Ramachandra 2020). In 2019, Popovich et al. reported the suitability of diatom *Navicula cincta* for biodiesel production along with the presence of value-addition compound, i.e., methyl palmitoleate formed by catalytic transesterification. The enhanced biodiesel yield of 81.47% from *Amphiprora* sp. was reported in the culture medium with 2% catalyst and methanol:oil::1.5:1 ratio at 65 °C for 3 h (Jayakumar et al. 2021). Table 16.1 mentioned few recent studies about different types of biofuel production using diatoms.

The study performed using cold-tolerant *Mayamaea* sp. JPCC CTDA0820 was reported to overcome the seasonal constraints for culture and growth (Matsumoto et al. 2017). This diatom was selected for culture in winter-like condition, i.e., at 10 ° C. Consequently, the combined culture of winter diatom *Mayamaea* sp. along with *Fistulifera solaris*, diatom from another season, in outdoor reactor showed consistent whole-year production of biofuel. Although the advances in technology endorsed diatom-based biofuel production, available statistics revealed the different constraints of the biosynthetic process. Therefore, mixed form of fuel, i.e., biodiesel along with petrodiesel, would be a suitable alternative. The relative research data of

Table 16.1 shows recently reported studies of biofuel yield by a variety of diatom species

Sl. no.	Diatom species	Type of biofuel	Yield	References
1.	*Navicula cincta*	Biodiesel	97.6%	Popovich et al. (2019)
2.	*Amphiprora* sp.	Biodiesel	81.47%	Jayakumar et al. (2021)
3.	*Staurosirella pinnata* and *Phaeodactylum tricornutum*	Biomethane (CH_4)	79.2 ± 5.9 and 239.4 ± 6.7 mL CH_4/g organic fraction, respectively	Savio et al. (2020)
4.	*Phaeodactylum tricornutum*	Biodiesel, bioethanol and biomethane	1.72, 0.35 and 1361 m^3/year of biodiesel, bioethanol, and biomethane, respectively	Branco-Vieira et al. (2020)

pure petrodiesel and mixed fuel (petrodiesel, 80%; diatom fuel, 20%) revealed no significant performance differences. Moreover, blended biofuel showed reduced carbon monoxide emission, unburnt hydrocarbons, and less smoke (Soni et al. 2020).

Furthermore, the production of biofuels has started the utilization of genetically modified diatoms by the companies like Synthetic Genomics and Algenol Biofuels (Sharma et al. 2021).

16.2.2 Metabolite Production

The potential use of diatoms for the synthesis of bioactive chemicals and compounds had already gained attention of the industries (Vinayak et al. 2015). The intracellular metabolites, like amino acids, necessary lipids, and eicosapentaenoic acid (EPA), are reported to be produced from cultured diatoms for cosmetic and pharma industries (Lebeau and Robert 2003; Hemaiswarya et al. 2011). Also, nutritional contents such as vitamins, vegetarian protein, antioxidants, and animal feed could be produced using diatoms (Sharma et al. 2021).

In addition, considerable quantity of nutrients for animal feed as well as human diet was obtained from extracts of *Nitzschia inconspicua*, *N. laevis*, *N. saprophila*, and *Phaeodactylum tricornutum* (Kitano et al. 1997; Wen and Chen 2001a, b; Wah et al. 2015; Tocher et al. 2019). The living diatoms could also serve as larval feed, such as *Thalassiosira* and *Chaetoceros* (Spolaore et al. 2006), while feeding material for bivalve mollusks could be diatoms like *Skeletonema costatum, Tetrasel missuecica*, *Isochrysis galbana*, *Pavlova lutheri*, and *Thalassiosira pseudonana* (Hemaiswarya et al. 2011). While in France, diatom *Odontella aurita* had been marketed as food in 2002 (Pulz and Gross 2004; Buono et al. 2014). Also in rats, it had shown antioxidant effects (Haimeur et al. 2012) and the haslenes or polyunsaturated sesterpene oils are reported to have anticancer properties (Lebeau and Robert 2003; Hildebrand et al. 2012).

The EPA, a potent agent to prevent heart and blood-related illnesses, was successfully produced in various photobioreactors using cultivated *Nitzschia laevis* and *Phaeodactylum tricornutum* (Lebeau et al. 2002). Interestingly, diatom's self-defense mechanism consists of an array of chemicals that confers protection against pathogens. For example, high quantities of palmitoleic acid, an omega-7 monounsaturated fatty acid, along with many other bioactive agents, are produced by *Phaeodactylum tricornutum* against gram-positive bacteria (Desbois et al. 2009).

The culture conditions' modification influences the metabolite production. In *Amphora* sp., report suggests that change in nutritional supplements and culture temperature had elevated the synthesis of polyphenol and flavonoid (Chtourou et al. 2015). In marine diatoms, the increased contents of primary and secondary metabolite along with growth promotion was achieved by inductively coupled plasma (ICP) nanosilica as catalyst in *Chaetoceros* sp. and *Thalassiosira* sp. (Saxena et al. 2021). Gerin et al. (2020) revealed the freshwater diatom's industrial significance in photoautotrophic batch cultures. Therein, high biomass culture of *Nitzschia palea* and *Sellaphora minima* improved yield of EPA and fucoxanthin.

Moreover, from the established eco-friendly and cheap bioprocess at the pre-pilot scale, it can be concluded that biomass production and metabolite compositions of a diatom are not fixed. However, the production of primary and secondary metabolites is influenced by species or strain, light, growth phase stage, temperature, nutrient media, the extraction process, different stresses, etc. (Ingebrigtsen et al. 2016; Popovich et al. 2020).

Ingebrigtsen et al. (2016) reported the variability in the production and chemical constituents of both secondary metabolites and biomass. Such differences were attributed to the variations in temperature, light, species, phases of growth, nutrient media, sample processing, and several other aspects. The only species of diatom that was proven to be promising in industrial application in eicosapentaenoic acid production and aquaculture is *P. tricornutum* (Hamilton et al. 2015; Huang and Daboussi 2017).

16.2.3 Diatom-Based Nanofabrication

The synthesis of nanoparticles via the physicochemical process for commercial utilization necessitates more time and energy, needs increased pressures and temperature, and subsequently released hazardous chemicals into the environment (Farjadian et al. 2019). Therefore, a quick, cheap, and eco-friendly way of synthesizing nanostructures is in need of time (Kiani et al. 2020, 2021; Tavakolizadeh et al. 2021). Thus, the mass production of nanoparticles could be achieved by diatom-based synthesis for a variety of applications. This diatom-based biological nanofabrication prevails over the complex process and reduces the cost of both issues, i.e., miniaturization and production enhancement for all industrial technologies. Such many advantages are witnessed in silica frustules of diatomaceous algae over recent technology (Korsunsky et al. 2020). Likely, a study on diatomaceous earth-derived silicon nanostructure used as anode for Li-ion battery showed enhanced performance of battery (Wang et al. 2012; Campbell et al. 2016; Cui et al. 2019).

The smallest species of diatom *Nanofrustulum shiloi* was reported to be a potent producer of triangular gold nanoparticles with tricationic gold solution within 72 h. This gold-decorated nanosilica could be visualized in imaging without labels by the virtue of its self-fluorescent property (Roychoudhury et al. 2021a, b). In another case, the study performed to decrease the reflection of electromagnetic radiation showed the utility of silicon nanoflake coating as antireflective material (Aggrey et al. 2020). The hybrid material like biosilica coated with polydopamine was proposed to add the silver nanoparticles on the silica surface. This is supposed to be applicable to biomedicine, bioelectronics, and more (Vona et al. 2018).

Ragni et al. (2018) explored the probability of easy synthesis of photonic nanostructures having tailored fluorophores in the frustules of diatom *Thalassiosira weissflogii* by feeding the algae with altered photoactive materials. At room temperature, the silver nanoparticles were used as sensing material to observe water-dissolved ammonia was synthesized by diatom *Navicula* species (Chetia et al. 2017). Interestingly, it was hypothesized that by the virtue of peptide embedding, diatom frustules can grasp the metal nanoparticles that could prove as highly efficient energy devices (Gupta et al. 2018).

In 2017, Borase et al. reported the synthesis of gold nanoparticles from *Nitzschia* diatom species. It showed higher antibacterial properties of the mixture of antibiotics (streptomycin and penicillin) with gold nanoparticles than the isolated antibiotics and gold nanoparticles. It was suggested that biofabrication of silver into nanoparticle silver is due to the Chlorophyll-c and fucoxanthin, a photosynthetic pigment (Mishra et al. 2020). Moreover, nanoparticles derived from *Skeletonema* sp., *Chaetoceros* sp., and *Thalassiosira* sp. are employed for the antipathogenic activities against some of the bacteria (Mishra et al. 2020).

Some other notable reports on the utility of diatom nanofabrication include photodegradation of pollutants in the visible spectrum by frustule with titania-deposition (Chetia et al. 2018), acetaldehyde abatement by titania nanoparticles from the species *Thalassiosira pseudonana* (Ouwehand et al. 2018), Si-ZrO_2 nanoporous complex from *Phaeodactylum tricornutum* as an electrochemical sensor for the detection of methyl parathion (Gannavarapu et al. 2019), and multifaceted applications of silver-silica hybrid nanoparticles derived from *Gedaniella* species applicable in biosensing, electronic device designing, medical field, etc. (Roychoudhury et al. 2021a, b).

16.2.4 Biomedical Industry

The estimated monitory requirement for drug development and release to the market is 2.6 billion dollars (DiMasi et al. 2016). To overcome the current system of drug design and delivery (Aw et al. 2011a, b), it is much necessary to conduct detailed studies on the applications of diatomaceous frustules along with other biological alternatives for utilization in biomedicine (Sharma et al. 2021).

The optimistic characteristics of ideal drug delivery tools, such as thermostability, adjustable surface chemistry, specific surface area, etc., are the key benefits offered by the frustules of diatom. The porous structures of diatom frustules show multiple patterns from nano- to micrometer (Chandrasekaran et al. 2014; Cicco et al. 2015; Ragni et al. 2017). These properties of diatoms make it worthy of exploring silica-based applications in biomedicine (Mishra et al. 2017; Terracciano et al. 2018).

Exploring the idea of the suitability of diatoms in biomedicines, *Coscinodiscus concinnus* and *Thalassiosira weissflogii* are reported to be excellent drug carriers owing to their morphology and amorphous nature (Aw et al. 2011a; Gnanamoorthy et al. 2014). Moreover, microcapsules from diatoms could be implanted or administered orally as an efficient carrier for water-soluble and poorly soluble drugs (Aw et al. 2011a; Ragni et al. 2017). An interesting development was reported by Losic et al. (2010), wherein an altered diatom surface with iron oxide dopamine modification was designed for a drug carrier guidance system using magnetic properties. This allowed the sustained discharge of inadequately soluble drugs for about 2 weeks. Additionally, anticancer drug delivery to tumor sites was possible due to genetically altered biosilica (Delalat et al. 2015). In another case, diatom surface activated by dopamine-altered iron oxide nanoparticles was used in tumor healing drug release (Medarevic et al. 2016). The improvement to this system was reported due to the use of biosilica-based drug encapsulation with optimized delivery features (Kabir et al. 2020).

The surface modification of diatoms and alternation applications have an array of possibilities in the biomedicine industries, such as biosilica-modified surface of *Chaetoceros* sp. using iron-oxide nanoparticles comprised of trastuzumab antibody, was used for differentiating normal and breast cancer cells (Esfandyari et al. 2020), detection of interleukin 8 in human blood using integrated gold nanoparticles into biosilica (Kaminska et al. 2017), on site and in vivo bone repair using biosilica, that is stable and well-suited for biological system (Rabiee et al. 2021), and controlling hemorrhage with chitosan-coated diatoms (Feng et al. 2016).

16.3 Conclusion and Future Perspectives

The evident studies reported the surprising possible applications of diatoms. The cheap and eco-friendly aspects of diatom's industrial applications are steps to augment human use of renewable resources for dipping carbon emissions. Even though the industrial utilization of diatoms still demands upgradation, it is certainly a decisive research field for human welfare. Furthermore, recent progression in sequencing and processing greater biological data has made it feasible to store the biodiversity of diatoms.

The chief lacking point in diatoms' industrial use is the maximization of the various aspects of biofabrication. Nevertheless, it is expected to conquer such lacunas in the coming future by genetic engineering techniques. Finally, to enhance the diatom-based industrial sector, shift from the current policies by the government and decreasing the gap between industries and academicians is the call of the hour.

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