Potential and Application of Diatoms for Industry-Specific Wastewater Treatment

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1 Introduction

The composition of the water body is greatly influenced by the anthropogenic activities in the vicinity. The nature of effluents entering the water body can be from diverse sources but can be broadly categorized as anthropogenic waste, agricultural waste, and industrial waste. The physical and chemical changes occur after the introduction of the pollutants into the water body, thereby contributing toward remarkable alterations in the structure of water body, severely affecting the aquatic flora and fauna. The intervention of myriad pollutants into the water system leads to the enhancement in the concentration of inorganic nutrients like phosphate, nitrate, ammonium, etc. triggering a sequence of consequences that adversely effects the entire inhabiting aquatic population (Thomas et al. 2016).

The nutrient accumulation enhances the algal growth due to which there is depletion of oxygen in the water and secretion of toxins and secondary metabolites, which might be fatal for the fish and other aquatic organisms. The nature of toxins varies from hepatotoxins, neurotoxins, dermatotoxins, etc. depending upon the nature of cyanobacteria (Tiwari and Pandey 2014). Often an obnoxious smell is observed in the surrounding area, and the water becomes unsuitable for consumption even for animals.

Diatoms are microscopic photosynthetic algae commonly classified under *Bacillariophyceae*, and they inhabit a wide range of aquatic niches. They are the integral part of the aquatic food web and constitute 40% of the primary producers

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(Thomas et al. 2015). Diatoms absorb the atmospheric carbon dioxide through photosynthesis and transform the carbon into carbohydrates, which I further utilized for the formation of different biomolecules (proteins, lipids, nucleic acids). Stimulated growth of diatoms in water body can aid in eradication of multiple problems related to the pollution of water by diverse sources. The occurrence of harmful algal blooms (HAB) is a common problematic condition evident in eutrophic water body, but copious diatom growth can result in nullifying or curbing the growth of cyanobacteria (blue-green algae) leading to the prevention in the formation of HAB.

Diatoms are the noteworthy algae in the phycoremediation of diverse wastewaters by virtue of their extraordinary cellular machinery. They are experts in utilizing of nitrate, phosphate, iron, copper, molybdenum, and silica; in addition, they are capable of remediation of heavy metals like lead, cadmium, chromium, copper, etc. Diatoms show high degree of flexibility in varied culture conditions that could be useful for their use in challenging conditions. Diatom algae can dominate under nutrient limiting and excess conditions. Diatom produced oxygen during photosynthesis which acts as stimulant for heterotrophic bacterial growth which in turn can enhance bacterial degradation and oxidation of organic pollutants and heavy metals. The remediation of wastewater is concomitant with its usage as source of macronutrients and macronutrients for growth of diatoms. The diatom biomass grown on the wastewater can be utilized for the generation of a range of value-added products like biofuels, nutraceuticals, antimicrobial substances, omega-3 fatty acids, and aqua feed to name a few applications of diatoms (Fig. 1). This approach is a sustainable solution of wastewater management as it is coupled with generation of useful products.

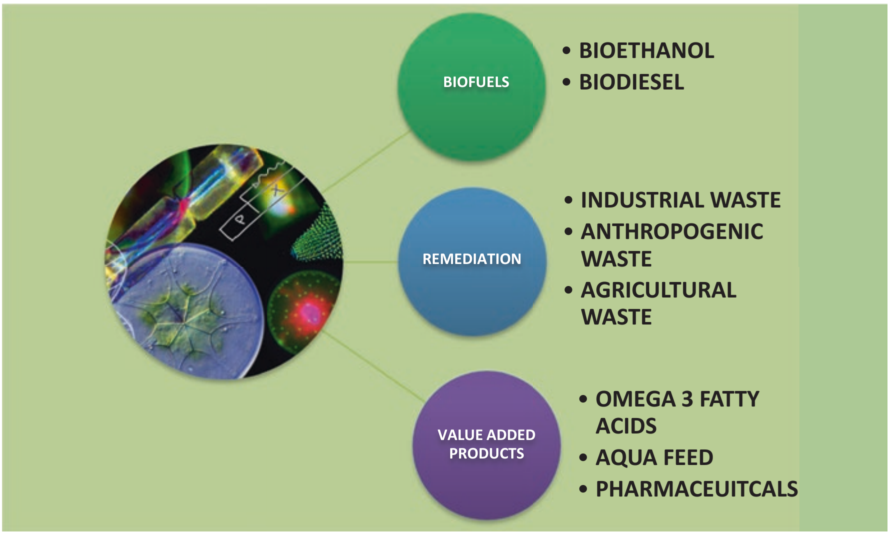

Fig. 1 Applications of diatoms

2 Physiological Advantages of Diatoms for Industrial Wastewater Treatment

Diatom algae play a significant role in controlling and biomonitoring of organic pollutants, heavy metals, hydrocarbons, PCBs, pesticides, etc. in aquatic ecosystems. Although diatoms are extensively studied for their role as indicators of different kinds of water pollution, their application in phycoremediation of polluted water bodies is in the incipient phase (Thomas et al. 2016).

Diatoms evolved dates back 180 million years, and at present, more than 100,000 species have been reported (Kroth 2007). They play a significant role in many of the earth's biogeochemical cycles like carbon, phosphate, and silicon (Falciatore and Bowler 2002). Diatoms are primary organisms in aquatic food webs. They form the basis of the most common and economically significant food web consisting of fish via copepods or to shell fish without any intermediate trophy level (Ryther 1969). They form these food webs in most productive regions and support many important economically important fish species. Diatom algae are ideal in size to be consumed by zooplankton (Ambler and Frost 1974); they also contain protein, carbohydrate, lipid, and vitamin; and they are known to be better diet than other algal species.

In coastal waters, diatom biomass contributes prominently to annual influx of organic material to benthos (Smetacek et al. 1984). Diatoms dominate under conditions optimum for phytoplankton growth like N, P, Si, and Fe concentrations (Hulburt 1990). Diatom dominance over other algae is often contributed to its silica frustules which gives protection from grazers (Hamm et al. 2003) and higher division rate (Smetacek 1999). This combination of ecological success and efficient transport of C to higher organisms can be the reason for diatoms being the base of the most productive ecosystems on the planet.

Diatom dominance in world's oceans was governed by silica availability, and distribution is due to their potential to utilize silicate for the construction of their cell walls called frustules. This makes them primary contributors for global silicon cycle. Producing silica cell walls needs less energy when compared with building with organic substances like cellulose; this gives an ecological advantage to diatoms over other algae (Raven 1983). So as long as silicate is present, diatoms will dominate other algae (Egge and Aksnes 1992). Diatom algae are main contributors to silicon pump which acts as a means for transport of silica and carbon to deep oceans (Dugdale and Wilkerson 1988). Diatom dominance in oceans altered the marine silica cycle (Racki and Cordey 2000). In modern oceans diatoms are dominant phytoplankton which utilizes N and SI and play a pivotal role in the biogeochemistry of aquatic ecosystems.

Diatom algae with their faster growth rate, nitrate uptake, and larger cell size results in faster sinking rate, so they contribute to export production (Buesseler 1998). These attributes enable diatoms to play a significant part in climate control (Traguer and Pondaven 2000). Optimum silica concentration in oceans has led to significant decrease in atmospheric pCO_2 by favoring diatom growth over coccolithophores (Archer 2006). The effect of silica-rich water in subtropics and beyond has led to diatom growth, thereby increasing the depth of organic matter remineralization; this has led to an estimated lowering of atmospheric PCO_2 by 60 ppm (Brzezinski et al. 2002). Carbon trapped inside silica frustules of diatoms acts as major components of carbon cycle on earth (Street-Perrott and Barker 2008). A silica body can sequester up to 50% of its weight of C (Elbaum et al. 2009). Diatom algae are used as indicators for climate change in lacustrine sediments due to their high temporal sensitivity, so they also act as indicators of temperature increase which is an early indication for climate change (Kilham et al. 1996).

Diatom nutrient uptake rate is significantly higher than any other group of algae (Litchman et al. 2006) and have been documented for their role in the initial uptake of nitrate at the equatorial upwelling zone of Pacific Ocean. The efficiency of nutrient uptake along with their higher growth rate makes them good candidates for nutrient accusation and transport. Diatoms are highly efficient in utilizing nutrients and are known to be responsible. This will have a significant impact on productivity and nutrient utilization. Due to their larger nutrient storage capacity, they can outcompete other algae in terms of productivity even in nutrient replete conditions. Amano et al. (2011) reported that in a eutrophic lake under low nitrate conditions, diatoms outcompete non-N-fixing cyanobacteria. Furnas (1990) reported that diatom doubling rates for both pennate and centric diatoms lie between two and four divisions per day, which is much more compared to any algae. Diatoms outcompete other phytoplankton under mixing and high turbulence (Tozzi et al. 2004). Diatoms possess higher carbon-fixing ability than other microalgae; this phenomenon is observed in both laboratory and field conditions (Thomas et al. 1978). Diatoms when compared with other algae grew better under low light conditions; this can be attributed to fucoxanthin, the major light harvesting pigment in diatoms which needs less light for saturation (Smetacek 1999). In a comparative analysis among *P. tricornutum* and *Chlorella vulgaris*, under light fluctuations, the light conversion proficiency into biomass was twice in diatoms. Diatoms store carbohydrate in the form of a chrysolaminarin (soluble form) instead of starch (insoluble form) like other algae. This gives them an advantage over other algae if we consider relative energy required to utilize soluble carbohydrate instead of insoluble carbohydrate (Libessart et al. 1995).

The presence of silica cell wall or frustule in diatoms is a unique characteristic, which not only acts as protective layer but also crowns advantageous dominance over other aquatic beings. Diatoms perform silica polymerization through an energy-efficient process even at low silica concentrations (Raven 1983). Silica cell wall plays a significant role in carbon-concentrating mechanism by acting as a pH buffer enabling enhanced carbonic anhydrase activity near diatom cell wall which results in bicarbonate to CO_2 conversion (Milligan and Morel 2002).

Diatoms with their efficient carbon fixing, nutrient utilization, and growth under varying nutrient, light, and turbulence are ideal candidates for co-processes like CO_2 sequestration and wastewater treatment. In spite of all these attributes, they are the least explored species in terms of research related to wastewater treatment and biomolecule production compared to green algae and cyanobacteria.

3 Factors Influencing Diatom Cultivation for Industrial Wastewater Treatment

The growth of algae is greatly influenced by multiple environmental factors like light, temperature, nutrients, carbon dioxide, and biological factors (Grobbelaar 2009). The utilization of wastewater for algal growth coupled with bioactive compounds requires the elucidation of factors that affect the growth and metabolism. Li et al. (2017a, b) have reported orthogonal test design for the diatom growth optimization, and it was reported that the lipid content was strongly influenced by the concentration of silica along with other factors. Elucidation of factors and their optimization can aid in better efficiency of the diatoms for wastewater management concomitant with several useful products for mankind (Fig. 2).

3.1 Light

Diatoms are photosynthetic in nature; hence, light has a profound influence on productivity. Diatoms are known to inhabit many diverse ecosystems with varying environmental conditions, making them one of the most adaptable to variations in the intensity of light, duration depending on latitude, season, and depth in order to keep growing and attain maximum productivity. In industrial wastewaters depending on the design of the treatment facility, drastic differences exist between light intensities available for algae to grow from high light in open oxidation ponds to low light in indoor effluent treatment ponds. The impact of light intensity (Falkowski and Raven 2007), relationship of light intensity and nutrient limitation (Sakshaug et al. 1989; Halsey and Jones 2015), and light fluctuations (Orefice et al. 2016) have been elucidated via competition models on diatoms (Litchman and Klausmeier 2001). In addition to the intensity of light, the growth is also effected by the dark

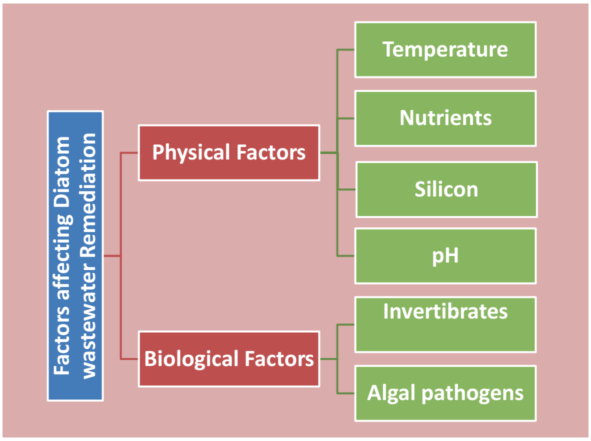

Fig. 2 Factors affecting diatom wastewater treatment

cycle. Other factors like night length, maximum irradiance, and spectral composition also influence diatom physiological response. The photosynthetic process in diatom photosynthesis comprises of intricate association with the chloroplasts and mitochondria (Bailleul et al. 2015). The cell size also plays an important role in growth of diatom at varying light intensity and photoperiods with larger cells favoring short photoperiods (Li et al. 2017a, b).

3.2 Silicon

The obtainability of silicon in wastewater is a major factor which defines diatom use for industrial wastewater treatment. Diatom metabolism and the role of silicon are quite conspicuous and perhaps account for their profound accomplishment due to their silica wall. The silicified diatom cell wall endows them additional potential and thus less energy requirement compared to other cellulose cell wall organisms. In the freshwater systems, the concentration of silicon is quite high and can sustain higher diatom productivity. This makes freshwater diatoms ideal candidates to treat fresh and brackish wastewater without the addition of silicon. In addition, many industrial wastewaters contain high amount of silica as it is used in majority of industries in a variety of production systems and in appliances, thereby making diatom-mediated remediation a good, effective, economic option coupled with other benefits associated with the further usage of residual diatom biomass (Thomas et al. 2018).

3.3 Carbon Dioxide

Diatoms can fix carbon dioxide from different sources like atmosphere and gases from industries (Wang et al. 2008). In nature diatoms are actively involved in the carbon dioxide assimilate from the air, and they can efficiently utilize substantially higher carbon dioxide levels (Bilanovic et al. 2009).

3.4 Other Nutrients

In addition to silicon diatoms also require other inorganic nutrients like nitrogen, phosphorus, etc. (Suh and Lee 2003). While cyanobacteria are capable of nitrogen fixation from the air, all other microalgae require it in a soluble form with urea being the best source (Hsieh and Wu 2009).

3.5 Temperature

The growth of diatoms in wastewater is greatly affected by temperature as it has a significant role in the enzymatic activities and thus metabolism. For optimum growth and remediation mediated by diatoms in wastewater, it is essential to sustain suitable temperature within constricted limits. In nature temperature variation exists on daily basis and on seasonal basis. During summer there exists huge variation in the temperature as early mornings are cooler followed by warmer climate in the daytime and then reduction in temperature at night.

In the open pond system of algal cultivation, variations in temperature are observed with change in seasons. The wastewater from various industries like cement industry not only enriches the inorganic carbons but also emits waste thermal energy, which can be utilized in open ponds in maintaining temperature particularly in cold climatic conditions. In fact the flue gas from the industrial wastewater should be cooled before entering into the wastewater cultivation system as too much of heat is not suitable for growth of diatoms (McGinn et al. 2011). The temperature has to be maintained at optimum levels to foster diatom growth, and hence effective remediation potential along with good biomass yields for valuable products (Fig. 3).

4 Cultivation Systems for Diatom-Based Industrial Wastewater Treatment

Excellent and efficient remediation of wastewater from different sources requires the systematic cultivation system for optimum removal of waste. In general the cultivation system meant for algae is open system consisting of variety of ponds or closed systems and modern hybrid systems (Fig. 4). The different cultivation systems have their own advantages and limitations. The open ponds are the simplest ways of algal cultivation under the influence of climatic conditions and controlled within limits. The closed systems require appropriate designing of photobioreactors, which can be expressive yet efficient. The hybrid systems culminate some features of open and closed system, and they are capable of attaining efficient nutrient removal from wastewater and production of biomass (Tiwari and Thomas 2018). The concept of exclusive algal cultivation began in 1950 for the application of algae as a source of protein (Brennan and Owende 2010). Later on the different algal products and most significantly wastewater treatment began to be explored. In algal cultivation systems have developed in due course of time through extensive research executed by phycologists around the world (Tan et al. 2018).

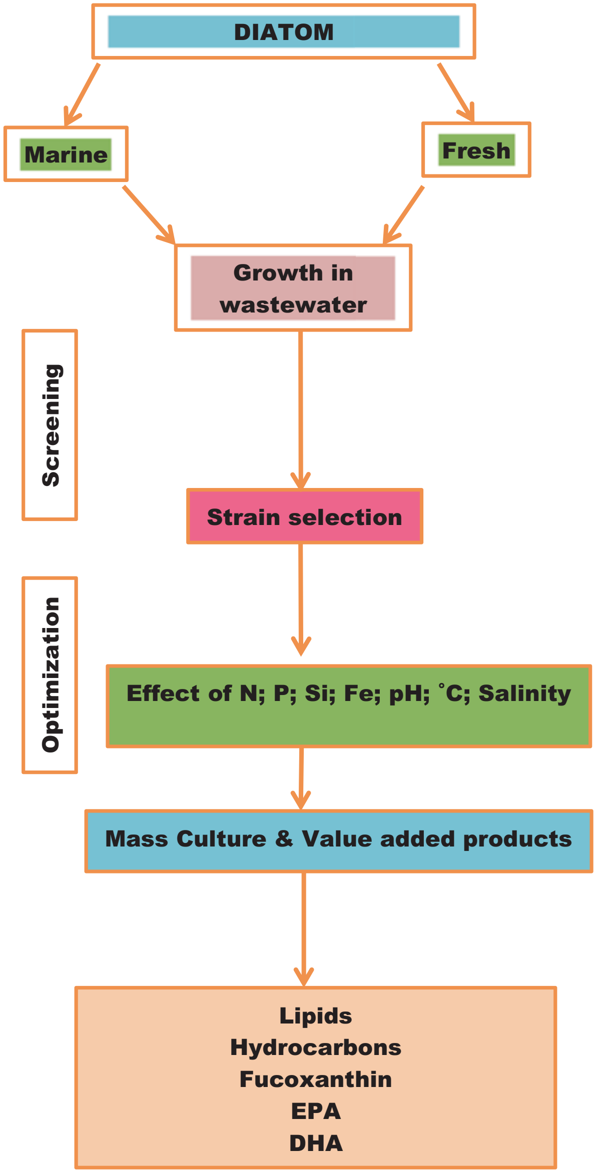

Fig. 3 Synergistic approach toward wastewater treatment

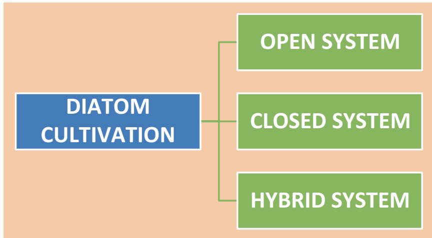

Fig. 4 Cultivation systems for remediation

4.1 Open Ponds

The open pond system has been extensively used for the cultivation of diverse algal species for wastewater remediation. Though it is an economical system of algal cultivation, there are certain constrains associated with open pond cultivation like the demand for land, climatic influence, and contaminants to name a few. The frequently used open systems include the raceway ponds, the inclined systems, circular tanks, shallow big pond, etc. In the inclined systems, the flow is in the inclined pattern to ensure the proper mixing of such systems has been reported to be successful in diatom cultures of *Phaeodactylum* and *Scenedesmus* (Fazal et al. 2018). Circular ponds are characterized by the centrally located agitator, which enables the adequate mixing of the cell suspension, and its efficiency is quite low in huge ponds.

The raceway ponds or the high-rate algal ponds (HRAP) are marked by the use of paddle wheel for uniform mixings and sedimentation prevention. These ponds are cost-effective and efficient in algal growth performance. The concept of high-rate algal ponds was conceived by Oswald and Golueke (1960), and later on, it was utilized globally in the treatment of municipal wastewater.

4.2 Closed Pond

The limitations of the open ponds are eradicated in the closed system to provide controlled culture conditions (temperature, pH, light, mixing) for optimum algal growth and suitable nutrient removal from wastewater. The photobioreactors used for algal cultivation includes:

- Tubular photobioreactors
- Vertical tank photobioreactors
- Horizontal tube photobioreactors
- Flat-plate photobioreactors
- Helical tube photobioreactors
- Airlift photobioreactors
- Vertical column photobioreactors

4.3 Hybrid Systems and Advanced Integrated Wastewater Ponds

The hybrid algal systems culminate the properties of both open and closed cultivation systems. Initially the algal culture is grown in the open pond, and later on, it is cultivated in the closed photobioreactor. The first open pond system cultivation induces nutrient stress on the algal culture which further leads to enhanced biomass and lipid productivity in the photobioreactor within the optimum set of culture conditions (Tiwari and Thomas 2018). The advanced integrated wastewater pond systems are well articulated for wastewater remediation, and it comprises of four integrated advanced ponds for rapid and effective remediation. The first pond is the facultative pond wherein the digester pit is located which flows the wastewater to the second pond called the HRAP, which eliminates the dissolved nutrients. The third pond is called the settling pond in which the sedimentations occur, and the last pond is the maturation pond which provides sunlight and sufficient oxygen (Sen et al. 2013) (Fig. 5).

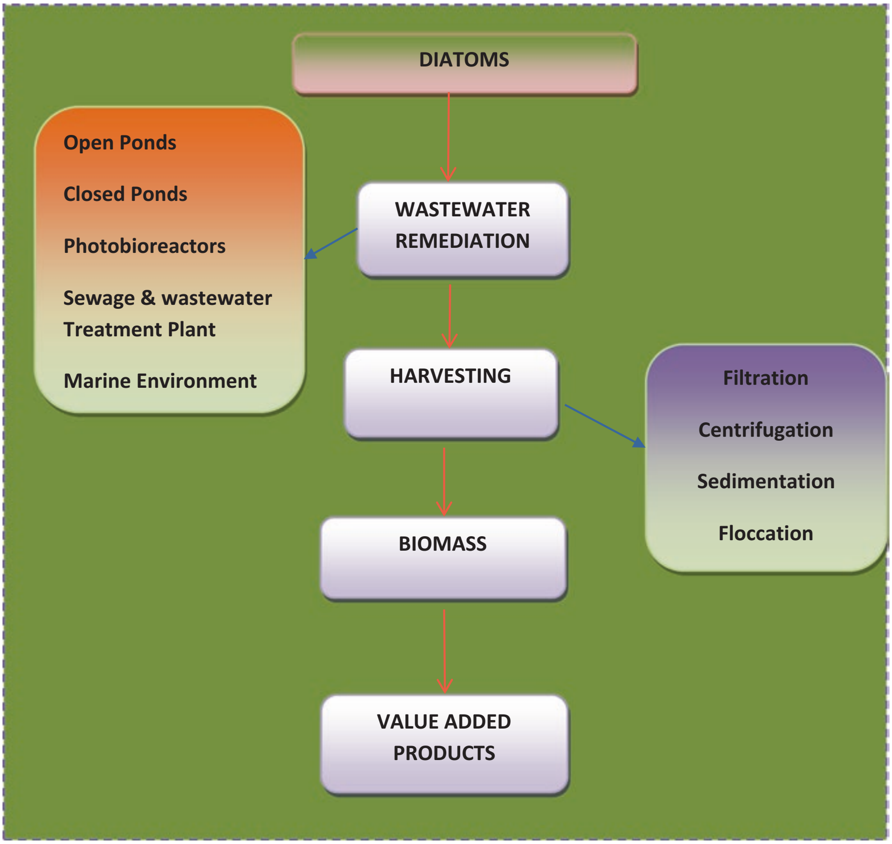

Fig. 5 Synergistic approaches toward wastewater remediation by diatoms

5 Integration of Diatom Cultivation with Industrial Wastewater Treatment

5.1 Municipal Wastewater

Municipal wastewater untreated, partially treated, and treated contains inorganic nutrients which when discharged into water bodies can lead to eutrophication. Due to rapid urbanization, many megacities are not able to treat even 50% of their domestic wastewater with their existing conventional sewage treatment infrastructure. For algae growth the main requirement is nutrients, and these are differentiated into major (C, N, P, Si) and micro nutrients (Ca, Mg, K, Fe, Mn, Cu, and Co). Any deficiency in nutrient availability can negatively affect algae growth in any type of wastewater. Depending on the strength, domestic wastewater contains 20–85 mg L^{-1} N and 4–15 mg L^{-1} P. This amount of N and P can produce 0.3–1.4 mg L^{-1} algal biomass, and micro nutrient concentration in any wastewater is always enough to sustain their growth as they are required in only trace amount (Christenson and Sims 2011). So domestic wastewater is ideal for grow microalgae. Taking this into consideration, many researchers used algae to treat wastewater from decades. In the 1960s, Oswald and Golueke (1960) proposed one of the first algae-based biological wastewater treatment system called advanced integrated wastewater pond systems (AIWPS). These systems work like present-day high-rate algae pond (HRAP) systems enabling fast growth of naturally occurring algae in paddle-wheeled ponds filled with wastewater. Subsequent research employed varied technologies like closed photobioreactors, HRAP, biofilm reactors, and raceway ponds. Of all the different microalgae species studied for their use in municipal wastewater treatment, the most studied species is green algae especially *Chlorella* sp. and *Scenedesmus* sp. followed by cyanobacteria. Compared to green and blue-green algae diatom, algae-related studies are very few. Thomas et al. (2018) studied effect of diatom growth on nutrient removal from municipal wastewater. In this study they triggered native diatom consortium in wastewater, and this resulted in 95% N, 88.9% P, 91% COD, and 51% BOD reduction in lab-scale experiments. Although many researchers prefer working with single species, working with consortium gives a distinctive advantage especially with diatoms; in diatom consortium, there are different species of diatoms which grow at different nutrient levels, so when we are treating wastewater in field-scale experiments, the inlet water nutrient strength always varies depending on factors like season, temperature, water usage, etc. To sustain this dynamic water chemistry and grow, we need robust multispecies cultures which can be possible only with diatoms. Nutrient dynamics always governs diatom species diversity in natural systems with certain species always favoring nutrient replete condition, while others prefer nutrient-depleted conditions, and this diversity and trophic flexibility of diatoms give them an edge over other algae when grown as consortium to treat wastewater. Untreated and partially municipal waste, wastewater is one of the main causes for eutrophication in urban lakes in developing countries. Traditional sewage treatment systems can remove nitrate but not phosphate due to their reliance on bacterial-based nutrient removal strategies. The main drawback with this system lies in the fact that very few phosphate-solubilizing bacteria present in these systems compared to denitrifying bacteria. This resulted in treated water with high phosphate content which is ideal for cyanobacterial growth leading to eutrophication. To counter this trend, proper system should be incorporated into existing sewage treatment infrastructure to simultaneously reduce N and P, using diatom consortium which can reduce nutrients rapidly and can create a nutrient equilibrium in treated water.

5.2 Dairy Wastewater

Dairy wastewater contains complex mix of inorganic nutrients in high concentration. One of the main challenges in treating livestock-derived wastewater is reduction of oxygen demand which can be quite high (2000–2500 mg/l for COD and 800 mg/l for BOD). It also contains high turbidity, total suspended solids (TSS), and dissolved nutrient like ammonia and phosphate. Majority of dairy waste which includes both solid and liquid is mostly treated using anaerobic digestion process, but the resultant effluent or liquid waste needs a special treatment for it to be fit to release into downstream. Improper treatment of these effluents can lead to a potential threat to watersheds, leading to eutrophication. Algae with their high nutrient assimilation rate combined with fast growth rates are extensively studied to treat dairy waste. Field-scale experiments and installations of algae-based technology for dairy effluent treatment were carried out using advanced oxidation ponds (Craggs et al. 2003) and algae scrubber technology (Mulbry and Wilkie 2001). Using a series of oxidation and settling ponds for wastewater treatment is a traditional technology used for many years which are cost-effective, but the treated water is often unsuitable for discharge due to partial treatment. Advanced pond system (APS) which is a modified version of traditional system with a series of oxidation ponds, settling ponds, high-rate ponds (HRP), and maturation ponds was successfully tested by Mulbry and coworkers to treat dairy effluents. They reported an improved effluent quality with APS with high BOD, TSS, ammonia, total phosphorus, nitrogen, and *Escherichia coli* removal. Using attached algae as a means of treating wastewaters was pioneered by Walter Adey (1989). Algae biofilm developed using attached substrate contains mainly benthic diatoms along with cyanobacteria. The algae biomass productivity in these scrubbers can reach up to 60 m^2 d^{-1} which is very high compared to other systems used for wastewater treatment. In many open pond systems, algae bacterial symbiosis remains the main mechanism for treatment. Benthic diatom and bacterial symbiosis are very strong in wastewater systems leading to maximum nutrient removal and oxygen production. Algae bacterial biofilms are highly productive leading to high assimilation and valorization of nutrient and heavy metals. Algal biomass generated using dairy effluents was tested as slow release fertilizer to vegetables and found that the growth of vegetables is same as commercial fertilizer when compared with algae fertilizer (Mulbry et al. 2005). Treating dairy effluents using microalgae is cost-effective using simple technologies like open ponds and algae biofilm scrubbers; the residual biomass can generate different value-added products ranging from biofuels to biofertilizers (Tiwari and Thomas 2016; Tiwari 2016).

5.3 Brewery Wastewater

Brewery industry generates huge amount of wastewater, although it is not very toxic in terms of heavy metals but it contains high inorganic nutrients and oxygen demand which need to be properly treated before discharge. Present treatment methods include employing anaerobic digestion using different bioreactors. Anaerobic process depends mainly on methanogenic bacteria, so it is slow time-consuming process, and it cannot remove inorganic nutrients. Biological treatment for brewery effluents was mainly confined to use of phytoremediation using macrophytes (Trivedy and Nakate 2000) and combination of macrophytes and green algae (Valderrama et al. 2002). Brewery wastewater typical N:P ratio which is critical for algae growth is 9 with total nitrogen concentration of 25–80 mg L^{-1} and phosphate at 10–50 mg L^{-1} (Basu 1975). Based on limiting nutrients, this N:P ratio can sustain theoretical algae biomass production of 42.8 g L^{-1} (Christenson and Sims 2011). In spite of the presence of nutrients required for algae growth in brewery wastewater, studies on their use are still limited. Mata et al. (2012) explored the use of green algae *Scenedesmus obliquus* for effluent treatment and reported 57.5% COD removal and 20.8% TN removal after 14 days of growth. Research articles on use of diatom algae for brewery wastewater treatment are nonexistent till now. But diatom algae have certain advantages which can make them good candidates for their use as bioremediation agents. Molasses wastewater a by-product of alcohol fermentation contains a brown pigment which hinders light penetration through the water column. This hindered light will negatively affect microalgae growth. Diatoms use fucoxanthin as the major light harvesting pigment which needs less light to reach saturation limit, so diatoms can grow even in low light. This gives them an advantage over other algae like green algae and cyanobacteria which need high irradiation as they use chlorophyll a and b as main light harvesting pigments. Diatom silica biogenesis performs more efficiently and pH 4–5 so diatoms can grow faster than other algae even at low pH wastewater from breweries. Diatoms due to their faster carbonic anhydrase activity can sequester more carbon from the atmosphere which results in higher oxygen production rate; this is ideal in reducing the huge oxygen demand of brewery wastewater. Benthic diatoms are the most productive algal community in wastewater ecosystems due to their symbiotic relationship with aerobic bacteria. This will help diatoms to survive harsh physicochemical conditions encountered in effluent treatment ponds. All these attributes makes diatoms one of the potential candidates for phycoremediation of brewery effluent treatment research.

5.4 Fish Farm Effluents

Aquaculture is one of the major industries supplying much needed nutrition to mankind. But due to excessive use of artificial food, chemicals, and antibiotics, the water after growing of cultured organisms becomes highly polluted. Indiscriminate discharge of these effluents can lead to severe pollution in downstream water bodies. Majority of the effluents from aquaculture industry which includes both production and postproduction operations contain high amount of inorganic nutrients which can be utilized by algae for their growth (Dosdat et al. 1996). Mass production of microalgae using these excess nutrients can be beneficial not only in terms of water treatment, but also the algal biomass generated can be used as high-quality nutritious supplement to aqua feed (Huntley 1995). In a study on treating fishing fish farm effluents using diatoms, Lefebvre et al. (1996) observed that nutrient addition especially silica to effluents increased diatom growth and thereby treatment efficiency with 90% nutrient removal rate in 3–5 days of outdoor culturing. Diatoms due to their ideal size and nutritional content are ideal for this purpose as they can be consumed easily by small fish, shrimp, and zooplankton. Diatoms due to their high growth rate coupled with their diversity in varied habitats can be grown using fish farm effluents. Due to their absolute requirement of silica for growth which is not the case with other algae groups, diatoms can be grown in open ponds by stimulating growth using silica dosing.

5.5 Heavy Metal and Other Pollutant Removal

Diatom algae produce oxygen during photosynthesis which acts as stimulant for heterotrophic bacterial growth which in turn can enhance bacterial degradation of organic pollutants (de Godos et al. 2010). Growth of benthic diatom *Nitzschia* sp. has resulted in enhanced aerobic bacterial activity in sediment layer which can lead to accelerated decomposition of organic matter (Yamamoto et al. 2008). Phthalate acid esters (PAEs) are commonly occurring priority pollutants and endocrine disruptors. Marine benthic diatom *Cylindrotheca closterium* has shown increased PAE removal rate in surface sediments. In bottom sediment it helped in the increase of aerobic bacterial growth by photosynthetic oxygen, thereby resulting in a combination of bacteria-diatom-dependent PAE removal. Diatom *Stephanodiscus minutulus* under optimum nutrient availability has shown increased uptake of PCB integer 2, 2′, 6, 6′- tetrachlorobiphenyl (Lynn et al. 2007). Poly-aromatic hydrocarbons (PAHs) phytoremediation has limited success rate due to their high toxicity, but diatoms *Skeletonema costatum* and *Nitzschia* sp. have shown accumulation and degradation of phenanthroline (PHE) and fluoranthene (PLA), two typical PAHs (Hong et al. 2008). Diatom algae produced O_2 that can help in bacterial degradation of PAHs and phenolic and organic solvents in benthic environments. Diatom *Amphora* *coffeaeformis* is known to accumulate herbicide mesotrione (Valiente Moro et al. 2012). The potential of diatom algae in biodegradation and accumulation of pollutants is enormous, but till date, little research is done in this field.

6 Diatoms Grown on Industrial Wastewater as Source of Biofuels and Nutraceuticals

Diatoms are capable of uptaking the organic and inorganic forms of carbon, nitrogen, and phosphorous accompanied by accumulation of trace elements from wastewaters and using them as a source of their growth (Li et al. 2017a, b; Xin et al. 2010; Hena et al. 2015). The growth of diatoms on the wastewater also produces good amount of biomass, which can be further processed into diverse useful components (Fig. 6) as they are great reservoirs of bioactive compounds like lipids, sterols, flavonoids, proteins, and pigments. The myriad of metabolites provide diatom robustness to act as antimicrobial, antioxidative, and therapeutic molecules in the treatment of diseases like HIV, Alzheimer, and cancer (Kuppusamy et al. 2017).

The algal biomass growing on the wastewater can find applications in the area of health food, good nutritive supplements, and also a live source of food for fishes, oysters, mollusks, mussels, and clams (Rico-Villa et al. 2008). They can also produce pigments like carotenoids, fucoxanthin, quinones, terpenes, and tocopherols (Hu et al. 2008). Diatom consortium grown on wastewater has been reported to produce biodiesel, EPA, and DHA and concluded that the silicon enriched consortium of economical for sustainable production of biodiesel and fatty acid growth on the wastewater (Thomas et al. 2018).

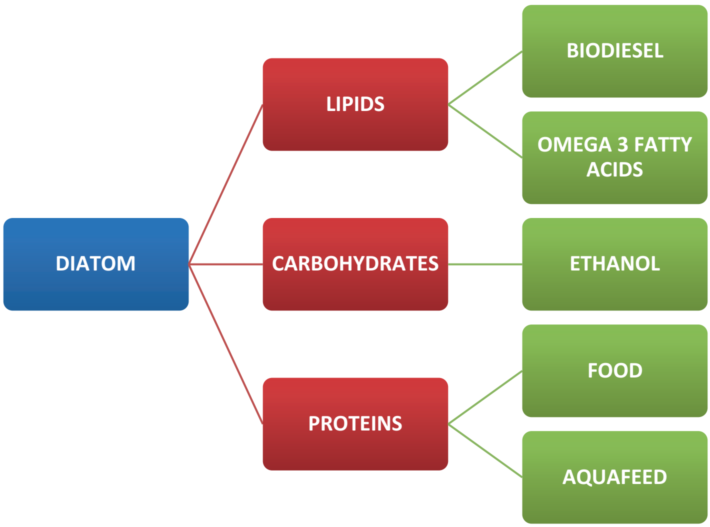

Fig. 6 Applications of diatom biomass

7 Conclusion

The efficiency of diatoms in remediation of wastewater is unparalleled and holds enormous scope in circumventing water pollution as an eco-friendly and sustainable option. More innovative approaches are indeed required to envisage novel diatoms and consortium for efficient and rapid waste remediation and biomass generation for other applications.

Diatom biorefinery approach can evoke a drastic beginning in the management of the wastewaters from different industries and simultaneous utilization of biomass for plethora of valuable products which find huge applications in the field of renewable biofuels, nutraceuticals, therapeutics, food industry, and cosmetics in the future.

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