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Chapter
[12]

Sustainable approaches towards wastewater treatment using algal technology along with management of post-harvest biomass

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Abstract

Industries like food processing, pulp, and paper, dairy, poultry, leather, etc. generate a huge amount of wastewater. The generated wastewater has a high toxicity in terms of BOD, COD, TDS, nutrients, heavy metals, carcinogenic pollutants, etc. The discharge of untreated wastewater into water bodies leads to their pollution and eutrophication, which gives rise to algal blooms and ultimately causes harm to the aquatic organisms. The wastewater generated from industries causes harm to many life forms therefore, its treatment before discharge has become an issue of concern. As wastewater contains enough amount of nutrients hence, can be used for algal growth. Algae are autotrophic organisms that require nutrients and sunlight for their growth. Algae provide sustainable means for wastewater treatment. Apart from wastewater treatment, algal biomass can be used in biofuels production, as biofertilizers, CO_2 sequestration, and for the production of value-added products. This book chapter deals with algae-based wastewater treatment along with various ways of algal biomass management and how algal biomass can be used as potential bioenergy material.

Keywords Algal biomass, Bioenergy, Value-added products, Wastewater treatment

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Introduction

The rapid industrialization around the world has created problems of contaminants and pollutants. Every day, huge amount of wastewater is being produced from different industrial processes globally (Bansal *et al*., 2018). Discharge of untreated wastewater poses threat to both ecological and human health. Earth has limited freshwater resources that are not being used judicially and either water is being wasted or polluted through waste disposal. Besides this, the increase in the world population has increased pressure on water resources (Wollmann *et al*., 2019). Shortage in the availability of freshwater for domestic and industrial purposes is a major challenge throughout the world which has raised the concern of developing appropriate wastewater treatment methods (Piao *et al*., 2016). Various processes can be used to clean wastewater like primary, secondary and tertiary treatment processes, phytoremediation/bioremediation, biosorption, etc. (Lema and Martinez, 2017; Kumar *et al*., 2020).

Besides all wastewater treatment methods, bioremediation is gaining much more popularity because of its environment-friendly aspect. Bioremediation involves the use of naturally occurring living organisms like algae, bacteria, and plants (aquatic and terrestrial) for removing hazardous pollutants from the environment (Kshirsagar, 2013). In the case of different aspects of bioremediation, the phycoremediation process is the most preferred method. Phycoremediation is the use of algal species for wastewater treatment and has numerous benefits over other conventional remediation techniques including, cost-effectiveness, eco-friendly, low input and maintenance costs, etc. (Wells *et al*., 2017). Industrial wastewaters contain a high load of organic and inorganic nutrients and therefore, can be used as a culture medium of algae (Simate *et al*., 2011). Algae are aquatic, eukaryotic organisms that can be microscopic or macroscopic, and cosmopolitan in the distribution in both fresh and marine environments. Algae have a fast growth rate, high lipid content when compared with terrestrial crops and do not compete for land with food crops and also helps in carbon sequestering (Gilbert and Ashraf, 2017).

The algal biomass generated after the phycoremediation has wide utility in the field of bioenergy. The population explosion has increased the energy demands of the world drastically. To meet the global energy demands fossil fuels are being used in direct or indirect ways. The excessive combustion of fossil fuels causes many negative impacts on the environment such as global warming, emission of greenhouse gases, air pollution, acid rain, change in global weather patterns, etc. (Alatraktchi *et al*., 2014; Lee *et al*., 2008). As fossil fuels are non-renewable energy sources and are near about their depletion. There is an urgent need to find environmental friendly alternatives to current energy resources (Mathimani *et al*., 2015; Subsamran *et al*., 2018). There is a wide variety of renewable and sustainable energy resources like solar energy, biomass, wind energy, hydroelectricity, tidal energy, etc. that can generate clean energy but are less energy-efficient sources (Kabir *et al*., 2018). Biomass includes organic material such as aquatic plants, algal biomass, agricultural residues, animal, poultry, food processing, leather industry, municipal solid wastes, etc. (Alam *et al*., 2015; Maity *et al*., 2014; Sims *et al*., 2010). Out of them, algae are rich in carbohydrates, lipids, proteins, pigments, and act as a good source to produce value-added products, like biodiesel, bioethanol, biogas, biochar, biohydrogen, biobutanol, etc. (Jones and Mayfield, 2012). The exploration of the utilization of algae for the reclamation of a damaged environment presents one of the best methods of its conservation. Keeping in view, this book chapter deals with the integrated approach of wastewater treatment using algae along with different possible methods of their biomass management.

Algal wastewater treatment

Wastewater refers to liquid wastes generated after a final product is obtained from households, commercial complexes, workshops, and industries like dairy, food processing, textile, leather, pharmaceutical, etc. Wastewater has high pollutant loads (Simate *et al*., 2011) and the direct discharge of untreated wastewater in water bodies is creating lots of environmental issues especially, water pollution (Cai *et al*., 2013). Due to its nutrient richness wastewater are often used for growing algae. Algal species are capable of utilizing nutrients from wastewater for its growth and development, therefore, has immense potential for treating wastewater (Bansal *et al*., 2018). Nowadays, most industries are adopting algal-based wastewater treatment because it is a cost-efficient and eco-friendly technique. Some of the algal species being used in wastewater treatment (Figure 1).

Table 1 shows the various studies on the treatment of different pollutants from wastewaters using various algal species. Recently, numerous studies have been done for the reclamation of different types of wastewaters. Out of them, Valizadeh and Davarpanah (2020) in their parametric study on dairy wastewater treatment using *Chlorella vulgaris* obtained 42.57% of COD removal efficiency. Gaughy *et al*. (2019) through their study on the treatment of wastewater produced from hydrothermally treated septage using *Chlorella* sp. attained 98 % of ammonia and 50 % of other nutrient removal efficiencies. In another study by Fazal *et al*. (2017), the potential of various microalgal species for the bioremediation of textile wastewater was assessed. They reported that the microalgae use dyes as a carbon source which are further converted into metabolites, besides other processes microalgal wastewater treatment turned out to be most promising for the treatment of textile wastewater. Another study conducted by Kshirsagar (2013) on bioremediation of domestic wastewater using *C. vulgaris* and *S. quadricauda* showed a significant reduction in BOD, COD, nitrates, and phosphates. In a case study conducted by Posadas *et al*. (2014) on a fish farm and domestic wastewater treatment using algal ponds it was found that a significant amount of nitrogen (>70%) and phosphate (>80%) removal was achieved.

Furthermore, Higgins *et al*. (2018) conducted a study on winery wastewater using *Auxenochlorella protothecoides* and *Chlorella sorokiniana* which attained more than 90 % of nitrogen, greater than 50 % of phosphate, and 100 % of acetic acid removal. Wang *et al*. (2010) cultivated *Chorella* sp. on municipal

Table 1. Use of different algal species for the treatment of different pollutants from wastewaters.

Wastewater	Pollutants	Algal species	Removal achieved	Reference
Municipal wastewater	Phosphorus and COD	*Chlorella* sp.	83.2 % - 90.6 % phosphorus and 50.9 - 83.0 % COD removed	Wang *et al.* (2010)
Piggery wastewater	TN,TP and COD	*Chlorella zofingiensis*	68.96 % to 81.03 % total nitrogen, 98.17 % to 100 % total phosphorous, and 65.81 % to 79.84 % COD removed	Zhu *et al.* (2013)
Primary-settled wastewater	Biological pollutants	*Galdieria sulphuraria*	98 % removal of total bacteria and complete removal of *Enterococcus faecalis* and *Escherichia coli*	Delanka-Pedige *et al*. (2019)
Domestic wastewater	TN, TP and COD	Algal biofilm	TN, TP and COD removal reached 96.0 %, 91.5 % and 80.2 % respectively	Yang *et al.* (2018)
Winery wastewater	TN, TP, and acetic acid	*Auxenochlorella protothecoides* and *Chlorella sorokiniana*	> 90 % of nitrogen, > 50 % of phosphate, and 100 % of acetic acid removed	Higgins *et al.* (2018)
Secondarily treated domestic wastewater	Ciprofloxacin	Mixed	> 84 ± 9% removal	Hom-Diaz *et al.* (2017)
Dairy wastewater	COD	*C. vulgaris*	42.57 % COD removed	Valizadeh and Davarpanah (2020)
Textile wastewater	COD	*Chlorella vulgaris*	70 % COD removed	El-Kassas and Mohammad (2014)
Fish farming wastewater	N and P	Microalgal consortia	83 ± 10 % of nitrogen and 94 ± 6% of phosphates removed	Posadas *et al.* (2014)
Urban wastewater	N and P	*Nannochloropsis oculata*	95 % of nitrogen and 98% phoshorous removed	Caporgno *et al*. (2015)

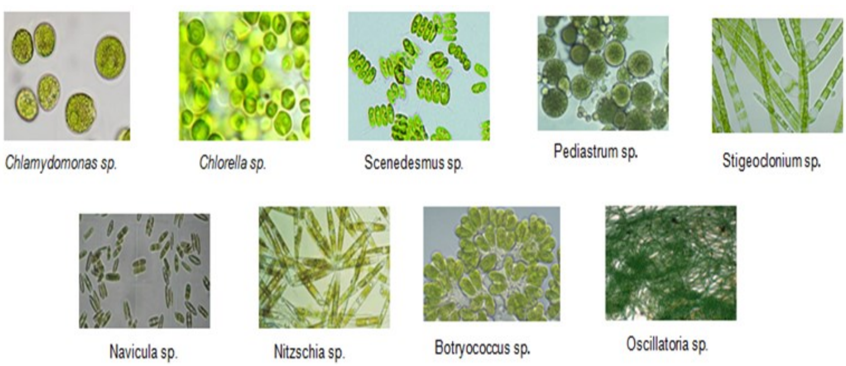

Figure 1. Some of the algal species being used in wastewater treatment.

wastewater for pollutant removal and achieved 83.2 % to 90.6 % phosphorus removal and 50.9 % to 83.0 % COD reduction.

Post-harvest management of algal biomass

The algal biomass harvested after the wastewater treatment process can be utilized in different ways (Figure 2). For example, algal biomass can be used to serve the purpose of biofertilizers, biofuels, biochar, etc. Moreover, various food products like nutraceuticals, protein animal feed, and various nutrient supplements can also be produced from waste algal biomass (Mathimani and Pugazhendhi, 2018).

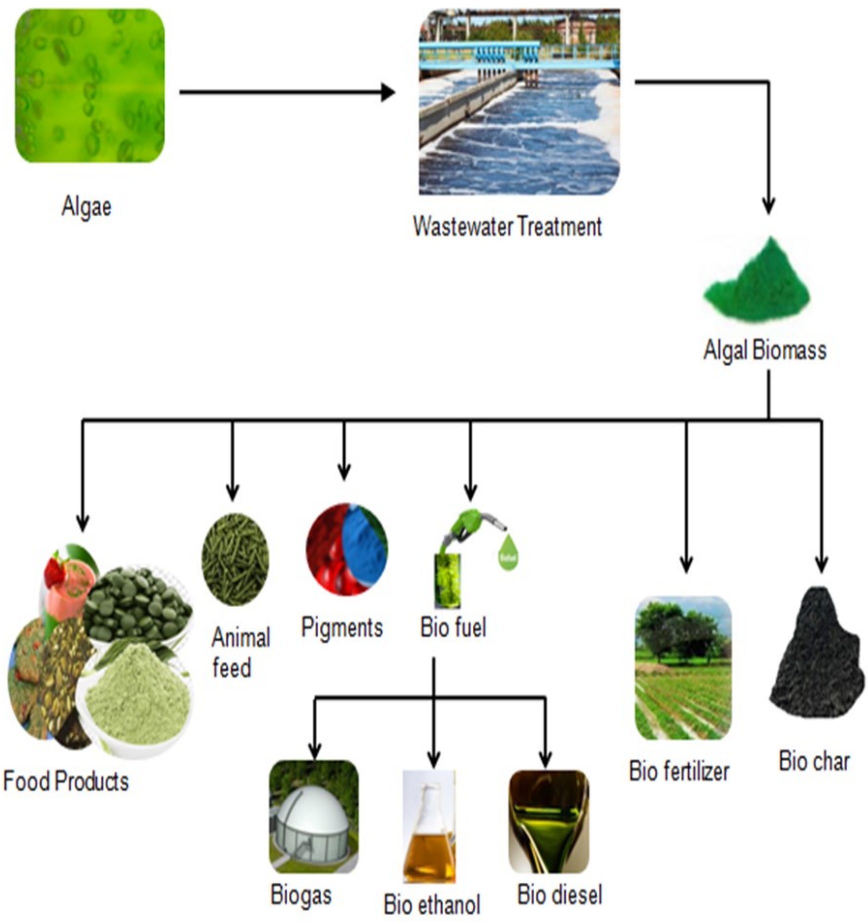

Figure 2. Different methods of algal biomass management.

Biofuels

Biofuels are produced from organic or biological wastes like lignocellulosic residues from agricultural, commercial, domestic, and industrial wastes. Biofuels are eco-friendly and pollution-free energy sources, moreover, it helps in reducing net carbon emission (Saad *et al*., 2019). Algal biomass is also a kind of organic waste and can be used to produce bioethanol, biodiesel, biogas, etc. Several countries like Brazil, Germany, United States, Sweden, and France are the leader in the production and consumption of these biofuels (Adeniyi *et al*., 2018).

***Bioethanol*:** Algal biomass can also be used to obtain bioethanol through the alcoholic fermentation of carbohydrates. Moreover, algal cellulose and hemicellulose can also be used to obtain bioethanol by converting them to sugars through various pretreatment processes. Fermentation is the conversion of sugars into bioethanol (C_2H_5OH). Bioethanol is a high octane fuel, and therefore, can be used as a petrol substitute or blended (10% to 20%) with commercial petrol in transport vehicles (Saad *et al*., 2019). In a study, Johan *et al*. (2010) reported the potential of various micro and macroalgal species for bioethanol production using different methods. Another study carried by Jalilian *et al*. (2019) on biofuel production indicated that *Chlorella vulgaris* FSP-E can be used as a potential feedstock for the production of bioethanol.

Biodiesel: Biodiesel is a kind of diesel fuel derived from a variety of lipid-containing feedstocks like oil crops (castor, sunflower), food crops (corn, soybean), algae, etc. Using food and oil crops for biodiesel production can lead to food security issues. High lipid content makes algal oil the most suitable feed-stock for biodiesel production (Rajkumar *et al*., 2014). Biodiesel is produced by the trans-esterification of algal bio-oil and can be used as vehicular fuel in pure form or as diesel additive. Marella *et al*. (2019) through their study showed the biodiesel production potential of algae cultivated on urban wastewater. A study carried by Caporgno *et al*. (2015) on the cultivation of microalgae *C. kessleri* and *C. vulgaria* in urban wastewater for biodiesel and methane production shows biodiesel yield of 7.4 ± 0.2 g/100 g_{vs} and 11.3 ± 0.1 g/100g_{vs} for *C. kessleri and C. vulgaria*, respectively. Furthermore, Mata *et al*. (2009), Gill (2013), and Jayakumar *et al*. (2017) also studied biodiesel production from various feedstocks (Table 2).

***Biogas*:** The wet algal biomass left after wastewater treatment can be converted into biogas. However, algal biomass has low digestion potential and the addition of activated sludge can help to increase the digestion rate (Dębowski *et al*., 2013). Organic matter of algal biomass breaks down through anaerobic digestion to produce CH_4 and CO_2 which are the main constituents of biogas. The biogas produced from algal biomass can be used for generating power by gas engines as well as an energy source for domestic cooking (Gilbert and Ashraf, 2017). Shchegolkova *et al*. (2018) conducted a study using microalgae for wastewater treatment and biogas production in which significant results were obtained and the biogas produced was composed of 57.0–59.7 % methane and 40.3–43.0 % carbon dioxide. Another study by Xiao *et al*. (2019) on biogas production from microalgal biomass via anaerobic

Table 2. Biodiesel production from various feedstocks (Source: Mata *et al*., 2009; Gill, 2013; Jayakumar *et al*., 2017).

Name of crop	Oil yield (L/ha)	Biodiesel production (kg biodiesel/ha-year)
Corn	172	152
Soybean	446	562
Canola	1190	862
Sunflower	1070	946
Palm Oil	5366	4747
Jatropha	741	656
Castor	1307	1156
Microalgae (wet biomass)	58,700	51,927
Microalgae (Dry biomass)	136,900	121,104

digestion showed that the highest exergy efficiency (40.85 %) was achieved by solar-driven hydrothermal pretreatment followed by biogas production with hydrothermal pretreatment (35.98 %) and without pretreatment (26.2 %).

Biofertilizers

Microorganisms, like, bacteria, fungi, and algae that are capable of degrading organic wastes and complex nutrients to simpler forms, and this final product can be used to enhance soil quality, nutrient transfer, crop growth, and yield which are known as biofertilizers. Algal biomass can also be used as biofertilizers. Blue-green algae are the most commonly used algal group as biofertilizers. Biofertilizers helps in promoting sustainable and organic farming (Castro *et al*., 2020). In a study conducted by Garcia -Gonzalez and Sommerfeld (2016), the authors investigated the use of *Acutodesmus dimorphus* extract as a foliar spray application at 3.75 g/L for tomato plant resulted in improved plant height, increase in flowering rate, and branches per plant. The *Acutodesmus dimorphus* extract can be employed as a seed primer at 0.75 gM/L as it triggered faster seed germination. Ronga *et al*. (2019) through their study on various microalgal species established the potential of microalgae as a biostimulant and biofertilizer for improving crop productivity and contributing towards agricultural sustainability and reduced environmental impact. Some of the algal species being used as biofertilizers are given in Table 3.

Biochar

Biochar is a dark-colored carbon-rich organic substance obtained from the pyrolysis of waste biomass. Biochar can be used as a soil conditioner as it improves soil pH, increases soil carbon and nitrogen exchange rates, and therefore, helps in increasing crop yields (Rizwan *et al*., 2018). Moreover, biochar can be used as an adsorbent for various treatment processes, as an energy source for the generation of heat and power, and as a carbon sequestration agent (Amin *et al*., 2016). Algal biomass is an ideal waste for the production of biochar as revealed from recent studies. Yu *et al*. (2018) from their study on biochar production from *Chlorella vulgaris* FSP-E suggested that the biochar yield obtained was 21.55

Table 3. Contribution of various algal species used as biofertilizers (Source: Castro *et al*., 2020)

Algal class	Name of species	Contribution
Blue-green algae	*Nostoc, Anabaena, Aulosira, Tolypothrix, Nodularia, Cylindrospermum, Scytonema, Aphanothece, Calothrix, Anabaenopsis, Mastigocladus.*	Produce growth-promoting substances
Red macroalgae	*Phymatolithon calcareum,Lithothamnion corallioides*	Trace elements
Brown macroalgae	*Laminaria digitata, Saccharina latissi-ma ,Fucus vesiculosus ,Ascophyllum nodosum,Ecklonia maxima,*	Rich in N P, K, Carbohydrates, enhance plant growth, drought and salt tolerance and resistance to fungi, bacteria, and virus.

wt% to 38.4 wt% The microalgal biochar showed an HHV of 23.42 MJ/kg and can be used as an alternative to coal for energy production. Through their study on biochar produced from microalgae, *C. vulgaris* Arun *et al*. (2018) showed the potential of algal biochar as a source for the removal of pollutants from wastewater. In another study, Torri *et al*. (2011) indicated that about 44 ± 1 % biochar and 28 ± 2 % biofuel were obtained from the pyrolysis of the biomass of microalgae *Chlamydomonas reinhardtii*, and also the obtained biochar was rich in nitrogen content.

Animal feeds

Due to their high protein, carbohydrate, and oil contents, algae are being used as feed for cows, pigs, cats, dogs, poultry, as well as in fish farming. Using algal nutrition even in small amounts results in an improved immune system, increases egg-laying capacity, growth promotion, and also improves reproductive performance (Madeira *et al*., 2017). Altomonte *et al*. (2018) in their study investigated the use of microalgae in ruminant nutrition and concluded that the use of an appropriate amount of microalgae in animal feed can improve omega 3 content in the milk of ruminants. In another study, Shah *et al*. (2018) explored the potential of microalgae in aquafeed as a supplement or feed additives as algae are a rich source of protein, lipid, pigments, vitamins, etc. Also, the presence of EPA and DHA in microalgae increases the significance of microalgae for its use in aquafeed.

Food products and other supplements

Algae are a rich source of proteins, vitamins, minerals, polyunsaturated fatty acids, antioxidants, etc., therefore, can be used in making health drinks, cookies/biscuits, protein bars, as thickening agents in ice-creams, marmalade, jellies, etc. (Piwowar and Harasym, 2020). Nowadays, various food supplements are being prepared from microalgal biomass. For example, a protein supplement is available in the market in the form of capsules, tablets, and powder which is derived from microalgae

Spirulina (Kovač *et al*., 2013). In their study by Ścieszka and Klewicka (2018), the potential of algae in the food industry in food supplements *like* dietary supplements and as additives in food products like in marmalade, dairy products, cereal-based products due to their enriched protein, lipid, pigment, vitamin, carbohydrate contents have been reported. Torres-Tiji *et al*. (2020) from their study suggested that algae have the potential to become a new food crop and with the implementation of the newest genetic engineering tools algae can efficiently meet the world's food and feed demand shortly.

Pigment extraction

Pigments like chlorophylls, carotenoids, and phycobiliproteins, etc. are responsible for giving beautiful colors to different algal species (Prasanna *et al*., 2007). Various applications of different algal pigments are given in Table 4. Being non-toxic and eco-friendly, pigments from some algal species can be used for a variety of purposes like natural coloring agent for food products (chewing gum, ice creams, soft drinks, desserts, cakes, milkshakes, etc.) (Suganya *et al*., 2016). In the pharmaceutical industry, these pigments are widely used as antioxidants, anti-inflammatory, anti-cancer, and anti-allergic materials (Chew *et al*., 2017). In the cosmetics industry, these pigments are used for giving color to soaps, skin, and hair care products due to their antiageing properties (Wang *et al*., 2015). Besides this, they can also be used in the textile industry as fabricating and dyeing agents. Huangfu *et al*. (2013) suggested that astaxanthin pigment obtained from alga *Haematococcus pluvialis* can extend the life span of fruit flies by complementing with the defective antioxidant defense system of fruit flies. Chakdhar and Pabbi (2017) in their study showed the importance of various algal pigments for improving human health as well as the commercial importance of algal pigments for the cosmetic industry.

Future scope and research recommendations

Algal species are rich in various colored pigments that are being used in various food products, cosmetics, and medicines but still there is much more in the field of algal pigments, the full potential of algal biomass concerning algal pigment is yet to be explored. Although algal biomass is widely being used for the production of biogas the complete biogas production potential of algal biomass has still not

Table 4. Applications of various algal pigments (Source: Li *et al*., 2019).

Algae	Pigment	Applications
Mutants of Dunaliella	Lutein	Food colorant, antioxidant
Dunaliella sp.	Carotenoids	Food colorant, pro vitamin-A, bioactive compound
Chorella, Spirulina	Chlorophyll	Cosmetics , antioxidant
Haematococcus sp.	Astaxanthin	Cosmetics, food colorant
Spirulina sp.	Phycocyanin	Diagnostic agent, bioactive compound (anti cancer), cosmetics
Porphyridium purpureum	Phycoerythrin	Cosmetics, food colorant

reached its full potential, the addition of suitable microorganisms can improve the biogas production potential of algal biomass. Phycoremediation has emerged as the most promising technique of wastewater treatment but genetic engineering can be applied to phycoremediation to improve its remediation efficiency. Algal biomass can be used in the synthesis of metal oxide nanoparticles which can provide an eco-friendly alternative to the toxic chemicals which are commonly used in the synthesis of metal oxide nanoparticles. Hybrid cultivation of algal biomass can be adapted which includes both open and closed pond systems as it can produce high biomass along with a reduction in contamination. The microalgae can be cultivated in membrane photobioreactors, it can reduce the requirement of dewatering. Besides this more exploration of potential of algal species can be done.

Conclusion

The discharge of untreated industrial wastewater causes serious environmental problems such as soil and water pollution. However, industrial wastewaters are rich in several nutrients so, can be used to grow algae. Therefore, algal species have great potential in wastewater treatment. Thus, this book chapter emphasizes the role of algal biomass after phycoremediation of wastewater, can be used as a good resource for bioenergy production and other value-added products. Algal based wastewater treatment is an eco-friendly and cost-efficient approach and serves dual approaches of environmental sustainability.

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