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REVIEW ARTICLE

Algal-based biofuel generation through flue gas and wastewater utilization: a sustainable prospective approach

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Abstract

Increasing concern towards climate change and water conservation has attracted wide attention of researchers to explore the biological carbon fixation and wastewater treatment by using microalgae. Algal biomass can be harvested in an integrated system provided with carbon dioxide from power plants and wastewater released from industrial and domestic sector. In this way simultaneous potential of microalgae can be utilized for simultaneous fixation of CO_2 and wastewater treatment. This article present a critical review focusing on challenges in algal biomass production technologies and how to achieve algal biofuel production in an integrated system of CO_2 fixation and wastewater treatment by suitable microalgal species. In view of these objectives, this article provides a comprehensive narration about the following: (a) perspectives of carbon uptake by algal biomass; (b) industrial emissions as a CO_2 supplement for algal cultivation; (c) water foot print for algal cultivation; and (d) genomics for improvement of algal biofuel production. This review found that technical feasibility, economic viability, and resource sustainability are the key steps for algal biofuel production that can be achieved through flue gas and wastewater nexus in algal cultivation. It also provides salient features of algae-nutrient-wastewater-flue gas dynamics to measure the influences of flue gas and wastewater on algal biomass productivity.

Keywords Wastewater · Flue gas · Water footprinting · Algal-nutrient-wastewater-flue gas dynamics (ANWFD)

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Abbreviations

GHGs	Greenhouse gases
WFP	Water footprint
GWN	Green water networking
CCS	Carbon capture and storage
EEE	Enhance energy efficiency
CCT	Clean coal technologies
CCM	Carbon capture mechanism
GWFP	Green water footprint
BWFP	Blue water footprint
G_yWFP	Gray water footprint
DWD	Direct water demand
WSG	Water to support growth
AP	Annual precipitation
PAR	Photosynthetically active radiation
WN	Water network
GWN	Green water network
GWNS	Green water network synthesis
COD	Chemical oxygen demand
AND	Algal nutrient dynamics

ANWFD	Algae-nutrient-wastewater-flue gas dynamics
FAEE	Fatty acid ethyl ester
DMB	Dry microalgal biomass
PUFAs	Polyunsaturated fatty acids

1 Introduction

Rapid population growth and increasing living standards of people have caused rapid consumption of natural resources like forest, petroleum, water, etc. Municipal, agricultural, industrial, transportation, and infrastructure sectors cause high level of water and air pollution. Similarly, cultivation of crops to produce food and energy also use a substantial amount of fresh water, which reduces the economic viability of conventional biomasses for various end products. Thus, reclamation of wastewater (municipal and industrial) and nutrient recycling are issues of paramount importance to gain sustainability. A conventional wastewater treatment system does not recycle its valuable nutrients (N and P), which is treated either by denitrification or by disposing it in the river. Apart from that, production of 1 kg of N and P fertilizer requires about 10–11 kWh of energy [17]. The other major global concern is emissions of gaseous exhaust from industrial and transportation sector causing global warming, which may result in flooding, melting of glacier, and rise in sea level that cause domino effect. Industrial revolution with technological progress caused the exploitation of fossil fuel reserves, which led the energy insecurity and climate change [115]. Due to increase in industrial emission, greenhouse gases are projected to increase globally by 1.3% per year from 2005 to 2011. Carbon dioxide (CO_2) is the major GHG that grew by 25% in the atmosphere since the beginning of industrial revolution [137]. Energy scenario of most of the fastest developing countries is characterized by large share of fossil fuel in electricity generation. In 2015, the share of fossil fuel in electricity generation was about 68% in Indian energy scenario, which has been reduced to 63.05% due to implementation of clean energy technologies [117]. Despite of development in renewable energy technologies, energy scenario of most of the countries is still dominated by fossil fuel-based energy generation. In view of these concerns, a cost-effective and efficient carbon sequestration technology is in demand for maintenance of environmental sustainability [162].

The potential of microalgae to eliminate nitrogen (N) and phosphorus (P) from wastewater and its ability to fix atmospheric carbon make algal biomass as a potential feedstock for valuable products. The water footprint (WFP) of algal cultivation is relatively lower than the conventional bioenergy feedstock [21]. Therefore, potential application of algae to restore the environmental health and renewable energy generation acquires wide attention at global level because: (i) algal biomass has high oil productivity per acre of land area than oil yield obtained from conventional feedstock, and (ii) algal biomass can be grown in marginal water sources (municipal, industrial wastewater, and agricultural runoff). Therefore, a cost-effective technology is required to scale up the algal biomass cultivation. In this context, conventional farming system such as raceway pond and tubular/flat plate photobioreactor system were globally explored. These cultivation systems require the excess of 6000 gallons of water to cultivate 1 gallon of algal oil, which involve about 385.71 MJ kg^{-1} of energy in pumping and circulation of algal suspension in the cultivation medium. Optimum culture medium/nutrient medium (N and P), CO_2 concentration, light, and pH are also added in the cost of algal cultivation [106]. Therefore, an integrated solution is of prime importance to resolve the challenges related to algal cultivation. A few researchers have reported cost-effective life cycle of algal cultivation process using wastewater and flue gas for the supplement of nutrient and carbon, respectively [1]. The initial focus should be given to low-cost and best available resources for photosynthetic biomass growth, i.e., waste effluents (water and flue gasses) from the point and non-point sources at local/national and global level [158]. Several researchers have optimized the efficiency of algal biomass for wastewater treatment and carbon sequestration but combined influence of wastewater and CO_2 for algal cultivation has not been the part of study with significant emphasis. Various algal species are found with variation in biochemical composition (carbohydrate, protein, and lipid), growth rate, and efficiency of photosynthetic pigments. *Chlorella vulgaris*, *Chlorella sorokiniana*, *Haematococcus pluvialis*, *Anabena* sp., *Scenedesmus obliquus*, *Chlorella pyrenoidosa*, etc. species produce 2–10× more biomass yield per land area in comparison to terrestrial systems [135]. Estimation of algal productivity based on maximum photosynthetic efficiency and annual algal biomass production yield was also calculated on numerous assumptions without addressing lowest possible returns by various researchers.

The use of metabolic engineering, transgenic technologies, and even system biology engineering to refine algal traits may greatly accelerate the commercial potential of algae as a source of energy and other products. Although there are number of segregated reviews available on wastewater treatment specific to bioprocess routes, wastewater reuse, causes of greenhouse gas emissions and their mitigation strategies, algal biomass for bioenergy applications along with experimental studies in well-reputed journals, but this type of interdisciplinary or integrated vision for all these at one place is not found even after extensive review [87]. Chen [36] very well discussed the concept of 3Es (energy, environment, and ecology) and its interrelatedness. Focus on anyone, directly or indirectly impose an unbalance in natural ecosystem. Proposal with nexus approach for broad issues of climate change, energy and food security, societal growths, and resource management has gained momentum for sustainable economy and to avoid the detrimental consequences also discussed and reported [37, 85, 110]. In this context, algal species being the pioneer community of ecosystem is responsible for eutrophication in freshwater bodies; if this process gets inter-related with nexus of nutrients from wastewater and carbon dioxide emitted flue gases from different point/non-point sources, an effective technology would be developed for the carbon capture and wastewater treatment [10, 145]. It can be a solution for 3Es, i.e., energy crisis due to exploitation of fossil fuels, environmental crisis due to rise in pollutants (air/water), and ecosystem crisis due to misbalancing in reserves and resource with increase in pollution. Due to limited availability of experimental research work on hybrid system of wastewater- and flue gas-based algal cultivation in global water network, this work is highlighting the research gap for this concept. In this regard, this manuscript is providing a critical review on integrated approach for cultivation of alga on wastewater and biofixation of CO_2 with emphasis on key factors affecting the biomass cultivation with WFP, to reduce its dependency from freshwater resource with the help of green water networking (GWN). Green water networking is an advanced concept for conserving uses of water and wastewater with sustainable applications [11]. Furthermore, other salient features of this manuscript are in favor of algal-nutrient-wastewater-flue gas dynamics for measuring the algal productivity under the varying parameters. Algal-nutrient-wastewater-flue gas dynamics provides a new insight into algal biomass enhancement.

2 Carbon capture and storage

Carbon dioxide is formed during the process of combustion and the combustion process directly affects the selective CO_2 removal process. CO_2-capturing technologies are accessible in the market but are costly and not environment-friendly for CO_2 capture from sources and transporting it to a storage site for its long-term separation. The chief gases of effluents are CO_2, methane (CH_4), and nitrous oxide (N_2O) along with halocarbons (chlorofluorocarbon). Although CH_4 has nearly 21 times more GHGs potential than CO_2, tremendous increase in concentration of CO_2 and GHGs potential poses great challenges to global environment. For effective CO_2 capture and storage or utilization thereof from point sources, various technologies have been explored over the century. Every technology has its own merits and demerits and sometimes it is required one to be used more than the other method for CO_2 capture from the flue gas (Table 1).

2.1 Perspectives of carbon uptake by algal biomass

Carbon is a most important nutrient for algal growth followed by N and P [141]. For algal biomass cultivation, up to 60% cost for carbon nutrient is needed in total nutrient cost. The most common resources of carbon for algae cultivation are as follows: (i) atmospheric CO_2, (ii) CO_2 from industrial exhaust gases (e.g., flue gas and flaring gas), and (iii) chemically fixed CO_2 in the form of soluble carbonates [68, 126] as described in Table 2. Thus, they have potential to convert major carbon sources (atmospheric carbon) into the glucose for their cell growth. CO_2 concentration plays a significant role in photosynthesis. As its level increases, it leads to increase in the mass transfer mechanism from the gas mixture to the medium, as a consequence, decrease in pH. Due to the decline in pH, there is a drastic reduction in algal cell growth [25]. One of the more attractive features of algal biomass production is the potential to trap gaseous CO_2 generated from point sources in ponds as bicarbonate.

Photosynthesis process is recognized as a foresighted option for sequestration of CO_2 from the atmosphere. The use of biomass is not only typically regarded as carbon sequestration [45, 91, 114] but also it will be preferably believed to be means of reducing CO_2 emission from the atmosphere in respiration. Biological CO_2 sequestration can be enhanced through the natural sink: (i) terrestrial forestation, (ii) ocean fertilization, and (iii) algal sequestration have acted upon the usefulness of photosynthetic organisms for CO_2 sequestration. Algae also show the carbon capture and storage (CCS) mechanism for sequestration of CO_2 by their unique structure as given in Fig. 1. In the last few years, several researches focused on to identify the potential of algae cultivation system to reduce CO_2 emissions [136]. It has been projected that algae produces approximately half of the atmospheric oxygen and simultaneously use CO_2 for photosynthesis. In comparison to natural forestry, agricultural, and aquatic plant, microalgae have > 10× higher growth rate and CO_2 fixation due to their energy-conserving structure. Among all the microbes, algae have been most commonly grown in photobioreactors [128]. Open pond and continuous cultivation not only help in biofixation of CO_2 but also yield value-added products such as protein, fatty acid, vitamins, minerals, pigments, dietary supplements for human and animal and another compound [76]. Microalgae-mediated CO_2 fixation can be rendered more sustainable by coupling microalgal biomass production with existing power generation and wastewater treatment infrastructure.

2.1.1 Potential of industrial emissions as CO_2 supplement in algal biomass production

Various carbon-emitting units/plants have been established to fulfill the economic growth and development at the global portal (Table 3). The big challenge of industrial processes is to minimize the flue gas emission. The flue gas mainly composed of N_2 (82%), CO_2 (12%), O_2 (5.5%), NO_x (400 ppm), SO_2 (120 ppm), and soot dust (50 mg m^{-3}) [142]. Thus, the big challenge is to separate the carbon dioxide from flue gas. The concentration of carbon dioxide varies with industrial

Table 1 Carbon capture and storage mechanism by different processes

Methods	Application	Advantages	Limitations	Ref.
Enhance energy efficiency (EEE) and conservation	Applied mainly in commercial industrial buildings	Saving up to 20% energy	High capital cost	[170]
Adopt clean coal technologies (CCT)	Integration of gasification combined (IGC) with gasification	Allow the use of coal with lower emissions of air pollutants	Significant investment needed to roll out technologies widely	[71]
Use of renewable energy resources	Hydro, solar (thermal), wind power, and biofuels highly developed	Use of local natural resources; no or low greenhouse and toxic gas emissions	Applicability may depend on local resources availability and cost. Power from solar, wind, marine, etc. are intermittent and associated technologies are not mature	[97]
Development of nuclear energy	Nuclear fission: adopted mainly in USA, France, Japan, Russia, and China. Nuclear fusion: still in research and development phase	No air pollutant and emission of GHGs	Usage is controversial; development of world's nuclear power is hindered due to the Fukushima Nuclear Accident in 2011	[154]
Afforestation	Applicable to all countries	Simple approach to create natural and sustainable CO_2 sinks	Restricts/prevents land use for other applications	[96]
Carbon capture and storage	Applicable to large CO_2 point emission sources	It can reduce vast amount of CO_2 with capture efficiency of 480%	CCS full chain technologies were not proven at full commercial scale	[66]

processes ranging from 10 to 15% along with other gaseous mixture [176]. Therefore, flue gases can be a best alternative among other major sources of CO_2 for algae cultivation, where carbon sinking implies as a potential growth factor for algal biomass production.

Waste stream emissions from different industries were investigated by scholars to suggest a valuable solution for anthropogenic emissions of carbon in coupling with algal culture. The relationship between algal-CO_2 sequestration and estimated biomass and oil production with industrial sectors are given in Table 4 on comparative basis. The CO_2 fixation and biomass production vary distinctly depending on the characteristics of algae species. The consequence of various process parameters in terms of carbon uptake, biofixation, and culture conditions viz, light intensity, dark–light cycle temperature, the pH of medium, etc. must be considered as an

Table 2 Results from various researches reviewed regarding CO_2 sequestration by algae

S. no.	Research outcomes	Algae strains	Ref.
1	Ratio of CO_2 absorption and desorption rate constant (k_1/k_2) was reported highest. In comparison with ambient CO_2, an addition of 1% volume of CO_2 shows best result with respect to algal growth	*Dunaliella*	[54]
2	Reported 56.4 mg L^{-1} day^{-1} of CO_2 biofixation in an open tank with the rate of 30 mg L^{-1} day^{-1} of algal growth	*Phomidium valderianum* BDU 20041	[52]
3	Performed an on-off feeding of pure flue gas to algal biomass and obtained growth rate 889 mg $L^{-1}day^{-1}$ with 75.6 g $L^{-1}day^{-1}$ of CO_2 fixation rate in a bubble column photobioreactor, using flue gas with 15% of CO_2	*Scenedesmus dimorphous*	[165]
4	The percentage efficiency of carbon fixation by algal biomass was reported 80% in an airlift photobioreactor with 0.245 g $L^{-1}day^{-1}$ of algal growth rate	*Chlorella vulgaris*	[132]
5	Reported that algal biomass is efficient to fix 96.89 mg $L^{-1}day^{-1}$ of carbon dioxide from the flue gas having 5–15% of CO_2 in an incubator with maximum growth rate 0.64 g L^{-1}	*Chlorella* sp.	[79]
6	Obtained that in a pilot-scale photobioreactor algal biomass is able to fix 0.8 kg CO_2 day^{-1} from the flue gas with 5–30% of CO_2 with maximum growth rate of 0.40 g L^{-1} day^{-1}	*Chlorella vulgaris*	[112]
7	Reported the optimum range of CO_2 sequestration lie between 10 and 15% of flue gas. Hence, the industries emission of 10–15% of flue gas can be best utilized for algal growth	*Chlorella vulgaris*	[148]
8	Performed a lab-scale study in closed photobioreactor, using flue gas with 13.8% of CO_2 with the efficiency of 252 g L^{-1} of CO_2 biofixation rate and 4.97 g L^{-1} of algal growth	*Scenedesmus* (KC7337)	[20]
9	Reported the biofixation rate of CO_2 (368 mg L^{-1} day^{-1}) by using coal flue gas having 2.5% of CO_2 with maximum algal growth of 196 mg L^{-1} day^{-1} in an airlift photobioreactor with domestic wastewater as nutrient medium	*Scenedesmus* sp.	[103]
10	Reported 85.6% of algal-based biofixation efficiency of CO_2	*Chlorella* sp.	[18]

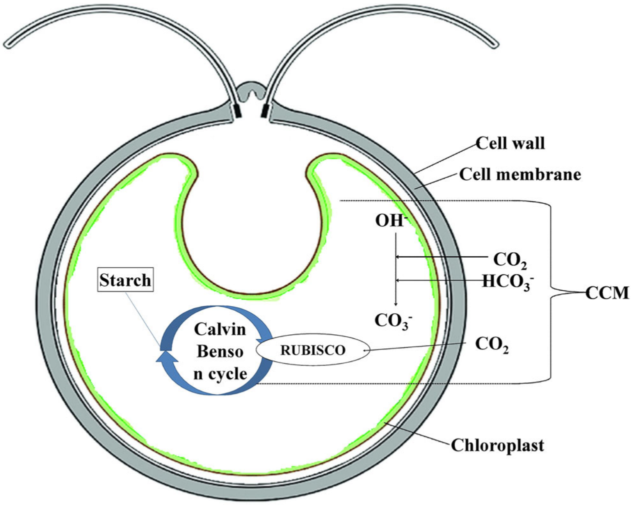

Fig. 1 Carbon capture mechanism (CCM) by algae

important part for cultivating strategies of algal biomass cultivation [48]. Different approaches are considered and adopted by various countries to reduce their CO_2 emissions, including improving energy efficiency and promote energy conservation, increase usage of low carbon fuels, deploy renewable energy, apply geo-engineering approaches, and CO_2 capture and storage. Among these, captured and stored CO_2 can be utilized for algal biomass cultivation at pilot scale which will provide a potential option of biomitigation.

There is a long list of industries available at the global level as contributors of CO_2 emission. Among these, only a few or large-scale product capacity industries come under point source emitters. Among the different point source emitters, cement industry alone contributes 5% of global anthropogenic CO_2 emission from total cement production at global level (222 kg of C t^{-1} of cement) [160]. Algal-based biofixation process, i.e., to capture flue gas (CO_2), appears to be the most feasible in the near-term application of algal biomass cultivation by Yadav et al. [166]. Mass cultivation of algae at large scale in the next 10 years seems more feasible while considered with diverse range of higher value co-products.

Table 3 Different carbon-emitting sources with their emission rates [142]

S. no.	Process	Number of sources	Emissions ($MtCO_2$ $year^{-1}$)
1	Power plant	4942	10,539
2	Cement production	1175	932
3	Refineries	638	798
4	Iron and steel industry	269	646
5	Petrochemical industry	470	379
6	Oil and gas processing	–	50
7	Other sources	90	33
8	Bioethical and bioenergy	303	91
	Total	7887	13,466

Algal carbon fixation capacity varies with strains due to differences in inorganic carbon assimilation pathways. To achieve high carbon fixation, CO_2 must be fed continuously during daylight. The control of CO_2 feeding can be evaluated by pH measurements to minimize the loss of CO_2. Cyanobacteria (blue-green algae) and eukaryotic algae use bicarbonate as a carbon source with pH between ~ 6.4 and 10.3. CO_2 rapidly gets captured into algal cells via bicarbonate transporters present in both the plasma membrane and in the chloroplast envelope of eukaryotic algae. Inside the chloroplast, bicarbonate is converted into CO^+ that can be fixed by RuBisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase, carboxylase-oxygenase) to produce two molecules of 3-phosphoglycerate [98]. To reduce the competitive inhibition of oxygen on carbon fixation by RuBisCO, algae actively pump sufficient bicarbonate into cells to elevate internal CO_2

Table 4 Algal mediated carbon capture and oil production [48]

Industry	106 ton (CO_2)	106 ton (algal biomass)	106 ton (oil)
Minerals	1307.84	608.30	121.66
Cement production	1299.20	604.28	120.86
Glass & ceramic production	2.78	1.29	0.26
Other uses of soda ash	5.86	2.73	0.55
Ammonia production	100.56	46.77	9.35
Nitric acid production	0.00	0.00	0.00
Carbide production	1.20	0.56	0.11
Titanium dioxide production	0.88	0.41	0.08
Methanol production	2.66	1.24	0.25
Ethylene production	70.73	32.90	6.58
EDC & VCM production	1.99	0.93	0.19
Ethylene oxide production	0.94	0.44	0.09
Acrylonitrile production	0.38	0.18	0.04
Carbon black production	11.56	5.37	1.07
Other chemical	88.00	40.93	8.19
Iron & steel production	1169.58	543.99	108.80
Ferroalloys production	24.61	11.45	2.29
Aluminum production	27.29	12.69	2.54
Lead production	0.84	0.39	0.08
Zinc production	0.76	0.35	0.07
Copper	0.63	0.29	0.06
Pulp and paper	52.23	24.29	4.86
Food processing	276.26	128.49	25.70
Textile and leather	18.61	8.66	1.73
Mining and quarrying	14.60	6.79	1.36
Non-specific industries	878.00	408.37	81.67

concentration by equilibrium with air, and competitively inhibit photorespiration. CO_2 emission from power plants, industrial emissions, etc. can be used as a source for CO_2, which aids in the maintenance of environmental sustainability [128].

3 Factors and associated challenges in algal cultivation

Algal cultivation is done in various facilities (lab scale/pilot scale), but production of sufficient amount of algal biomass which replace the fossil fuel is widely ignored. Thus, major constraints (Table 5) for commercialization of algal biomass need to be addressed. Despite the availability of potential algal strains, algal-based bioproducts are still expensive in comparison to the cost of conventional products, but major obstacles in cost-effective algal cultivation include minimization of freshwater input, low nutrient supply, low-cost carbon supplement, and regulation of optimum temperature and light conditions.

3.1 Water

Aquatic system provides habitat for algal species to complete their life cycle. It also delivers nutrients (N and P), removes waste products, and maintains thermal regulation [81, 84]. The WFP of algal biomass is relatively lower than the WFP of conventional energy feedstock, which is shown in Table 6. Approximately 5–10 L of water is consumed to produce per kilogram of dry algae biomass [80, 94, 140, 149], which is consumed in upstream and downstream steps and depends on desired final by-products. Water is consumed in the washing of biomass to remove salt and other impurities before the oil extraction. On the other hand, evaporative loss of water is another challenge to be resolved. Thus, an evaluation of the water footprint in the cultivation of algal biomass is essential. Marine algae have a lower water footprint than the freshwater alga and terrestrial crops [69, 158]. WFP for algae grown in fresh water open ponds observed WFP of ~3700 kg kg^{-1} of biodiesel in the absence of water recycles. Recycling reduces the WFP ~600 kg kg^{-1} of biodiesel [62, 124].

Table 6 Water footprint, land use, and biofuel yield of various energy crops [58, 131]

Biodiesel	Water footprint (m^3 GJ^{-1})	Land use (m^2 GJ^{-1})	Energy (GJ ha^{-1} a^{-1})	Biofuel yield (L ha^{-1} a^{-1})
Soybean	383	689	15	446
Jatropha	396	162	62	1896
Rapeseed	383	258	39	1190
Cotton	135	945	11	325
Sunflower	61	323	31	951
Palm oil	75	52	192	5906
Coconut	49	128	78	2399
Groundnut	58	220	45	1396
Microalgae	<379	2–13	793–4457	24,355–136,886

Algal cultivation in closed photobioreactor reduces the evaporative loss of water, but the cost of closed photobioreactor reduces the economic viability of such system [6]. Thus, water consumption in biomass processing is a significant challenge for scientists and commercial corporate in the future. So, clear incentive to reduce the net consumption of water in these processes will be needed with stringent

Table 5 Role of various factors in algal biomass production

Key factors	Effect on algal biomass growth	Optimum range	Ref.
Water	It provides an aquatic environment and habitat for survival of algal life cycle. It work as medium to deliver nutrients as well as thermal regulator	Species-specific	[32]; [14]
Light	Light is the primary requirement for algal growth and obtaining their metabolic energy by long list of photosynthetic process, which shows the enormous importance of light supply for their growth	400–700 nm	[116, 118];
Oxygen (O_2)	It show +ve & −ve for growth of algal cell growth the concentration of oxygen affect according to Warburg effect	–	[35]
CO_2	CO_2 along with bicarbonate (HCO_3^-) forms the primary carbon sources for algae	1.63–1.84%	[51]
Temperature	It plays an important role by affecting the biochemistry and physiology due to change in rate of chemical reaction. Most of the algae demonstrate an increased exponential growth rate up to optimal temperature but after cross of this optimal point there is a turn down in structural integrity	25–30 °C	[44]
Nitrogen (N_2)	7–10% of algal biomass is comprised of nitrogen, making it an essential nutrient. Higher concentrations increase biomass growth	>1% for 1 g of dry algal biomass	[29]
Phosphorus (P)	Phosphorus is a second essential nutrient for algae, and its higher concentrations increase biomass	>10% for 1 g of dry algal biomass	[118]
pH	It important parameter because several enzymatic activities take place at particular pH only	7–7.5	[48]

environmental regulations on water use and wastewater discharge [72]. Hence, water scarcity noticed through data observed and predicted increasingly becoming scarce as seen in Fig. 2. In fact, it is projected that in 2025, two thirds of the world population will experience water stress [59, 63]. This is clearly anticipated that water consumption in biomass processing is a significant challenge for scientists and commercial corporate in future. So, clear incentive to reduce the net consumption of water in these processes will be needed with rigid environmental regulations on water use and wastewater discharge.

3.1.1 Water footprint for cultivation of algae

WFP refers to an input of total freshwater volume for production of a product and services for the society and personal use, at a place where it has the origin. Three components of WFPs have been defined, i.e., green water footprint (GWFP), blue water footprint (BWFP), and gray water footprint (G_yWFP), in which BWFP is relevant for algal biomass cultivation in the artificial systems. The algal cultivation by water foot print set lifecycle boundary includes upstream which is defined as the water (BWFP, GWFP, and G_YWFP) consumed to produce materials and energy inputs to the microalgae-to-biofuel process, such as electricity, fertilizers, and photobioreactor material [77]. GWFP and GyWFP are mainly concerned with the amount of rainwater consumed to grow the crop and amount of freshwater for dilution or assimilation of pollutants, respectively. Freshwater, seawater, or wastewater on the part of water footprints for biofuel production using conventional feedstocks has been reported. In the case of microalgae cultivation, G_yWFP is almost zero due to complete recycling of nutrients, but microalgae have significant BWFP [161]. Therefore, algal cultivation is still under the continuous scrutiny to ensure its environmental sustainability and economic viability to produce various by-products. Therefore, large-scale algal cultivation system has been criticized for overconsumption of a significant amount of freshwater [11, 69, 74]. But in contrast, algae-based biodiesel production may utilize much less potable water than conventional feedstock-based biodiesel production if microalgae are grown in seawater or wastewater [93, 125]. Algal culture process requires a regular supply of freshwater to reimburse water loss and avoid salt accumulation due to evaporation in open system. After harvesting of algal biomass, the culture water can be partially recycled by pumping it back into the culture pond. Also, 1 mol of water dissociates into O_2 and H_2/mol of CO_2 consumed in photosynthesis process. In photosynthesis process, estimated water loss of almost ~5–10 kg^{-1} dry algal biomass has been found [55]. Direct water demand for algal growth and development can be calculated as

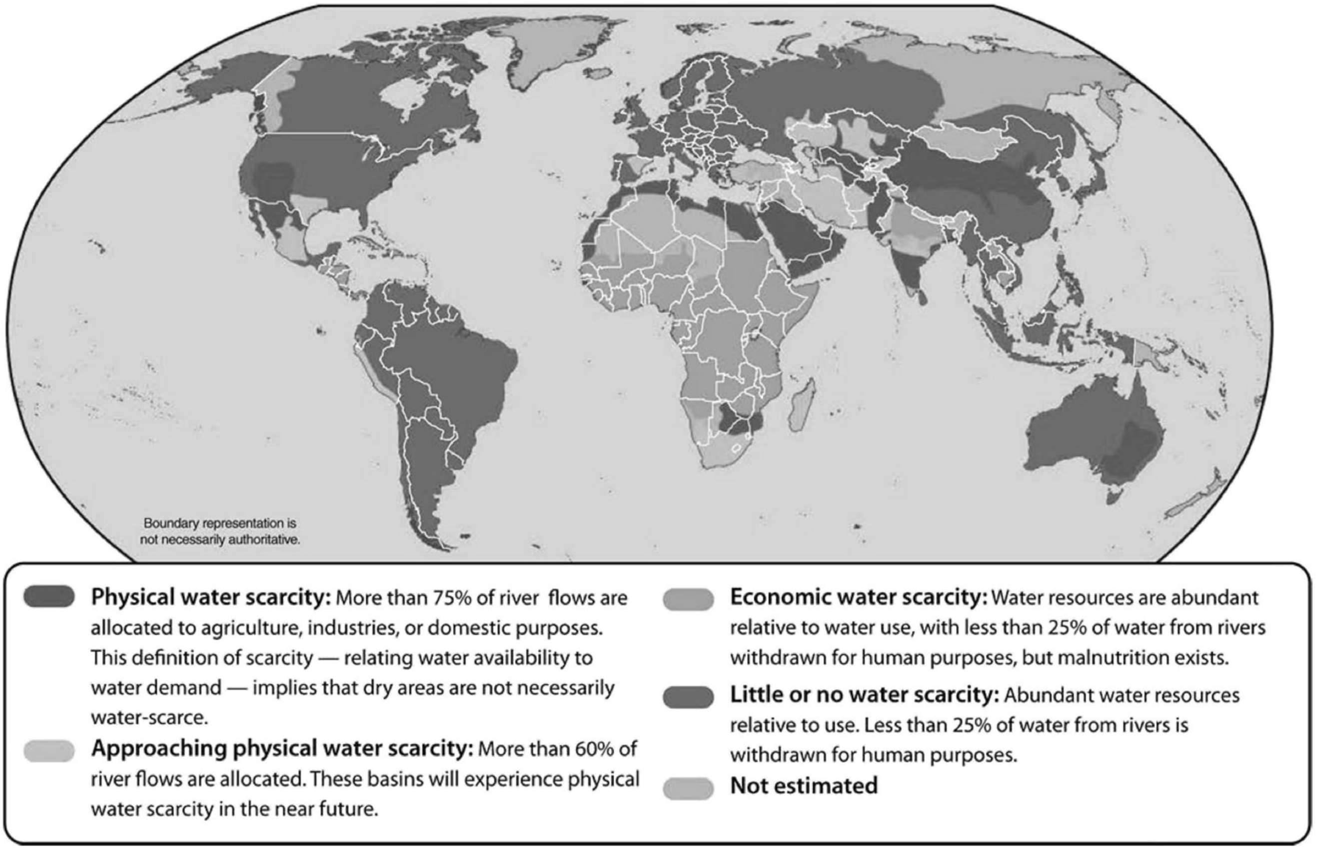

Fig. 2 Projected water scarcity in 2025 https://www.fewresources.org/water-scarcity-issues-were-running-out-of-water.html

the difference between the volume of water required to support growth and annual precipitation as given in Eq. 1 [169].

$$\mathit{Direct\ Water\ demand}\ (DWD) = \mathit{Water\ to\ support\ growth}\ (WSG) + \mathit{Annual\ precipitation}\ (AP)r^2 \quad (1)$$

The volume of direct water demand required to support the growth of algae at optimum conditions can be calculated by two key factors: (i) amount of water required to sustain the growth and development, and (ii) quantity of water that needs to be restored in growth and development due to water loss or to compensate for GWFP. Particularly, total required water input for cultivation of algae would be the sum of newly acquired water and water recoup along with water loss as shown in Eq. (2). The total volume of freshwater can be computed by the following expression [55]:

$$\mathit{Vtotal} = \mathit{Vfill} \times \mathit{freq} + \mathit{Vevap} + \mathit{Vleakage} + \mathit{Vblowdown} + \mathit{Vphoto} + \mathit{Vharvest} + \mathit{Vdrying} + \mathit{Vbiomass} + \mathit{Vgray\ water} \quad (2)$$

Where V_{fill} = total volume of water required to compensate the evaporative water, V_{evap} = amount of water consumed in evaporation, V_{leakage} = amount of water loss due to leakage, V_{blowdown} = amount of water loss in blow-down, V_{photo} = amount of water loss in photosynthesis, V_{harvest} = amount of water loss in harvesting, V_{drying} = water loss during biomass drying, V_{gray} = water required to assimilate the pollution (ignored in case of algal cultivation).

The water demand for algae production system ranges ~ 4.59 $m^3\ m^{-2}\ year^{-1}$ in a tropical region and ~ 6.39 $m^3\ m^{-2}\ year^{-1}$ in an arid environment. Leakage rate of water usually for an ORP was ~ 0.0011–0.0036 $m^3\ m^{-2}\ year^{-1}$ [64]. The significant water loss from algae cultivation due to evaporation is directly associated to the availability of solar radiation and wind velocity. WFP for algal cultivation varies geographically due to physical factors (solar radiation, temperature, and wind speed). Geographically, higher accessibility of photosynthetically active radiation (PAR) adds elevated algal biomass productivity whereas higher water loss is due to enhanced evaporation rate [155]. The WFP highlights the wide geographical differences which are reflected in particular by the GWFP; generating a unit of biofuel by using same feedstock present in different geographical regions with variable climatic circumstances could result in momentous differences to make up the WFP. An evaporation loss from the surface of ORPs is generally dependent on the local average temperature in addition to relative humidity. Water requirement can vary from 3.5 to 3365 L of water per liter of algal biodiesel. Few studies have been found with the concept of WFP among different algal species given in Table 7 [61]. Lower end of estimate assumes efficient water capture and recycle [22, 108, 138]. Without recycling or reuse of harvested water, the WFP is ~ 3726 kg-water kg^{-1} biodiesel and ~ 84.1% of the water is discharged after harvesting of algal biomass, while the rest is lost by either pond evaporation or drying. If the harvested water would recycle, the WFP of biodiesel can reduce too as low as 591 kg-water kg^{-1} of biodiesel. To produce 1 kg of algae through ponds, 1564 L of water is required. When PBRs are used, only 372 L water is required; however, the energy requirements for PBRs are about 30 times higher than for ponds. The variation in microalgae species and geographic distribution is analyzed to reflect microalgae biofuel development in all over the world.

3.1.2 Reducing WFP via green water network with wastewater

Most of the industries refused the concept of reuse and recycling of wastewater. However, it should be recycled to lower the freshwater input. Therefore, an appropriate treatment network in the industrial process is required to reduce the input of freshwater. Various models of water network (WN) system were proposed with the concept of industrial ecology to minimize the flow and cost of the entire process network. Researchers have mainly focused on particular wastewater treatment unit design for fixed outlet concentration and a fixed contaminant removal ratio. The resulting formula from their study represents a simplified model of the network. Both, insight-based method and mathematical optimization-based techniques have been investigated for green water network synthesis (GWNS). Although GWN analysis is applicable for industrial units, it may be a ground-breaking

Table 7 Water footprint among different microalgae species [61, 69]

	Species	Algal growth rate ($gm^{-2}\ day^{-1}$)	Lipid content (%)	Water footprint (WFP)
1	*Dunaliella primolecta*	12	27 ± 5	1818.5 ± 339
2	*Phaeodactylum tricornutum*	22	20 ± 3	1456 ± 205
3	*Monallanthus salina*	28.1	21 ± 6	1230 ± 380
4	*Tetraselmis* sp.	25	19 ± 6	1440 ± 427
5	*Nannochloris* sp.	31.9	28 ± 11	863 ± 331
6	*Isochrysis galbana*	28.1	28 ± 6	911 ± 256
7	*Cyclotella cryptica*	30	30 ± 2	758 ± 62
8	*Botryococcus*	3.4	52 ± 33	3595 ± 2245
9	*Nanocloropsis* sp.	20.4	49 ± 19	721 ± 376
10	*Chlorella vulgaris*	35	37 ± 11	591 ± 170
11	*Chaetoceros gracilis*	40	30 ± 14	708 ± 331

solution which might be incorporated into algal biorefineries for a compatible solution. By GWN synthesis technologies, WFP can be reduced up to 1/5 to 1/3 for algal biofuel per liter. There are two main water consumption stages in the production of biofuels: (i) the water that is used in the production of the biomass, mainly due to irrigation, and (ii) water that is used along the process to transforms the biomass into fuels [25]. Use of wastewater or saline water has been reported by various researchers to reduce the consumption of freshwater in the production of algal biofuel [111]. Commercial production of algal fuels continues to be strong, suggesting that the possibility of an economically viable production at some scale and within a reasonable timeframe should not be entirely discounted. Integrated water network synthesis for recycling and reuse of water for different processes of algal growth and biofuel applications for the case of five process unit and three contaminants was introduced. The integrated process water network is basically a mathematical model, which consist of mass balance equation for water and contaminants present in every unit of network [70]. Thus, it was possible to design an optimal network that efficiently treats and reuses the water by using the superstructure with multiple effects.

Industrial wastewater, i.e., municipal, tannery, dairy, agricultural, wastewater, may be the source for algal culture, with different algal strains, with various wastewaters and their biomass productivity. Therefore, conventional water treatment processes such as aerated lagoons, trickling filter, activated sludge process, oxidation pond, septic tank, Imhoff tank, anaerobic stabilizing pond, etc. and their freshwater use for different industrial processes pose a problem. Conventional water utilization in the industrial process does not use, reuse, or recycle into different water streams. Coupling of bioenergy production options with municipal wastewater treatment makes sense because it represents nutrients reuse and provides a sustainable energy saving for wastewater treatment units. Though, there is a generous spatial and temporal disparity between the water requirements of algae growth and the accessibility of municipal wastewater treatment plant effluent in the southern 17 states, which is an important factor affecting the degree of freshwater replacement for algae biomass cultivation [46]. By the accessibility of spatial and temporal municipal wastewater as a sole source of water, 8.6 billion liters of bio-oil can be produced annually with a freshwater BWFP, but due to lack of technology sharing, it is almost negligible [164].

Algal-based wastewater treatment can opt for secondary or tertiary treatment process for different types of wastewater. It has potential to assimilate the broad range of pollutants, given in Table 8. Selection of alga for wastewater treatment reduces the need for energy-intensive cleaning

Table 8 Assimilation of various compounds by microalgae

	Nutrient recovery	Endocrine disruptors	Heavy metals	Oil/grease	Poly-aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs)	Carbon dioxide	Ref.
Source	Wastewater from municipal and industrial discharge, agricultural runoff, industrial exhaust, anaerobic digestion of waste	Pharmaceuticals, plasticizers, hormones, pesticides, poly-aromatic hydrocarbons	Industrial/municipal wastewater	Dairy effluent spills, mining activity	Oil/coal industry, diesel gas engine, incinerators, asphalt, production coke stove	Emissions from power plants, biomass combustion, etc.	[133]
Potential effects	Excess nitrogen leads to methemoglobinemia and excess P leads to kidney damage in humans. Eutrophication of lake due to uncontrolled algal growth	Neurological disorders, birth defects, reproductive health problems	Bioaccumulation in the food chain, health impacts leads to organ dysfunctions	Lethal to aquatic wildlife, bioaccumulation issues	Carcinogenic, mutagenic and teratogenic	Leads to the phenomenon of climate change, global warming	[121]
Changes in microalgae	Enhanced biomass accumulation Change in biomass composition	Enhanced growth in cyanobacteria < 100 mg/L. Photosynthesis completely inhibited in marine microalgae	Sulfur accumulation limits uses of algal biomass	Higher biomass production with long growth phase	Bioaccumulation and biotransformation of PAHs, PCBs accumulate in lipids	Carbon sequestration by alga leads to its high biomass productivity	[156]

process and chemicals used in standard treatment procedures.

The mechanism for nutrient removal depends on algal species, which is based on shared fundamental steps, such as a consortium of alga and bacteria successfully degrade the organic matter through photosynthetic aeration. Commonly algal-based treatment is carried out in maturation ponds and facultative or aerobic ponds [34, 67]. Algae enhance the removal of nutrients, heavy metals, pollutants, and pathogens, and provide O_2 to aerobic heterotrophic bacteria to oxidize organic pollutants, and the CO_2 released from bacterial respiration [12]. Algal potential to uptake nutrients added more value to wastewater remediation. A recent study showed achievement of complete NO_3^- removal and 33% PO_4^{-3} removal, by *Chlamydomonas* sp. and similarly demonstrated *Chlorella* sp. for removal of a high level of ammonia, total nitrogen and phosphorus, and chemical oxygen demand (COD) in 14 days [102]. Heterotrophic and mixotrophic cultivation system also attributed to removal of BOD and COD; for instance, mixotrophic condition facilitates higher algal growth rates (Table 9) and lipid yields. Industrial and municipal wastewater contains a wide variety of pollutants such as heavy metals, phenols, endocrine disruptors, viruses, antibodies, oils, and grease, which can be treated by alga in different ways. Microalgae perform bioaccumulation, inactivation, and biodegradation in response to these pollutants. Uptakes of compounds are species-specific and limited up to a toxic concentration.

3.2 Effect of combined influence of wastewater and flue gas on algal biomass

Flue gas provides a higher concentration of CO_2 (~20%) in comparison to the atmospheric carbon source, i.e., air (> 360 ppm). Carbon capture by alga involves the photoautotrophic growth of cells; however, algae photosynthesis efficiency declines with increasing temperature, since CO_2 solubility is significantly reduced [82]. The constituents of flue gas such as sulfur dioxides (SO_x) and nitrogen oxides (NO_x) are toxic in nature. SO_x from flue gas can be eliminated by chemical desulfurization system. However, NO_x removal is more difficult due to its lower solubility in the liquid phase. Thus, potential algal strains such as *Botryococcus braunii*, *Chlorella vulgaris*, *Chlorella kessleri*, *Chlorocuccum littorale*, *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, *Scenedesmus* sp., *M. minutum*, *Tetraselmis* sp., and *Spirulina* sp. [92] can be cultivated in these stress conditions. Some algal species are tolerant to high temperatures, high CO_2 concentrations, and toxic compounds such as NO_x and SO_x, as described in Table 10. It shows that a few species of *Chlorella* and *Cyanobacteria* could grow well and accomplish a high CO_2 fixation rate (500–1800 mg L^{-1} day^{-1}) with a relatively high tolerance for temperature. Compared with other algal species, i.e., *Cyanophytes* and *Chrysophyte*, *Chlorella* was observed by Zhao and Su [173] to have a better performance in capturing CO_2. Its biomass production and carbon fixation rates range between 1060 and 1992 mg L^{-1} day^{-1}, respectively [143].

Treated industrial effluent/urban wastewater consists of low CNP ratio, which is a major drawback for algal cultivation in wastewater. Integration of flue gas with wastewater for algal cultivation maintains the C/N/P 100:16:1 ratio in wastewater which is required to achieve optimal algal growth [105]. Flue gas addition in wastewater also helps in the pH control of wastewater. Arbib et al. [16] have studied pH control of cultivation medium through flue gas supplement and achieved biomass with less nitrogen reserve and higher lipid content. Thus, the addition of CO_2 in culture medium not only improves the carbon availability but also control pH of

Table 9 Different algal strains and biomass productivity with diverse range of wastewater

Microalgae species	Wastewater type	Biomass productivity (mg L^{-1} day^{-1})	Ref
Chlorella pyrenoidosa	Activated sludge extract	11.55	[123]
Chlorella pyrenoidosa	Digested sludge extract	51.82	[27]
Chlorella pyrenoidosa	Settled sewage	275	[90]
Chlorella pyrenoidosa and *Scenedesmus* sp.	Activated sewage	92.31	[105]
Botryococcus braunii	Secondarily treated sewage	35.00	[39]
Scenedesmus sp.	Carpet mill	126.54	[78]
Polyculture of Chlorella sp., *Micractinium* sp., *Actinastrum* sp.	Dairy wastewater	NA	[153]
Chlorella sp., *Micractinium* sp., *Actinastrum* sp.	Primary clarifier effluent	NA	[175]
Chlamydomonas mexicana	Piggery wastewater	NA	[99]
Scenedesmus sp.	Carpet mill	126.54	[175]
Chlorella sp.	Centrate municipal wastewater	231.4	[175]
Scenedesmus sp.	Centrate municipal wastewater	247.5	[175]
Auxenochlorella protothecoides	Concentrated municipal wastewater	268.8	[47]
Chlorella vulgaris	Poultry waste water	0.13 g L^{-1} day^{-1}	[157]

Table 10 Temperature and flue gas tolerance of various algal species [16, 56, 139]

Algal species	Maximum temperature tolerance (°C)	Maximum CO_2 (%) tolerance	Maximum NOx/SOx (ppm) tolerance	Biomass productivity rate (mg L^{-1} day^{-1})
Cyanidium caldarium	–	100	–	–
Nannochloris sp.	25	15	0/50	350
Nannochloropsis sp.	25	15	0/50	300
Chlorella sp.	50	50	60/20	950
Chlorella sp.	40	20	–	700
Chlorogleopsis sp.	50	5	–	40
Chlorococcum littorale	22	50	–	44
Dunaliella tertiolecta	–	15	1000/0	–
Cyanidium caldarium	60	100	–	–
Scenedesmus sp.	30	80	–	–
Chlorococcum littorale	–	70	–	–
Synechococcus elongates	60	60	–	–
Euglena gracilis	–	45	–	–
Chlorella sp.	45	40	–	–
Chlorella sp. HA1	–	15	100/0	–
Eudorina sp.	30	20	–	–
Chlamydomonas sp.	35	15	–	–
Nannochloris sp.	25	15	125/0	–
Tetraselmis sp.	–	14	0/185	–

wastewater. Such integration of flue gas and wastewater is useful to mitigate the pH inhibitions related to the higher free ammonia concentration at higher pH. In another observation by Gentili [57] in algal cultivation in dairy and pulp industry wastewater with added flue gas, higher biomass yield was reported with 96% removal of ammonia. Combined influence of wastewater and exhaust from coal-fired plants was also observed by Ahmad [5]. They observed the highest biomass productivity of 0.44 g L^{-1} with high lipid productivity. The delivery system of flue gas in culture medium is also found to influence the uptake of CO_2 by algal biomass. Sparging of CO_2 with large bubbles was found to reduce the CO_2 utilization efficiency of alga while small bubbles flow showed better CO_2 uptake efficiency [127]. Supply of CO_2 up to a concentration range of 5 to 10% is identified as an optimum concentration range for microalgal growth [151]. Chiu et al. [42] investigated the growth of *Nannochloropsis oculate* in a semi continuous culture and found higher biomass growth in the culture medium with 2% CO_2 concentration, while higher CO_2 concentration resulted the inhibition of cell growth due to decrease in pH of medium and sedimentation of phosphorus compounds. Bhowmick et al. [26] evaluated the influence of carbon dioxide and wastewater cocktail for sustainable production of lipid and lutein using *Chlorella* sp. The result shows that in this integrated cultivation system alga efficiently removes nitrogenous and carbon-phosphorus substance by 100 and 85–91%, respectively. The author also achieved twofold increases in the lipid content with 80.74 ± 0.07 mg L^{-1} day^{-1} of CO_2 uptake. Yadav et al. [166] investigated the biorefinery valorization of industrial wastewater and flue gas by *Chlorella vulgaris*. Results showed that nutrient removal by 75% was achieved on the fifth day of batch process. They also observed improvement in lipid (17–34%) and carbohydrate (21.5–23%) under mixotrophic cultivation with CO_2 biofixation of 5% CO_2 concentration.

Hence, algal CO_2 fixation, generated from flue gases, part of industrial and transport exhausts, may be an environmentally sustainable when combined with clean environmental processes like wastewater treatment [159] and heavy metal removal [49]. Future research attention on the concept of algal base CO_2 removal from flue gases is needed on the practical or commercial part of the investigation. Similarly, non-point sources of flue gases (Brick kilns, small industrial exhausts) should also be targeted for capturing CO_2 by algal biomass at local and regional level. Similarly, ethanol plants are also considered to be an ideal carbon source for growth of algal biomass, since it can be used without expensive purification process [23, 122].

Despite having potential for carbon fixation, algal carbon sequestration has various challenges on the technical ground. Various researchers have analyzed the life cycle of algal-based carbon fixation process and revealed that enormous cost and energy is required for algal cultivation, which reduces the positive effect of algae culturing with CO_2 sources. For effective cultivation of algae, it needed high surface area per volume ratio and better hydrodynamics to attain maximum surface area for the penetration of light and gas (CO_2) transfer. The efficient fixation system must have proper mixing, high gas-liquid transfer rate, and even distribution of light. In the case of algal cultivation in raceway pond, poor light penetration, contamination, and low biomass productivity affect the algal potential for carbon fixation, though it is a low-cost technology for cultivation. However, closed photobioreactor (airlift, flat plate, tubular) for algal cultivation provides several advantages over the raceway pond such as controlled process parameters (pH, nutrient concentration), better mass transfer rate, and higher biomass productivity.

3.3 Algae-nutrient-wastewater-flue gas dynamics

To enhance the algal productivity under certain transitory conditions such as inorganic carbon, nitrate (NO_3^-), phosphate (PO_4^{-3}), light and temperature, etc., it is critical for assessing the profitability in sustainability of algal cultivation at any substantial scale with algal-nutrient-wastewater-flue gas dynamics (ANWFD). The purpose of ANWFD is to design and experiment a combined flue gas sequestration and nutrient-rich wastewater treatment via photosynthetic microalgae. Algae have the potential to grow in nutrient-rich wastewater to capture primarily CO_2, and flue gas constituents such as NOx and SOx too from combustion process with aim to improve water quality. This concept provides a technical feasibility, economic viability, and environmental sustainability regarding its indoor and outdoor cultivation. ANWFD focuses on bioprocess geometry (pond depth, light incidence angle), operation (hydraulic retention time, homogenous distribution of nutrients), and environmental stresses [8]. Although, the environmental factors regarding outdoor cultivation is a challenging task for algal activities, influenced by the various environmental parameters. But under ideal environmental conditions, it is possible to enhance the algal biomass productivity per unit of land area. CO_2 injections help to maintain the pH at its optimal value while nutrient concentration can be retained by at saturation level to flourish the algal productivity and proper mixing condition for homogenous distribution of nutrients. To overcome these limitations, several models have been proposed to achieve higher algal biomass which in turn reduces environmental limiting factors. ANWFD-based wastewater treatment and flue gas assimilation is the most economical and environmental approach to enhance algal biomass and biofuel conversion. In this regard, advanced technologies have been developed to enhance the microalgal-based CO_2 fixation efficiency. Table 11 summarizes different nutrients modeling equations for various algal species used by different researchers. In addition to low carbon supply and reduced water consumption, cost-effective way of the nutrient supplement is equally essential to achieving sustainability in algal biofuel production [144]. On the other hand, atmospheric N-fixation through Haber-Bosch process involves a considerable amount of energy. In this context, wastewater can be again used as a low-cost source of N and P for the cultivation of algae. Various industrial wastewaters such as dairy wastewater and municipal wastewater can provide sufficient nutrients (N and P) for algae growth [84]. As per the estimation provided by Chisti [41], algal oil from wastewater contributes at most 1% of US demand for petroleum and wastewater generated from 10 cities have potential to produce 425,000 Mton of algal oil annually, which is based on the assumption that the wastewater has high nitrogen (85 mg L^{-1}) and phosphorus content (10 mg L^{-1}). Having such a model will be particularly useful for the design and operation of algal mass production systems, as it provides a relationship that can be determined from relatively easily measurable parameters.

4 Genomics strategies to improve algal biofuel production

Recently for the production of biofuels, microalgae have emerged as potential sources of production of carbon-neutral fuels such as biohydrogen and bio-oil. Advances in genomics tools and in silico prediction models have paved the way for the bioprospecting of algae and for developing better traits suited to biofuel production under varied climate conditions. Several strategies have been employed in algal biotechnology for this purpose, from changing carbon flux to obtain increased lipid accumulation, improving light utilization efficiency to enhance biohydrogen production, and modifying lipid production or lipid engineering to modify chain length, and the degree of saturation [19, 86, 110]. For algal biofuel production, systems biology is essential for understandings the molecular mechanisms behind specific phenotypes and that will help in the prediction of cellular response using high-throughput methods coupled with bioinformatics tools. Banerjee et al. [19] reviewed several aspects of systems biology, including enzyme discovery, pathway reconstruction, pathway prediction, and strain optimization for producing better algal strains. System biology played important role in diverting the metabolism of algae to over synthesize the desired products, i.e., lipids, polyunsaturated fatty acids, hydrogen, pharmaceuticals, etc. These metabolic changes in the algal metabolic machinery are guided by transcriptomics, proteomics, and metabolomics approaches. In order to improve the algal strains for biofuel production, some targets such as salinity tolerance, heavy metal tolerance, pest tolerance, disease resistance, and other abiotic (pH, temperature, and light) tolerance traits must be genetically engineered to enhance the fuel productivity.

Table 11 Role of algal nutrient dynamics (AND) to improve algal biomass cultivation with wastewater according to literature available with different models

Descriptions	Model Equation	Parametric value	Ref.
Relationship between light intensity and nutrient			
Docostere model Modeled growth of the species as function of CO_2 and HCO_3^- with preference for CO_2	$\frac{dX_A}{dt} = \mu_{\max}\left(\frac{K_{HCO_3}}{K_{HCO_3}+K_{HCO_3}}\right) \times \left(\frac{K_{CO_2}}{K_{CO_2}+S_{CO_2}}\right) \times X_A$	*Chlorella vulgaris* $\mu_{\max}$ (day^{-1}) = 0.48 to 0.52 K_{HCO3} gm^{-3} = 3 K_{CO2} gm^{-3} = 0.2	[41]
Modeled algal growth as a function of carbon dioxide, total nitrogen, and light intensity	$\frac{dX_A}{dt} = \mu_{\max} f\left(\frac{S_{CO_2}}{K_{CO_2}+K_{CO_2}}\right) \times \left(\frac{K_{CO_2}+S_{NO_3}}{K_{NH_4 \times NO3} \quad +S_{NH4}+S_{NO3}}\right) \times X_A$	$\mu_{\max}$ (day^{-1}) = 0.991 K_{CO2} ($g(C)m^{-3}$) = 0.14 $K_{NH4+NO3}$ = 0.001 mol/m^{-3}	[50]
Steele model Relationship establishes between algal growth and light intensity and can also be calculated by Lambert beer law	$\frac{dX_A}{dt} = \mu_{\max} \times \frac{f(I)S_N}{K_N+S_N} \times (I-\left(\frac{Q_0}{q_p}\right) \times X_A\ )$	*Scenedesmus sp.* LX1: *f*(*I*) = as the Steele function $\mu_{\max}$ (day^{-1}) = 0.79 S_N = concentration of nitrogen K_N ($g(N)\ m^{-3}$) = 9.5 ± 2.9 Q_0 = phosphorus content in algal cell q_p = 0.019 0.003	[138]
Modeled algal growth as a function of temperature, light intensity, ammonium and nitrate	$\frac{dX_A}{dt} = \mu_{\max}.f(t) \times (I/(K_I + I) \times \left(\frac{S_{NH4}}{K_{NH4}+S_{NH4}}\right) \times X_A$ $\frac{dX_A}{dt} = \mu_{\max}.f(t) \times (I/(K_I + I)\times) \times \left(\frac{S_{NO3}}{K_{NO3}+S_{NO3}}\right) \times \left(\frac{K_{NH4}}{K_{NH4}+S_{NH4}}\right) \times X_A$	$\mu_{\max}$ (d^{-1}) = 2 Θ = 1.07 T_0 = 20 °C K_{NH4}(mol/m^{-3}) = 0.01 K_{NO3}(mol/m^{-3}) = 0.01	[163]
Modeled algal growth as a function of ammonium, nitrogen, phosphorus, light intensity, pH, and temperature	$\frac{dX_A}{dt} = \mu_{\max}.\min\left[\min\left[\frac{K_{NH_4}+S_{NO_3}}{K_{NH4+NO3}+S_{NH4}+S_{NO3}}\right]f(I)\right] \times \frac{K_{pH}}{K_{pH}+Y(pH)} \times f(t)\ X_A$	T_0 = 20 K_{pH} = 0.5 $\mu_{\max}$ (day^{-1}) = 1.13 $K_{NH4+NO3}$ ($(g(N)m^{-3}$) = 0.025 K_{PO4} = 0.01 g^{-3} K_{pH} = 150 optpH = 7.1	[147]
Modeled algal growth as a function of carbon dioxide, light intensity and temperature according to *f*(*T*)	$\frac{dX_A}{dt} = \mu_{\max}.f(I) \times \left(\frac{S_{CO_2}}{K_{CO_2}+S_{CO_2}}\right) \times X_A$ $f(I) = e^{-F_D(S_D+S+B_D+X+A_D.A)} \times L(t)$ $L_{(t)}$ as a function describing the diurnal variations in light intensity, F_D as a scattering and absorption factor, *S* and S_D as the substrate and its density, *X* and B_D as the bacteria and its density, and *A* and A_D as the algae and its density	$\mu_{\max}$ (day^{-1}) = 1.13 K_{CO2} ($g(C)\ m^{-3}$) = 0.14	[172]
Modeled algal growth as a function of carbon dioxide, light intensity, pH, and temperature	$\frac{dX_A}{dt} = \mu_{\max}.f(T).\left(\frac{I}{K_F+I}\right).\left(\frac{S_{CO_2}}{K_{CO_2}+S_{CO_2}}\right).\frac{K_{pH}}{K_{pH}+y(pH)}.X_A$	$\mu_{\max}$ (day^{-1}) = 0.5 K_{CO2}(gm^{-3}) = 0.12 K_{pH} = 189 *y*(pH) = 7.1	[60]
A model describing algal growth as a function of temperature, light intensity, ammonia, and soluble phosphorous	$\frac{dX_A}{dt} = \mu_{\max}.f(T).f(I).\left(\frac{K_{NH_3}}{(K_{NH_3}+S_{NH_3})}\right).\frac{S_P}{(K_P+S_P)}.\left(1-\frac{X_A}{\acute{\eta}_A}\right).X_A$	$\mu_{\max}$ (day^{-1}) = 0.5 Θ = 1.07 T0 = 20 C	[113]
A model describing algal growth as a function of light intensity and carbon dioxide	$\frac{dX_A}{dt} = \mu_{\max}.\min\left(f(I).\frac{S_{CO_2}}{(K_{CO_2}+S_{CO_2})}\right).X_A$	$\mu_{\max}$ (day^{-1}) = 0.98 K_{CO2} (gm^{-3}) = 0.082	[50]
A model describing algal growth as a function of light intensity, carbon dioxide, and total inorganic nitrogen	$\frac{dX_A}{dt} = \mu_{\max}.f(I).\left(\frac{S_{CO_2}}{(K_{CO_2}+S_{CO_2})}\right).\left(\frac{S_{NH4}+S_{No3}}{K_{NH4+NO3}+S_{NH_3}+S_{NO3}}\right).X_A$	$\mu_{\max}$ (day^{-1}) = 0.9991 K_{CO2} = 0.12 mol m^{-3} $K_{NH4+NO3}$ = 0.014 mol m^{-3}	[172]

To improve the economy of biodiesel production from microalgae, the first step is to obtain improved microalgal cultures having high biomass and lipid feedstocks from diverse environment for biodiesel production. Second step is genetically improving microalgae; for this, a variety of bioengineering technologies have been introduced, such as RNA gene silencing, homologous recombination, alteration of gene sequences, tissue culture and transformation optimization, enhancing abiotic stress tolerance, and multi-gene engineering. These technologies can be applied as a useful tool for genetically altering microalgal-based biodiesel. Creation of various algal strains through domestication, hybridization, mutation breeding, gene editing, genetic engineering and simultaneously selection of algal strain, evaluation, multiplication, and release of new variety is an innovative approach for algal-based biofuel production. In the same line, one of the most efficient and cost-effective ways of biodiesel production is the direct synthesis of fatty acid ethyl ester (FAEE) biodiesel in microalgae cells bioengineered with the co-expression of the three enzymes: pyruvate decarboxylase, alcohol dehydrogenase, and wax ester synthase, because these enzymes play a key role in the synthesis of FAEEs [43]. In general, the quality of biodiesel is determined by its chemical composition and structural properties; thus, high oleic acid and high oxidation stability of biodiesel may be the key molecular properties for high-quality biodiesel [7, 11]. The main target for high biodiesel production from algae are as follows: (i) enhancement of PS efficiency of microalgae by over expression of CA; (ii) extracellular production of FFA and TAG by genetic manipulation of fatty acylthioesterase and acyl-CoA synthetase (ACS); (iii) extracellular production of fatty acid ethyl ester (biodiesel) by genetic manipulation of pyruvate decarboxylase, alcohol dehydrogenase, and wax ester synthases; and (iv) quality biodiesel production by genetic manipulation of stearoyl-ACP Δ9 desaturase, thioesterase, ACS, and denaturizes. The availability of sequence and assembled genomes of most of the algae is no longer a limiting factor for algal domestication, though the functioning of whole of their genes is limiting our understanding. Today, our understanding of algal genomes, coupled with high-throughput screening and sequencing methods, including high-throughput sequencing, allows us to rapidly associate genotypes with phenotypes [120]. This increased understanding of gene function will help in increasing the rate at which we improve algal productivity. Du and Benning [53] and Guihéneuf et al. [65] sequenced the genome and developed transformation methods for manipulating the lipid synthesis pathways of *Nannochloropsis gaditana*, enabling considerable strain improvements using genetic engineering (GE) technologies (Fig. 3).

5 Bioeconomic assessment with suggestive measures

The economic feasibility of mass cultivation of algal biomass depends on a variety of facts, i.e., the feedstock entailed for

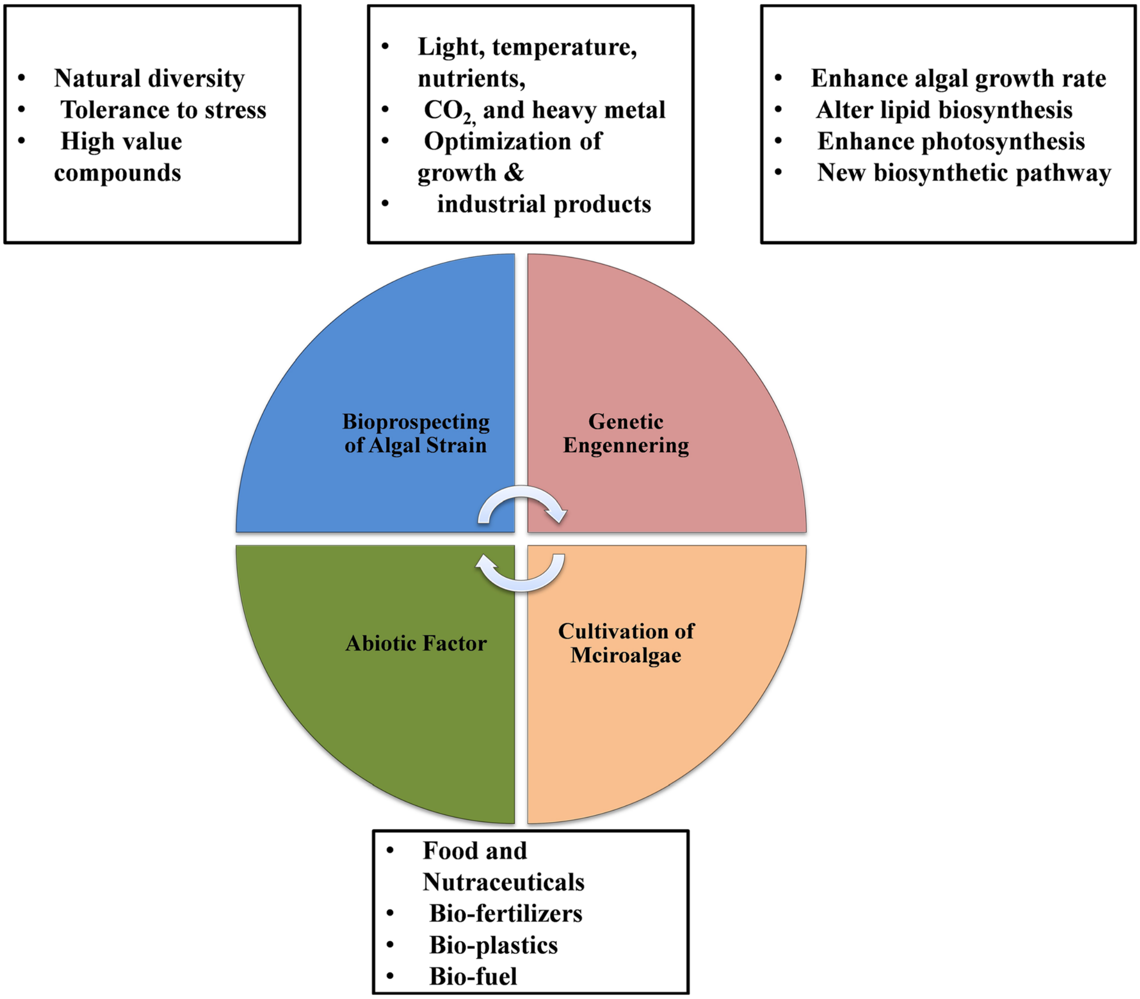

Fig. 3 Proposed different ways to improve microalgal strains for multifarious benefits

algae should be with low input such as consumption of CO_2 from waste flue gases, nutrient constraint from wastewater generated from diverse industries, development of wasteland (arable and non-arable) with low agricultural value, etc. Use of an alternative feedstock focuses to curtail the cost of algal biomass production [13]. To make algal biodiesel and other value-added products cost competitive with another source of fuel, inexpensive substitute/raw materials are extremely required, or it (algae) can be directly grown on eutrophicated source of water, i.e., sewage water. The authentic cost of biomass generation and biocrudes production entirely depends on the value of procurements of seeds, the scale of manufacturing, government policies related to taxation, appropriate marketing of biofuel and by-products, and utilization of algae given in proposed in Eq. (3).

$$C_{\text{production}} = \sum_i C_{\text{capital}} + \sum_i C_{\text{operating}} - \left(\sum_i C_{\text{product}} \right) \tag{3}$$

Typical algal biomass productivity in open pond system is 30 to 50 ton ha^{-1} year^{-1} and only harvesting cost contributes to about 20 to 30% of total cost of mass cultivation of algal biomass. Hence, to minimize the harvesting cost, the input raw material must be cheaper, i.e., of zero cost [88]. Earlier it was not feasible on the technical ground, but now it is possible to make established plant near the flue gas emission sources. Carbon sources from flue gasses can be utilized by the algal biomass. Although it requires some technological expenses, it is on time venture and longtime attainment in Eq. (4).

$$C_{\text{production}} = \sum_i C_{\text{capital}} + \sum_i C_{\text{operating}} - \left(\sum_i C_{\text{product}} + \sum_i C_{\text{wastewater}} + \sum_i C_{\text{fluegas}} + \sum_i C_{\text{wasteland}} \right) \tag{4}$$

Table 12 Capital cost of open pond system (per hectare) [129]

Parameter	Cost analysis ($) with conventional type of system before suggestive measure	Cost analysis ($) after suggestive measures marked in their study to replace the conventional parts of system
Site preparation, gardening, compacting	2500	2500
Pond leave geotextile	3500	3500
Paddle wheel	5000	5000
CO_2 supply and diffuser	10,000	Nil
Settling ponds	7000	7000
Flocculation, centrifugation, oil extraction	14,500	14,500
Water and nutrient	5200	Nil
Building, roads drainage	1000	1000
Electricity infrastructure	2000	Nil
Backup generators	–	–
Instrumentation, machinery	500	500
Land	2000	Nil
Engineering and contingency	8280	8280
Total	61,480	42,280 (~ 31%) reduction

For the establishment of an overall cost production value, evaluation of capital cost and operating costs minus the revenues generated from the entire main and co-products generated from algal biomass must be known [152].

Table 12 is portraying the cost analysis for different parameters associated before and after suggestive measures on comparative basis, where utilization of wastewater, flue gases, and wasteland took with a zero cost; a remarkable reduction of ~ 31% has been predicted in cost at commercial scale on replacement of eco-friendly option with conventional ones where cost was estimated in USD ($) [146]. Therefore, these suggestive measures are economically viable for mass cultivation of algae.

Capital cost is usually related to the one-time expense, i.e., cost of land area (non-arable/barren land), buildings (i.e., indoors or outdoors cultivation system, offices, laboratories, etc.), types of equipment (i.e., reactors, dryer and filter, etc.), other infrastructures (piping and pumps). While, operating cost regarding mass cultivation of algal biomass is combined with the day to day expenses such as power supply (i.e., power required to operate photobioreactors/ padded wheels in open pond system, etc.), raw material required for algae (i.e., water, carbon sources, nitrate, phosphate etc.), expertise cost, labor cost, and other maintenance cost. There are various co-products after lipid extraction is produced such as carbohydrate, protein, pigments, and carotenes, which can be used further in different fields, i.e., medicine, pharmaceutics, biofertilizer industries, and nutritional food, which is adequate to enhance the market potential of algal-derived products as described in Table 13.

Therefore, it would minimize the overall cost given to the whole system as given in Table 13. Similarly, commercialization of any technology would not be complete if cost involvement not used from raw material to final product including revenue generation after the system establishment till next 20 year. Hence, revenue generation or profit analysis from the system totally depends upon what type of reactor (close or open) is chosen for the gain of large quantity of algal biomass. In a study conducted by Zemke et al. [171], cost–profit analysis has been done with the use of photobioreactor for revenue generation, i.e., if photobioreactor was built with a capital cost, C, to be recovered in t years, with an annual rates of returns i, the required annual payment, Q, would be expressed in Eq. (5-7).

Table 13 Various commercialized firms working with CO_2 capture technology for algae culture

Algae companies	Country	Founded	Description	Product	Ref.
IGV Biotech	Germany	1960	This company uses advanced technology for the cultivation of photosynthetic microorganisms and CO_2 capture	IGV Biotech develops microalgae biotechnology processes for the production of several products such as food, pharmaceuticals, and chemicals	[75]
Seambiotic Ltd.	Tel Aviv, Israel	2003	Use flue gas from coal burning power stations	Company aims to develop microalgae biomass for the production of food additives and biofuel	[28]
Algenol Biofuels	Florida, USA	2006	The company uses CO_2 and seawater as a culture medium. Nitrogen fixing technology is used to reduce production costs of fertilizers by cyanobacteria	Bioethanol	[3]
Solix Biofuels, Fort Collins, Colorado	USA	2006	Proposed to build its first large-scale facility at the nearby New Belgian Brewery, where CO_2 produced during beer production would be used to feed the algae	Intends to use microalgae to create commercially viable biofuels	[73]
AFS Bio-Oil Co.	San Francisco, USA	2010	Algae fed by nutrients recovered from wastewater treatment plants, and thermal power plant	Biodiesel, the primary product produced	[4]
AFS Biofarm™	San Francisco, USA	–	Uses CO_2 sequestered from industrial facilities and power plants	For conversion into renewable fuels and other valuable products such as food additives	[3]
Aeon Biogroup	Chile	–	This company develops biomass production methods with CO_2 capture from winegrowing	For the production of oil, nutraceuticals, food additives and biochemical compounds	[40]
A2BE Carbon Capture, Boulder, Colorado	USA	–	The companies develop carbon capture and recycle systems to use industrial CO_2 for algae culture follow by biomass gasification	Biofuel production	[30]

$$Q = C_i(1+i)^t/(1+i)^t\Big)-1 \tag{5}$$

Q must be less than or equal to the revenue from the photobioreactor minus the expenses:

$$Q \le \Big[\Big(\Big(V_{cl}\times F_{cl}\Big)/P_{cl}\Big) + \sum_i Fi.Vi + \sum_i Si - \sum_i Mi\Big] Pa - \sum_i Ai \tag{6}$$

$$Q \le \Big[\Big(\Big(V_{cl}\times F_{cl}\Big)/P_{cl}\Big) + (1+Fcl)Va + S - M\Big] Pa - A \tag{7}$$

The current techno-economic assessment of algal biomass cultivation should be interdisciplinary, by the use of flexible modeling and analysis scaffold that must address the multiple pathways, in coupling with various integration systems for mass cultivation of algal biomass production as well as biofuel and other value-added productions. Although the lipid production and its value-added products are superior to terrestrial oil bringing plants, nevertheless, the cultivation and downstream processing required lots of energy but by the use of biorefinery concepts, i.e., a ground-breaking solution over cost reduction has been proved a milestone. For amplifying the economic feasibility of the whole scenario, this concept must be applied to move towards the biorefinery concept. Biorefinery concept has significant credibility to minimize the capital cost by many folds, which is an attractive approach concerning sustainable algal biomass cultivation as given in Fig. 4. As a consequence, the positive opportunity for using algal biomass with bioenergy options including another value-added product is best suited for biorefinery concept. Algal biorefinery could generate about tenfold more profit than the single use of bioenergy option.

6 Applications of deoiled algal biomass

To explore algal-based green economy with significant benefits, focus should not be restricted primarily on fresh or known algal-based biofuel production

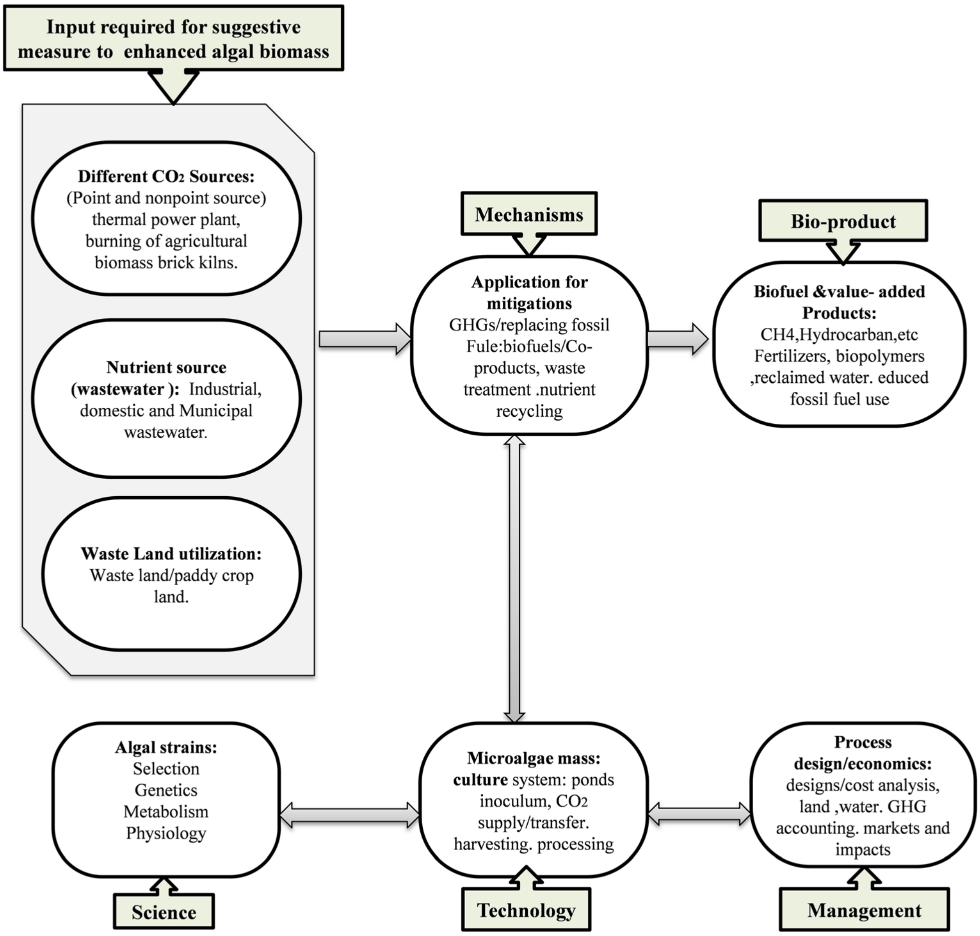

Fig. 4 Low-cost approaches to enhance algal biomass production

processes, deoiled algal biomass (remaining algal biomass after oil extraction) also have the potential to use it for other value-added bioproducts without exploiting environmental and economic benefits; different processing routes to explore these products are shown in Fig. 5. Biomass conversion into biofuel is potentially significant as the remaining biomass can be further applied to produce other chemicals and biomaterials in order to maximize the value of waste algal biomass as well as minimizing waste over the environment, considered here as spent algal biomass. The sustainable cultivation and processing of algal biomass make a broad spectrum of products generated by pure and raw algal biomass. The broad spectrum of algal-based main products and by-products is economically feasible to support the green economy based on algal biomass. Therefore, it is easy to produce high value (biodiesel, bioethanol, biohydrogen, and biogas) and low-value products (cosmetics, pharmaceuticals or neutraceuticals, feed, and fodder, fertilizer, etc.) simultaneously by the application of pure and raw algal biomass [7, 87]. A wide range of industries are being targeted for the use of algal biomass: (i) food industry (bioemulsifier, edible coating, etc.); (ii) cosmetic industry (antioxidants, antibacterial cream, other skin enhancement lotion, etc.); (iii) pharmaceuticals (formulation of vaccines, healing agent, immune modulator agents, inflammatory agents, etc.), given in Table 14.

The spectrum of applications of algal biomass with biodiesel and glycerol ethers from algal bio-oil is a new field of research and need more attention from scientific community [9]. Lipid is the main focus of algal biomass for biodiesel production but bioplastics is another example of commodity bioproducts with huge market opportunities which can be produced by lipid, protein, and carbohydrate. Therefore, in conversion of biofuel and fractionation process of algal biomass, the aqueous hydrolyzate residues along with cell debris is enriched in protein, carbohydrate, peptides, and amino acids. These value-added products, i.e., protein as food and feed, bioplastics, foams, adhesive, biocomposites, are being produced from the deoiled algal biomass after biofuel production.

It has been estimated that 4.5 million tons of residual biomass (algae) are being generated from every billion gallons of

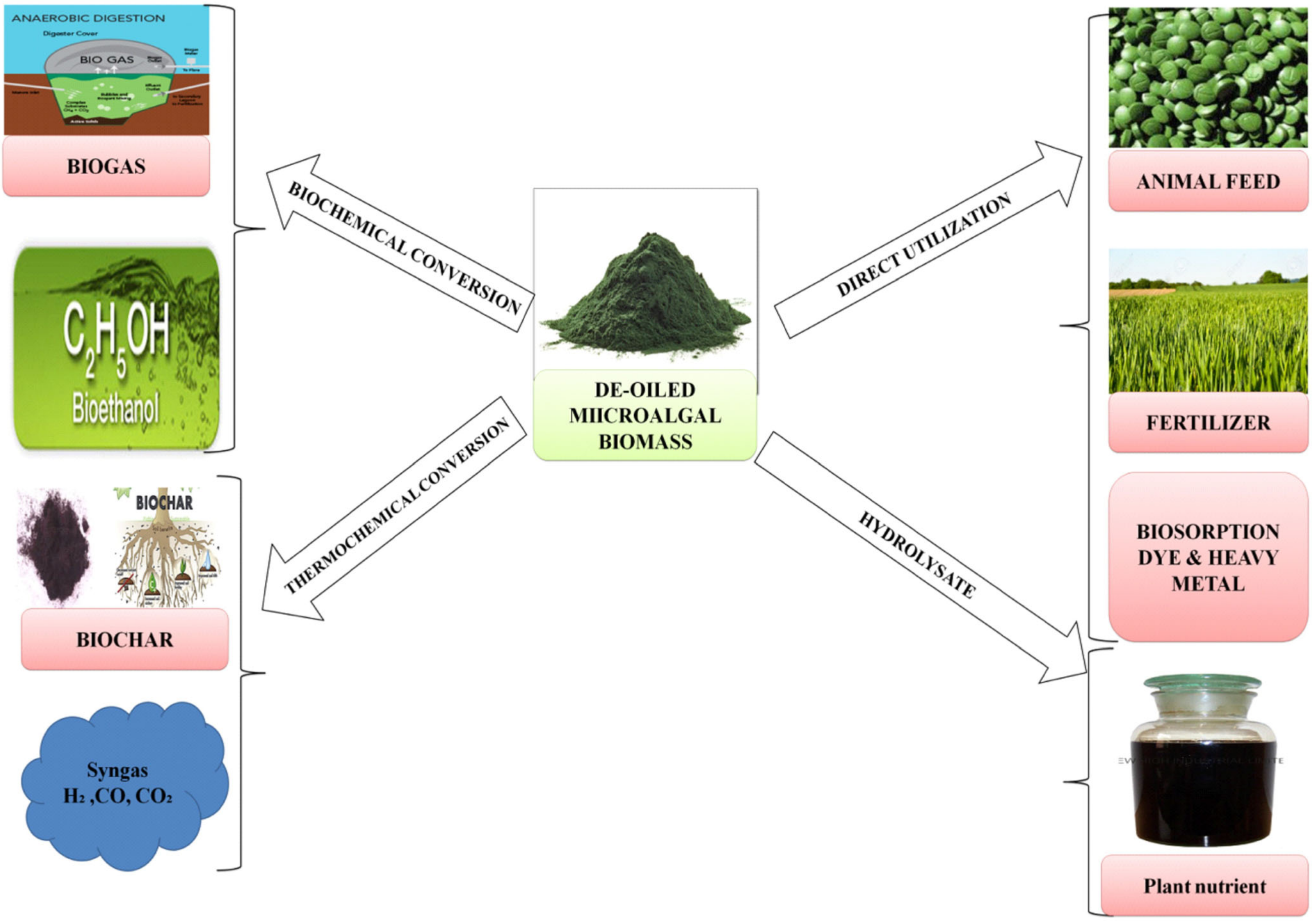

Fig. 5 Various products and their routes from deoiled algal biomass (DAB)

produced biodiesel. Although, the algal-based economy is challenging; hence, it is important to harness maximum valuable products from residual biomass. Adessi et al. [2] reported stoichiometric H_2 yield, i.e., 33–397.8 mL H_2 g^{-1} from residual algal biomass. Yu et al. [167] reported 15 ± 2% lipid content in dry biomass of *C. reinhardtii* strain D1 after hydrogen production. The total obtained lipid content was characterized by the presence of 3.3% w/w oil of phytols, 21% w/w oil of triglycerides, 39% w/w oil of polar lipids, and 41% saturated fatty esters, 53% mono unsaturated fatty esters, and 7.2% poly unsaturated fatty esters. The residual biomass (oil cake) after biodiesel production is rich in glycerol and stores 35–73% carbohydrate and proteins which is by-product of the transesterification process and can be used in livestock feed [168]. Quinn et al. [119] have reported 140 mL CH_4 g^{-1} from deoiled algal biomass of *Nannochloropsis salina.* Similarly, Mishra et al. [101] have also reported an average production of biogas, i.e., 426.26 and 446.02 mL/day from deoiled algal biomass (*Microspora* sp. and *Chlorella vulgaris*). Subhash and Mohan [150] have reported a significant hydrogen yield, i.e., 4.9, 3.3, 3.0, and 2.4 mol/kg from different forms of deoiled microalgae, i.e., extract, slurry, solid, and untreated algae, respectively. Zhang et al. [172] have utilized *Chlorella* sp. (deoiled algae) and molasses for lipid production. The author has reported 335 mg L^{-1} day^{-1} of lipid production with maximum concentration of biomass mixture, i.e., 5.58 g/L from deoiled microalgal biomass hydrolysate and molasses. Anaerobic co-digestion of deoiled microalgae, i.e., *Botryococcus braunii*, with activated sludge (413 mL CH_4 g^{-1}) and glycerol (448 CH_4 g^{-1}) for biogas production has been reported by Neumann et al. [104] and Beltrán et al. [24].

Similar to this context, a wide range of research has been conducted and is being processed for algal-based biofuel production with variation in wastewater composition [83, 89, 109]. Use of dairy industry wastewater, textile industry wastewater, and wastewater from common effluent treatment plant is very well explored with the use of *Chlorella pyrenoidosa* and *Chlamydomonas polypyrenoideum* for algal bio-oil and lipid content by the authors and his research team, although various other researchers also explain the algal-based bio-oil content in integration with wastewater treatment [86].

Table 14 Applications of DAB after biofuel production: literature view

DAB	Uses	Comments	Ref.
Chlorella sorokiniana	Biogas and butanol	Butanol yield: 0.19 g L^{-1} carbohydrate, 8.83 kJ CH$_4$ g L^{-1} DMB, 0.68 kJ H$_2$ g L^{-1} DMB	[134]
Scenedesmus sp.	Saccharification	Chemo-enzymatic hydrolysis of DMB: achieved 37.87% (w/w) and 43.44% saccharification yield respectively for 0.5 M HCl and viscozyme L (20FBGU g1) treatments on DMB	[107]
Scenedesmus dimorphus	Bioethanol	Maximum 0.26 g bioethanol per gram of DMB without any pretreatment	[134]
Lyngbya majuscule	Nutrient source	Protein-rich hydrolysate of DMB used for enhancement of lipid and growth of *C. vulgaris*: 25% replacement of BG11 media with hydrolysate found optimum for growth & lipid enhancement	[100]
Chlamydomonas sp., *Chlorella sorokiniana*	Pyrolysis	Non-isothermal pyrolysis of DMB, five pseudo-components model was applied for kinetic modeling	[33]
Nannochloropsis salina	Soil additives	Increases the organic carbon in soil	[130]
Chlorella variabilis, *Lyngbya majuscule*	Fertilizer	DMBs were used directly as a fertilizer substitute for *Zea mays* L.	[100]
Nannochloropsis salina	Biogas	220 mL CH$_4$ g L^{-1} VS from untreated DMB; 15% increased CH$_4$ production by enzymatic treatment	[31]
Chlorella sp.	Pyrolysis, fertilizer	Biochar produced through slow pyrolysis could be used as a high-N ($> 10\%$), rich minerals, and porous fertilizer	[38]
Chlorella sp.	nutrient source	Highest biomass concentration of 5.58 g L^{-1} and lipid productivity of 335 mg L^{-1} day^{-1} at the mixture ratio of DMB hydrolysate and molasses of 1/4	[174]
Nannochloropsis sp.	Biogas production	Maximum biogas production was obtained 417 mL CH$_4$/g, at the same time it was found that thermal pretreatment process of deoiled microalgae enhances 40% of biogas production	[15]
Dunaliella tertiolecta	Bioethanol	Bioethanol was obtained 82% from the saccharification process	[95]

7 Conclusion and discussions

It is clear from the present review that algal cultivation coupled with wastewater treatment and CO$_2$ capture from flue gas released from industrial exhaust fulfills the criteria of technical feasibility, economic viability, and resource sustainability. Wastewater generated from different sectors such as municipal, industrial, and agricultural sector offers a cost-effective source of nutrients for algal cultivation. Such process not only reduces the cost of algal nutrients but also save the energy expenditure in wastewater reclamation. On the other hand, algal cultivation in wastewater coupled with flue gases supply from various point and non-point sources is found more efficient in terms of economic and technical viability. In this process, enhancement in algal productivity, lipid content, and carbohydrate content was observed by various researchers. Further investigations are required to improve the system designs/reactors based on earlier investigations to achieve maximum efficiency and biomass productivity. For commercial-scale algal production, open race way pond is still found as suitable and cost-effective cultivation system; however, it require further investigations focused on location of selected site, climatic conditions (light intensity and temperature), with different aquatic medium (saline/brackish/industrial wastewater) as a nutrient source in addition to input of CO$_2$ concentration and cell concentration. With large-scale algal production processes, the wastewater-nutrient-flue gas dynamics is the subject of significant consideration with multifaceted approaches. Modification in the existing technologies and their integration with biorefinery concept with water footprinting and water networking can cut down production cost and product cost as well (Fig. 5). Environmental waste streams of water and air from industries with point and non-point sources with emphasis on WFP and GWN with wastewater and combined influence of both waste streams on algal biomass are discussed here with all related pros and cons. Similarly, ANWFD to increase biomass is a salient feature of this article.

Algal biomass cultivated under such integrated system can be used for synthesis of value-added compounds such as lipids, carbohydrate, polyunsaturated fatty acids (PUFAs), etc. Since wastewater grown biomass may contain harmful organic and inorganic substances, hence it is not suitable for use as food or feed. Thus, conversion of lipid into biodiesel is considered as mist suitable end product of these integrated processes. Energy recovery from algal biomass can be enhanced by applying various energy conversion pathways with different components of algal biomass. It is important to identify suitable energy conversion pathway for maximizing the energy recovery from algal biomass. Spent algal biomass is also used as a feedstock for bioenergy production; most of the researchers have investigated biomethane potential of spent algal biomass in integration with biodiesel production. In order to attain environmental sustainability, concepts of green chemistry should be employed in different energy conversion pathways; for example, enzyme-mediated single step transesterification of algal oil involves less chemical consumption with greater efficiency than the conventional transesterification process. It is suggested to identify the resource availability by implication of remote sensing and geographic information system-based technologies, which are important to locate the available aquatic bodies for algal cultivation and industrial establishments. Algal farms equipped with wastewater–flue gas supply, genomics tool, and with in silico prediction models are required for development of better algal traits for high yield biofuel production under varying climatic conditions. These discussed factors could create standard long-term economically viable solutions to overcome the present limitations of the oil sector with prospective bioeconomy.

7.1 Prospective approach

1. ANWFD approach assured to disinfect the environment (air and water) in our surroundings from harmful emissions and discharged pollutant loads (N and P) as algal biomass is the only solution that sequesters both and generates oxygen for sustainable ecosystem.
2. ANWFD approach although involves high capital cost of the system but long-term benefits cut down the cost with multifaceted applications generated by this proposed concept.
3. Water footprinting process in integration with specific strains of algal biomass provides a positive aptitude for alternative clean and low-cost fuels.
4. Symbiosis between the several aspects of systems biology, including enzyme discovery, pathway reconstruction, pathway prediction, and strain optimization for producing better algal strains in search of sustainable bioeconomy with interdisciplinary field of engineering, opens a new door with ANWFD approach.
5. Algal-based bioresource for production of biofuel (from fresh algal biomass and spent algal biomass) has an edge over others as it leaves the least load of waste over the environment due to the wide application of remaining biomass in producing different versatile range of products.

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