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REVIEW PAPER

Emerging trends in algae farming on non-arable lands for resource reclamation, recycling, and mitigation of climate change-driven food security challenges

Fatima Tahir · Hira Ashfaq · Aqib Zafar Khan · Mahwish Amin · Iqra Akbar · Hafiza Aroosa Malik · Mohammed Abdullah · Abdulrahman H. Alessa · Ahmad A. Alsaigh · Peter J. Ralph · Muhammad Aamer Mehmood · Sana Malik

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Abstract The current agri-food systems are unable to fulfill global demand and account for 33% of all greenhouse gas emissions. Conventional agriculture cannot produce more food because of the scarcity of arable land, the depletion of freshwater resources, and the increase in greenhouse gas emissions. Thus, it is important to investigate alternate farming methods. Algae farming is a feasible alternative that produces food, feed, and feedstock using wastelands and unconventional agricultural settings such as coastal regions, salt-affected soils, and urban/peri-urban environments. This review focuses on three emerging scenarios. First is seawater, which makes up 97.5% of the water on Earth. However, it is nevertheless used less often than freshwater. Second is a growing trend of people moving from rural to urban regions for improved employment prospects, living standards, and business chances. However, most rural migrants are essentially skilled in agriculture, which limits their applicability in metropolitan environments. The third scenario focuses on excellent crop yields and soil fertility; it is essential to maintain appropriate levels of organic matter and soil structure. In this case, algae have remarkable potential for osmoregulation-based salt tolerance and may provide valuable metabolites when cultivated in brackish or saltwater. Using brackish water, treated wastewater, and saltwater, algal culture systems may be established in arid/semi-arid, urban/peri-urban, and coastal areas to fulfill the increasing need for food, feed, and industrial feedstocks. It may also provide migrants from rural areas with work possibilities, which would allay environmental footprints.

Keywords Non-arable lands · Algae farming · Alternative agri-food system · Food security · Climate change mitigation

F. Tahir · H. Ashfaq · M. Amin · I. Akbar · H. A. Malik · M. Abdullah · M. A. Mehmood (✉)
Department of Bioinformatics & Biotechnology, Bioenergy Research Centre, Government College University Faisalabad, Faisalabad 38000, Pakistan
e-mail: draamer@gcuf.edu.pk

A. Z. Khan
Guangdong Provincial Key Laboratory for Plant Epigenetics, Guangdong Engineering Research Center for Marine Algal Biotechnology, College of Life Sciences and Oceanography, Shenzhen University, Shenzhen 518060, China

A. H. Alessa
Department of Biology, Faculty of Science, University of Tabuk, 71491 Tabuk, Kingdom of Saudi Arabia

A. A. Alsaigh
Department of Biology, Faculty of Science, Umm Al-Qura University, Makkah, Kingdom of Saudi Arabia

P. J. Ralph · S. Malik (✉)
Climate Change Cluster, University of Technology Sydney, Ultimo, NSW 2007, Australia
e-mail: sana.malik@uts.edu.au

1 Introduction

Food insecurity is a growing global concern due to the expanding population, expected to rise from 7.7 billion people to 9.2 billion in 2050. Besides the expansion in global population, other factors, including climate change, evolving consumer preferences, and limited/depleting natural resources such as arable lands and irrigation water, are going to make it even more challenging to meet the increasing demands of food, feed, and industrial feedstock (Mok et al. 2020; Varzakas and Smaoui 2024). Around two billion people are already suffering from malnutrition globally, where one in every nine individuals is experiencing hunger due to inadequate protein and calorie intake (Hosseinkhani et al. 2022). To effectively meet the Sustainable Development Goals outlined by the United Nations, particularly SDG2: zero hunger and SDG12: responsible production and consumption, it is indispensable to devise strategies that can address existing challenges related to food security driven by climate change and promote synergies among different SDG targets. (Atukunda et al. 2021; Cernev and Fenner 2020). Based on the comparison of different economic models of world food consumption, it is predicted that food demand will rise from 50 to 60% between 2019 and 2050 (Falcon et al. 2022). Therefore, we can no longer rely on conventional approaches, such as increasing primary production through traditional farming techniques, to address the emerging challenge of food security (Mok et al. 2020). Instead, to deal with the subsequent food shortages, research efforts are being focused on finding novel and sustainable alternative sources for food, feed, and industrial feedstock (Roohinejad et al. 2017).

Traditional food production systems contribute significantly to environmental issues; 33% of the greenhouse gases are contributed by the agri-food systems (Unicef 2023; Soussana 2014; Lulovicova and Bouissou 2024). Methane, carbon dioxide (CO_2), and nitrous oxide are significant contributors, accounting for 23% of total greenhouse gas emissions, equivalent to the CO_2 produced between 2007 and 2016 (Shukla et al. 2019). Additionally, conventional food production systems face diverse problems, including soil degradation, freshwater shortage, run-off of excessive nutrients that pollute rivers and estuaries, and loss of biodiversity caused by improper land management practices. Due to widespread land degradation, the world's arable lands are facing an immense challenge that requires an enormous increase in production to maintain food security worldwide. An evaluation that imposed restrictions on biomass availability to alleviate food scarcity, habitat destruction, and land degradation projected a potential reduction of 3.7–6.6 $GtCO_2$-eq per year, including 2.6–4.6 $GtCO_2$ per year for carbon stabilization (Shukla et al. 2019). Land degradation and food security are strongly connected because 99% of food is produced using land (Prăvălie et al. 2021). Considering these challenges, it is widely believed that current food production methods must be revolutionized to achieve sustainability and scalability to meet global demands and ensure nutrition security and healthy lives for current and future generations (Torres-Tiji et al. 2020).

Algae (microalgae and cyanobacteria) have the potential to be used as a sustainable food, feed, and carbon–neutral industrial feedstock source, but further investigation is required before these organisms can be used in commercial-scale food production systems. The numerous species that comprise the polyphyletic group of organisms known as algae range in size from microscopic unicellular organisms like *Chlamydomonas* sp. to enormously huge multicellular organisms like giant kelp. For thousands of years, people in various cultures have consumed algae as a food source (Dillehay et al. 2008). Global demand for algae-based food is rising for several functional benefits (Table 1) besides traditional health and nutrition considerations (Wells et al. 2017). The components extracted from algal biomass such as carotenoids, omega-3 fatty acids, β-carotene, phycobiliproteins, and EPA are used as a food supplement or their health benefits in functional foods and nutraceuticals (Lucakova et al. 2022). In countries like the United States of America, Japan, China, Northern Africa, and many European countries, people consume *Spirulina*, a type of blue-green algae, as a dietary supplement. *Spirulina* is considered one of the most studied algae due to its higher protein content (Singh et al. 2023c) and health benefits (Wang et al. 2024). Specifically, *Spirulina* is the most commercially produced alga in Europe and is produced at more than 200 facilities, yielding 150 tons of dry biomass annually. This amount covers around half of the market's present demand for *Spirulina*, which is predicted to grow by 8.7% until 2025 (Kurpan et al. 2024). Algae are

Table 1 Market trends of algae-based products

Algal products	CAGR (%)	Current demand ($)	Projected demand ($)	Database
Eicosapentaenoic acid	10.8	3.2 billion	6.5 billion (2030)	https://www.futuremarketinsights.com/ https://www.expertmarketresearch.com/ https://www.alliedmarketresearch.com/ https://www.marketdataforecast.com/ https://www.fortunebusinessinsights.com/
Phycobiliproteins	8.5	34.5 million	78.3 million (2032)	
Astaxanthin	17.1	2.34 billion	7.28 billion (2030)	
Carotenoids	3.4	1.5 billion	1.9 billion (2030)	
Phycoerythrin	6.2	4.2 million	7.6 million (2032)	
β-Carotene	4.8	200 million	280 million (2028)	
Crude Protein	11.4	700 million	1.2 billion (2028)	

CAGR compound annual growth rate

different from traditional food crops in several ways, specifically the higher lipid productivity, shorter doubling time, and faster growth than oilseeds, which allows them to produce biomass that can produce up to 20 times more oil per unit area compared to the best oilseed crops like soybeans or corn (Hasnain et al. 2024; Griffiths and Harrison 2009). Algae can also make 4–15 tons/ha/year of protein, which is substantially higher when compared to wheat soybean (0.6–1.2 tons/ha/year) and (1.1 tons/ha/year) (Bleakley and Hayes 2017).

Although promising, the higher production cost of algal biomass is one of the primary disadvantages that limit its utilization for high-value products only (Lafarga et al. 2021). However, algae have numerous attractive features for sustainable large-scale production, such as high biomass production per unit area and the ability to be grown on non-arable land by using saline water or even non-potable water (Torres-Tiji et al. 2020). It does not directly compete with traditional agriculture and land and might also boost the economic activities in the areas that are unfit for conventional agricultural activities, including arid/semi-arid, non-arable regions, urban, and peri-urban ecosystems (Trentacoste et al. 2015). Besides, algae cultivation can also minimize the burden on freshwater reservoirs by utilizing unfit water (which is not fit for agriculture or household activities, such as brackish and sea) as a low-cost nutrient source for algal cultivation due to its abundance and high nutrient load (Chen et al. 2015).

Algae farming directly contributes to SDG2: *Zero Hunger* and SDG12: *Responsible Consumption and Production,* promoting food security and a sustainable future. For example, nutrient-rich algae-based food sources like *Spirulina* help overcome hunger and malnutrition. Algae also play a vital role in the sustainable production of various bioproducts, including bioplastics, biofuels, nutraceuticals, and pharmaceuticals, through adequate consumption of waste nutrients that directly relate to SDG12, focusing on environmental impact reduction and sustainable resource management. Although algae farming has incredible potential to ensure substantial development towards SDG2 and SDG12, it has yet to be practically straightforward where and how to produce vast amounts of algal biomass for food, feed, and feedstock for industrial applications. This review article highlights the scope of opting for alternative systemic strategies to utilize non-arable lands (saline soils, water-logged soils, coastal lands, urban and peri-urban areas) for algal cultivation using traditionally unfit water to combat rising climate change and food security challenges. Opting the proposed strategies will lead to establishing an alternative algae-agriculture system without competing for land and water for agriculture with concomitant production of vast amounts of algal biomass for food, feed, and industrial applications. It would also highlight new entrepreneurial opportunities, eco-friendly job markets for urban/peri-urban communities, and small landholders who own unproductive lands.

2 A comparative overview of arable and non-arable lands worldwide

In the next few decades, the arable soils may not be sufficient to support agricultural production due to continuously increasing population, industrialization, loss of nutrition because of intensive agriculture, and climate change (Montanarella et al. 2016). The adverse effects of land degradation are expected to worsen in the future. Around 50–700 million people may be forced to migrate by the simultaneous impact of land degradation and climate change by 2050. Globally, arable lands cover 14.2 million km^2, nearly 10% of the Earth's surface. Asia owns the highest proportion of arable land (Table 2) of the world's continents (37.2%), followed by North and Central America (15.1%), Africa (19.8%), South America (10.5%), Europe (13.8%), while Oceania and Australia (3.5%) has the lowest continental areas (Prăvălie et al. 2021).

The arable lands are affected by various degradation processes, including aridity, soil erosion, soil salinization, reduced vegetation, and declining carbon content, leading to reduced food production. Arable lands on all continents are at least exposed to one of the degradation processes. Regarding multiple degradation, it was found that more than 2 million km^2 (about 16%) of the global arable area is affected by two processes at once, while the incidence of three processes is currently affecting less than 0.2 million km^2 (about 175,000 km^2, or about 1%) (Prăvălie et al. 2021). The global distribution of lands and its utilization in various anthropogenic activities is shown in Fig. 1.

Around 11% of the global land area was considered arable (FAO 2021), while the remaining land, which includes deserts, woods, and urban regions, is considered non-arable. The global distribution of arable and non-arable lands plays a vital role in evaluating their utilization among different sectors like food production, animal feed cultivation, and feedstock cultivation for various industries. Arable lands are defined by their suitability for crop cultivation and are mainly utilized for growing food crops such as vegetables, fruits, and grains. Conversely, non-arable lands, which may cover deserts, grassland, and forests, are often considered for cultivating feed crops and livestock grazing to support animal husbandry. Non-arable lands can also be utilized to produce feedstock for industries through algae farming. Interestingly, the economic feasibility of algal biomass production is

Table 2 Global distribution of arable lands (Prăvălie et al. 2021)

Geographical region	km^2	a %[a]	b %[b]
Globe	14,234,399.4	9.7	100.0
Australia and Oceania	495,497.8	6.1	3.5
North and Central America	2,150,691.4	8.9	15.1
Europe	1,968,805.7	20.0	13.8
Asia	5,297,469.1	11.9	37.2
Africa	2,824,027.6	9.4	19.8
South America	1,497,907.8	8.4	10.5

[a]Absolute arable lands (%) in proportion to total continental land

[b]Absolute continental arable land (%) in proportion to the total global arable land

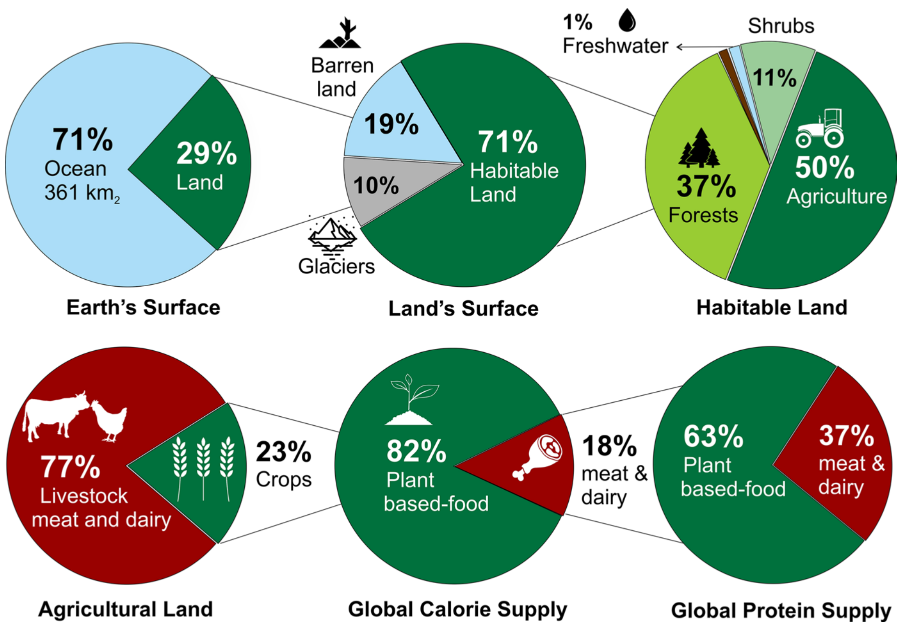

Fig. 1 Global distribution of arable and non-arable lands with reference to utilization for various food, feed, and feedstock sectors (Prăvălie et al. 2021)

believed to be increased by certain aspects, including higher annual temperatures, lower cloud coverage, and better light exposure, typical features of semi-arid areas (Winckelmann et al. 2015). Utilizing non-arable land for algae farming would raise the area available for biomass production. In contrast, selecting suitable algae species and developing practically feasible farming systems would be required. The following sections focus on some of these scenarios for cost-effective algae farming to ensure food security in the best possible and eco-friendly way.

3 Algae farming as an alternative agri-system for food, feed, and feedstocks

Due to the increasing human population and industrialization, freshwater resources are continuously depleted, limiting water availability for algae farming. Also, the need for a massive land for algae cultivation does not seem practical. Alternative possibilities should be explored and evaluated to cope with these challenges. Here, some of the alternative horizons are briefly discussed.

3.1 Comparison between algae-based food products and conventional agriculture

Algae are rich in essential nutrients, including lipids, proteins, carbohydrates, vitamins, and minerals. For instance, *Spirulina* and *chlorella* are considered highly nutritious. They contain protein up to 50–70% of their dry weight and are a great source of antioxidants, omega-3 fatty acids, beta-carotene, and other essential nutrients (Dhandwal et al. 2024 Abdel-Wareth et al. 2024). Despite this, staple crops such as rice, wheat, and maize generally have a lower protein content and lack some essential nutrients in microalgae (Gohara-Beirigo et al. 2022). Algae are more environmentally friendly than traditional protein sources and require less land and water for cultivation (Mosibo et al. 2024). Food products made from algae have been successfully introduced, demonstrating their benefits over conventional agricultural products. For example, companies like Solazyme (Now Erravia), Sophie's BioNutrients, and Triton Algae Innovations have developed innovative algae-based food products integrated into traditional food systems (Su et al. 2023).

In terms of production efficiency, conventional agriculture uses many resources; it frequently needs a lot of arable land, fertilizers, and a massive amount of freshwater. Meanwhile, crops are influenced by climate conditions and seasonal variations and typically have longer growth cycles. Algae farming requires less land, is highly efficient, and consumes less water compared to traditional agriculture. Algae can thrive in various conditions, including brackish water, seawater, and non-arable lands, which conserves freshwater resources. The growth rate of algae is also much faster, with certain species able to double their biomass in a few hours (Ullmann and Grimm 2021; Singh et al. 2023a).

Conversely, the conventional agriculture system significantly contributes to greenhouse gas emissions (GHG); the primary sources of GHG emissions are methane produced by livestock, nitrous oxide from fertilized soils, and carbon dioxide from deforestation and machinery. An algae-based agriculture system offers a more sustainable alternative with significantly lower greenhouse gas emissions. Due to their rapid growth and high photosynthetic efficiency, microalgae can capture and utilize carbon dioxide more efficiently than terrestrial plants (Tarafdar et al. 2023). Wastewater-based algal cultivation minimizes the need for synthetic fertilizers and leads to a reduction in nitrous oxide emissions (Zou et al. 2021). Moreover, biofuels, which have a lower carbon impact than fossil fuels, can be made from the algal biomass (Sarwer et al. 2022).

3.2 Algae farming on non-arable lands using brackish water

Due to increasing human activities, nearly 40% of the Earth's surface has now been occupied by arid and semiarid regions. However, due to the high salinity and brackish nature of the water in these regions, they are unsuitable for irrigation and human consumption. Consequently, these lands cannot be utilized for agricultural purposes. Interestingly, these regions provide ideal conditions for algae cultivation due to higher annual temperatures, sufficient light exposure, low cloud coverage, and less rain during annual seasonal variations. The salinity problem has continuously risen during previous decades due to improper cultivation practices, substantially compromising agricultural productivity (Jumpa et al. 2024). Brackish water has a salinity level between freshwater and seawater and is present in those regions where both water sources mix (Rich and Maier 2015). Brackish water typically contains total dissolved solids between 1000 and 15,000 mg/L and major solutes such as chloride, calcium, sodium, sulfate, and bicarbonate ions in varying concentrations depending on location and source (Gray et al. 2011). Salinity is mainly caused by chloride ions (Knuth, 1998), while its concentration varies from 30 to 150 mg/L in freshwater, 300–1000 mg/L in brackish water, and 30,000–35,000 mg/L in seawater (Stuyfzand 1986). Carbon is present in the form of carbonates, bicarbonates, and carbon dioxide that support photosynthesis (Cavalcante et al. 2022). Nitrogen exists as nitrates, nitrites, and ammonium, which is crucial for the nitrogen cycle and biological productivity (Nazneen and Raju 2017). For example, the Panoche Water District Well brackish water composition showed the presence of 337 mg/L of nitrates, 274 mg/L of bicarbonate, and 8500 mg/L of TDS along with other essential nutrients (Cohen and Christofides 2010). Although filtration technologies are being improved, these techniques are energy- and cost-intensive in treating water (Qu et al. 2013). Therefore, it is crucial to discover cost-effective and eco-friendly biological processes to utilize and recycle brackish water. Utilizing brackish water for algae cultivation may decrease the water footprint (Guieysse et al. 2013). In addition to higher biomass production, algae farming using brackish water also has the potential to reduce the competition with cash and food crops. However, brackish aquaculture encounters specific challenges due to its reliance on essential natural resources like land and water. By cultivating salt-tolerant species, brackish water can produce algae biomass (Table 3) (Elimelech and Phillip 2011). Algae require less water than oleaginous food crops, and salt stress triggers their metabolism to produce more lipids (El-Sheekh et al. 2024).

Selection of an elite strain would be the first step for large-scale cultivation using brackish water. The use of the indigenously adapted strains should be the most suitable option as the origin of those strains in the same climatic conditions will reduce the impact on growth due to biotic or abiotic factors (Rawat et al. 2013). The process of acclimating algae to high salinity levels can be divided into three stages: (1) restoring turgor, (2) adjusting the cell membrane to facilitate the absorption and release of ions, and (3) inducing the production of stress proteins and glycerol which are synthesized through photosynthesis (Thomas and Apte 1984). Salinity variation is the main factor that impacts algae growth; however, each microalga species is adapted to specific salinity ranges. It was reported that microalgae exhibited different growth responses when exposed to varying salinity levels (Mata et al. 2010). For example, the *Tetraselmis suecica* exhibited optimal growth at moderate salinity level, but its photosynthetic activity and growth rate were reduced at high salinity. Salinity stress improved lipid productivity by nearly 22% in salinity from 30 to 50 and 60 ppt (Pugkaew et al. 2019). Another study reported the impact of salt stress on growth of *Chlorococcum* sp. and *Chlamydomonas debaryana*. Results suggested that *Chlorococcum* sp. is more tolerant of salinity stress and can tolerate 200 mM NaCl concentration, while the growth of *Chlamydomonas debaryana* was reduced when salinity exceeded 50 mM NaCl (Assobhi et al. 2024). Similarly, *Monoraphidium braunii* exhibited a 10% increase in the growth of 150 mM NaCl concentration; above this range, significant inhibition was observed (El-Sheekh et al. 2024). Another study reported the impact of salinity on *Chlorella vulgaris* under NaCl concentrations between 1000 and 11,000 ppm. Results suggested that the color of microalgae changed from green to yellow, which could be due to decreased chlorophyll content at higher salinities. A decrease in the microalgae growth was observed when the salt concentration was increased beyond 4000 ppm. The dissolved NaCl is present in the form of ions and the concentration of these ions above osmotic pressure will disrupt the balance of $K+/Na+$ in the algal cells. Under these conditions, microalgae cannot perform properly (Barahoei et al. 2021).

However, contamination is the major issue among various challenges, impacting the microalgal growth and metabolite composition. The contaminants such as bacteria, other microalgae, and fungi can compete for nutrient availability and light, leading to decreased biomass production (Wang et al. 2013). Unwanted contamination might introduce some metabolites or toxins, ultimately impacting biomass quality and limiting its application in biofuel production and food supplements (Minkina 2023). Effective control of contamination includes monitoring water quality, selecting indigenous strains, and using

Table 3 Impact of salinity on algae biomass and metabolite productivity for diverse applications

Algae species	Cultivation conditions	Biomass productivity (mg/L/d)	Carbon Fixation rate[a] (mg/L/d)	Reported outcome	Industrial applications	References
Oocystis pusilla	Brackish water (3000 ppm) with 25, 50, 75% dilution	71	130	536.8 mg/L lipids, mainly monounsaturated and saturated fatty acids	High lipid yield made it suitable for biodiesel production	Osman et al. (2023)
C. vulgaris	Synthetic brackish water (1000–11000 ppm), photobioreactor	50–321	91–588	Salinity > 4000 ppm had no impact on growth. Some cells were active even at 11,000 ppm	Biological desalination and biomass production	Barahoei et al. (2021)
S. obliquus	BG11, Synthetic brackish water (1200–8800 mg/L NaCl)	–	–	Lipid content enhanced to 21%, sedimentation efficiency 77–83%	Biological desalination, Biodiesel production	Gan et al. (2016)
Botryococcus braunii	Modified Chu medium (17–85 mM salinity)	50–84	91–154	12–28% hydrocarbons. 25–28% lipids rich in palmitoleic and oleic acids	Biodiesel production	Rao et al. (2007)
N. salina, *S. abundans* *C. vulgaris*	Municipal wastewater (5000–15000 mg TDS/L)	140 160 141	256.6 293 258	Biomethane production (241–422 mL CH_4/g VS) in *N. salina* compared	Biogas production	Mohseni et al. (2021)

[a]CO_2 fixation rate is calculated based on biomass productivity

cultivation systems that minimize exposure to contaminants (Wang et al. 2013). During cultivation, some cyanobacteria and microalgae improved the pH of wastewater to alkalinity (pH > 10), resulting in the development of a suitable ecosystem for their growth. With such high pH, chances of bacterial and fungal contamination are very low (Malik et al. 2022a; Khan et al. 2022). Therefore, selecting halotolerant microalgae species with high salinity tolerance or stains isolated from brackish water can help mitigate this issue (Barahoei et al. 2021). To cope with this issue, we must have to select the indigenous strain, especially in the case of wastewater. Various research studies have documented the successful cultivation of algae in brackish wastewater of varying salinity levels, resulting in enhanced biomass production and improved water quality. The increasing salinity affects the metabolic activity of the algae cells, leading to the diversion of metabolism to diverse metabolite synthesis, especially lipids (Fig. 2).

A few algae species, such as *Chlorella* and *Scenedesmus* have shown promising potential to grow in brackish water in a wide range of salinity because they can absorb salts for subsequent metabolic activities (El Nadi et al. 2014). Studies suggested that *Scenedesmus* sp. biomass after desalination could be a potential feedstock for different industrial applications, including biohydrogen and biofuel production (Sahle-Demessie et al. 2019). Lipid-rich *Nannochloropsis* sp. was cultivated in brackish groundwater where the strain was initially grown on the lowest salinity level of 2 ppt (parts-per-thousand), suggesting that salinity had no negative impact on growth (Sousa et al. 2014). Similarly, four microalgae species, including *Mesotaenium* sp., *Scenedesmus quadricauda*, *Dunaliella armatus* and *Tetraedron* sp. were cultivated in brackish wastewater to analyze the impact of different salinities on growth and biochemical composition. Among these species, *D. armatus* had shown exceptional salt tolerance up to 18 ppt with a biomass production of 700 mg/L. While *Mesotaenium* sp. was the least halotolerant, showing no negative impact on growth up to 11 ppt, its growth was significantly compromised with a further increase in salt concentration (18 ppt). Although *D. armatus* showed higher halotolerance, *Mesotaenium* sp. accumulated more lipids (20–25% of DW) than the other three species (von Alvensleben et al. 2016). Contrarily, cultivating marine algae in brackish water has increased biomass production from 750 to 1800 mg/L at salinity ranges of 18–22 ppt (Zafar et al. 2021b). Among freshwater algae, *S. abundans*, *C. vulgaris*, *C. reinhardtii*, and *Coelastrum microporum,* and among marine algae*, N. salina* showed the highest salt tolerance (Mohseni et al. 2020). Besides, salinity has also been shown to improve the biomass and biomethane production potential of marine algae (Bhargava et al. 2003; Mohseni et al. 2021). However, selecting the most suitable strain would depend on several factors, including the salinity of available brackish water, light, annual temperature variations, and other geographical parameters. Future research endeavors should evaluate the extent of salt-affected lands and the accessibility of brackish water to integrate the potential utilization of brackish water for algae farming on non-arable salt-affected lands to produce high-value biomass for subsequent industrial valorization.

3.3 Algae farming in coastal areas using seawater

Oceans cover almost two-thirds (71%) of the Earth's surface. Earth's total water volume comprises about 97.5% of seawater; still, it is an underutilized resource when compared to freshwater resources (Mishra 2023). The unmanaged anthropogenic activities relying on freshwater resources for different domestic, agricultural and industrial sectors are leading to freshwater scarcity and environmental degradation (Baggio et al. 2021). Algae are a diverse group of microorganisms and are of great importance due to their high adaptability and survivability with more straightforward nutrient requirements and ability to produce ecologically viable bioactive compounds coupled with bioremediation (Sánchez-Bayo et al. 2020). Algae inhabiting the coastal regions and open-ocean regions have adapted to salt tolerance by osmoregulation and can uptake essential nutrients from seawater, which are vital for their growth and metabolism (Kholssi et al. 2024).

Seawater has been extensively evaluated as a cultivation medium for algae farming (Table 4). Cultivation of *Arthrospira platensis* BEA 005B in seawater resulted in reduced protein content but with profoundly increased contents of oleic acid, zeaxanthin and some essential amino acids (Villaró et al. 2023). *Golenkinia* sp. SDEC-16, which is a halotolerant limnetic alga, achieved a biomass productivity of 260 mg/L/d, while the overall lipid productivity

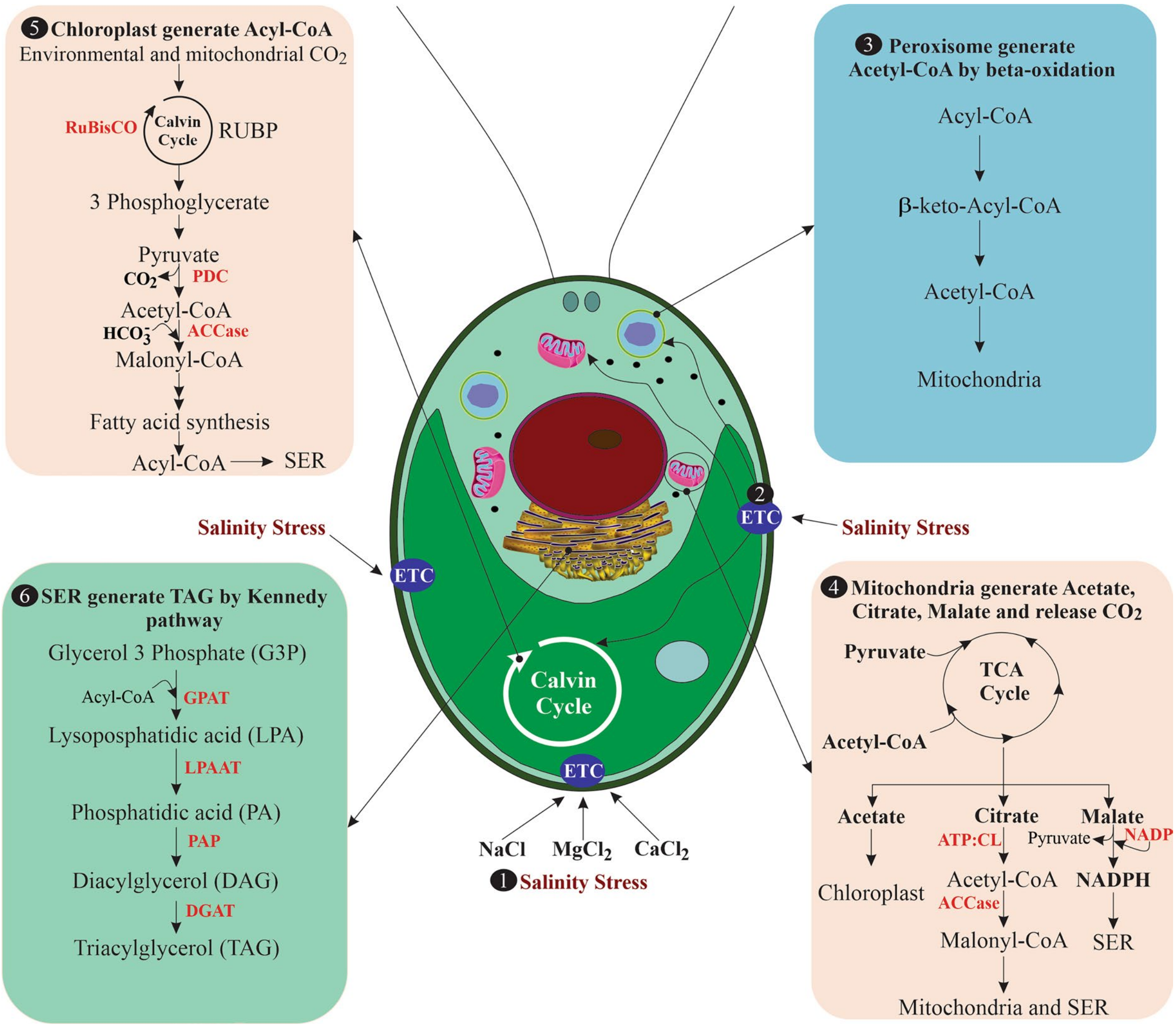

Fig. 2 Impact of salinity on metabolic pathways of algae to enhance lipid biosynthesis. (1) Salinity stress downregulates PSII and PSI and disrupts the Electron Transport Chain (ETC) of chloroplast by reducing ATP and increasing NADPH production (mainly due to upregulated alanine transaminase and glucose-6-phosphate-1-dehydrogenase under salinity stress) and adversely affects photosynthesis (2) ETC-associated proteins give signal to peroxisome, mitochondria, chloroplast to initiate lipid biosynthesis pathway. (3) Salinity stress-induced upregulation of genes (mainly pyruvate dehydrogenase E1, pyruvate decarboxylase, and phosphoglucomutase) and enhanced peroxisomal β-oxidation activity increase acetyl-CoA production (intermediate signaling molecule of multiple biosynthesis pathways) (4) Peroxisomal produced acetyl-CoA transported to mitochondria by Carnitine Shuttle System (Peroxisomal acetyl-CoA converted to acetyl-carnitine in peroxisome cytosol and transported from peroxisomal membrane to mitochondrial cytosol where it again converted back to acetyl-CoA and participated in Krebs cycle and oxidative phosphorylation) and synthesize acetate, citrate, malate, and CO_2. These products then migrate to chloroplast and smooth endoplasmic reticulum (SER) for further proceedings. (5) Chloroplasts utilize environmental and mitochondrial-generated CO_2 and synthesize fatty acids and acyl-CoA as end-products by using the Calvin cycle (6) Under salinity stress, upregulated fatty acyl-ACP thioesterase A and acyl-desaturase and downregulated acyl-CoA dehydrogenase, enoyl-CoA hydratase, and acyl-CoA oxidase genes activate Kennedy pathway of SER. Kennedy pathway uses chloroplast-generated acyl-CoA and generates triacylglycerol (TAG) as the final metabolite, lipid

was twofold higher than the control when cultured in seawater augmented with monosodium glutamate wastewater (1:1000 ratio) in a pilot scale study (1000 L cultivation) (Yu et al. 2023). *Picochlorum celeri* achieved a biomass productivity of 31–36 $g/m^2/d$ when cultured in seawater containing 35–50 ppt salts

Table 4 Biomass productivity potential of selected algae species in seawater

Algae species	Cultivation conditions	Biomass productivity (mg/L/d)	Carbon Fixation rate[a] (mg/L/d)	Reported outcome	Applications	References
Chlorella sp.	Seawater (20%, 40%, 60% and 80%) mixed with domestic wastewater	18.33 mg/L/d in wastewater containing 60% seawater	33.5	Improved algal-lipid productivity, enhanced EPS production, better sedimentation-based harvesting	Resource recovery from wastewater and seawater utilization. Biodiesel production	Gao et al. (2022)
Chlorococcum sp. RAP-13	Seawater (30–100%) in Erlenmeyer flasks	10.06 mg/L/d for 50% seawater concentration	18.44	Improved MUFAs and PUFAs	Biodiesel production and nutraceutical applications	Ummalyma et al. (2020)
Tetraselmis suecica	F\2 medium with salinity ranging from 10–60 ppt	80.70 mg/L/d obtained under 30 ppt salinity	147.9	Improved biomass production and lipid content	Biodiesel production and nutraceutical applications	Pugkaew et al. (2019)
Phormidium sp.	Walne's medium-enriched with seawater (salinity 20–60 ppt), range of light intensities	Biomass productivity was 60 mg/L/d attained at the highest salinity	109.8	Improved phycocyanin, allophycocyanin and phycoerythrin	Pigments important in food\feed and health industries	Hotos (2021)
Spirulina sp. LEB 18	Seawater augmented with 25%, 50%, 100% $NaNO_3$, K_2HPO_4, $FeCl_3.6H_2O$ and Na_2-EDTA,	140 mg/L/d at 25% nutrient concentration	256.6	Enhanced carbohydrate content	Nutraceuticals, food/feed, and biomaterials industry	Bezerra et al. (2020)

[a]CO_2 fixation rate is calculated based on biomass productivity

for approximately 143 days, in an 820 L raceway open pond. This alga was shown to be suitable in seawater cultivation at high temperatures (up to 40.5 °C), high light intensity (> 2000 μmol/m/s), and high salinity (~ 100 ppt) (Krishnan et al. 2021).

Although seems promising, algae farming using seawater faces different challenges, including the high salinity of seawater due to higher concentrations of Sodium chloride (NaCl), Sulfates (SO_4^{2-}), Calcium chloride ($CaCl_2$), Potassium ions (K^+), Magnesium chloride ($MgCl_2$), and Bicarbonates (HCO_3^-) and limited availability of land for cultivation (Novoveská et al. 2023). To obtain an integrated sustainable and circular bio-economy approach, algae can be cultivated on non-arable coastal areas and other sites unfit for crops to reduce competition for agricultural lands. Along with climate mitigation by fixing atmospheric carbon dioxide during photosynthetic activity, seawater can be utilized as a source of nutrition for cultivating indigenous algae, which have acclimatized to high salinity and have the potential to produce high biomass, rich in value-added metabolites, including lipids, proteins, pigments and other bioactive compounds having vast industrial applications (Balan et al. 2023). Besides, the desalinated seawater could be used as a sustainable water source for different agricultural and inland purposes in water-stressed regions.

However, future studies must investigate the following factors when developing large-scale seawater-based cultivation systems. Techno-economic and life-cycle assessment along with technological advancements for process automation and upscaling, bioprospecting and characterization of indigenous algae strains inhabiting the seawater, genetic engineering of algae to increase halotolerance and resource recovery, improved biomass and metabolite productivity, designing specific photobioreactors, evaluation of open ponds cultivation systems, optimizing the cultivation conditions (light intensity, pH, temperature, salinity, macro/micronutrients composition) and developing cost-effective harvesting strategies.

3.4 Challenges of using brackish water for algae cultivation

Brackish water often contains varying levels of salinity, pollutants, and other contaminants, which can directly influence the biomass productivity of microalgae (Guimarães and França, 2021). Not all algal species can tolerate salinity variations in brackish water, narrowing the diversity of algal species to be used in a wide salinity range, respectively. Therefore, the selection of algal species with high tolerance to variable salinity levels or gradual acclimatization of the freshwater algae can help to eliminate this issue (Barahoei et al. 2021). Consistent water quality management is necessary but challenging. These infrastructures need regular maintenance, adding to the operational costs (Matos et al. 2024). Urban and peri-urban areas might provide a solution for using non-arable lands, but still algae require water for cultivation, which if fulfilled by using brackish water, requires establishing facilities such as pipelines, pumps, and treatment systems, which can increase the overall cost (Bhatt et al. 2022; Singh et al. 2023b). Additionally, there are strict regulations and policies governing the use of water resources in urban and peri-urban areas (Babalola 2023).

Higher salinity levels in seawater cause osmotic stress, leading to stunted growth and varying biochemical composition in different algae species (Venckus et al. 2021). Thus, identifying species with high tolerance to saline conditions and optimizing their growth conditions is crucial (Medeiros and Moreira 2022). Other than that, seawater comprises an inadequate concentration of required nutrients essential for algae growth (Wu et al. 2021). Regular monitoring and supplementation of nutrients will increase the overall process cost (Zafar et al. 2021a). Furthermore, seawater is highly corrosive, which can damage the equipment and infrastructure used to cultivate algae. This necessitates the use of corrosion-resistant materials, increasing initial capital and maintenance costs (Kumar Patel et al. 2021).

3.5 Algae farming in urban and peri-urban environments

Urban areas have higher population density, extensive infrastructure, and some vacant and under-utilized land, such as areas unsuitable for building, gardens, and areas around the roads and streams (Li et al. 2020). However, peri-urban areas are transitory zones that experience the interface between urban and rural areas located outside of the urban centers and have a significant role in balancing urban expansion due to having more vacant and leisure areas than metropolitan areas (Sahana et al. 2023). As the world becomes more urbanized, it is estimated that developing countries will experience over 95% urban expansion during the following decades (Nation 2020), and that will come with a cost in the form of natural resource depletion, environmental pollution, climate change, and enormous human, social, and economic loses (Ahmed et al. 2020). Despite being 3% of the Earth's land, 60–80% of global energy consumption, 75% of carbon, and more than 70% of GHG emissions are contributed by urban cities (Chew et al. 2021). The UN claims that millions of fatalities are caused by air pollution exposure among city dwellers, which is 2.5 times greater than the recommended safe levels (Nation 2020). Vacant sites in urban and peri-urban areas can play a crucial role in developing green cities to fight against the climate crisis, recycle waste, cultivate renewable resources, and ensure a sustainable urban future for the next generations.

Peri-urban agriculture (PUA) is considered one of the opportunities to cope with urban and peri-urban environmental challenges (Mulya et al. 2023). PUA lands are the fertile lands in urban and peri-urban areas that yield a variety of high-value agricultural products that can become sources of food, animal feed, bioenergy, and medicine (Mulya et al. 2023; Martin-Moreau and Ménascé, 2019). PUA landscapes also serve as rainfall reservoirs, green spaces, and wildlife habitats on the fringe of urban centers (Mulya et al. 2023; Zhou et al. 2022). It is successfully established in multiple countries worldwide, including the US, England, France, China, and Israel (Mulya et al. 2023). Urban and peri-urban food production makes food more resilient to climate change and keeps food costs down by reducing the shipping costs between the farms and markets in urban areas, generating jobs and revenue (Fantini 2023). Although peri-urban agriculture systems have many advantages, they also have several constraints and drawbacks that must be carefully considered for sustainable development. To create jobs in rural areas, Antenna Technologies (a Non-Governmental Organization) has promoted spirulina farming in Tamil Nadu, India. This model was proof of the concept that a small-scale algae cultivation setup could be a good source of income for a living (http://www.algonauts.org/jacqueline/spiruline.html). AlgaePARC, a collaborative initiative of Wageningen University and industries in the Netherlands, is aimed at creating job opportunities in rural areas with algae farming using non-arable land (https://www.algaeparc.com/about). One of the significant obstacles faced by urban and peri-urban agriculture systems is the competition for land use (Ayambire et al. 2019). As cities expand, peri-urban areas frequently see increased demand for residential, commercial, and industrial spaces (Ayambire et al. 2019). The viability of peri-urban agriculture can be threatened by converting agricultural land into urban development due to this competition and can also disrupt long-standing agricultural practices (Ayambire et al. 2019). Another major challenge of this system is environmental pollution near peri-urban agriculture areas, which risks the quality and safety of crops due to industrial pollution and vehicular emissions (Gaurav and Sharma 2020). The proximity of these areas also contributes to water scarcity and soil degradation, which are made worse by increased human activity (Gaurav and Sharma 2020).

One possible and sustainable way to address issues related to urban and peri-urban culturing/cultivation systems, food and feed dilemmas, and environmental concerns is the integration of algae cultivation with the water sources available in peri-urban environments. It is estimated that terrestrial plants absorb roughly 30% of anthropogenic CO_2 emissions (Vicca, 2018), and algae, especially microalgae, can biofix CO_2 10–50 times faster than terrestrial plants (Iglina et al. 2022). It shows the tremendous photosynthetic efficiency of algae, allowing them to successfully trap carbon dioxide, helping to cope with the climate change crisis (Iglina et al. 2022). The algae biomass could be an incredible source of valuable metabolites for various applications, making them an environmentally and economically sustainable source for peri-urban culturing.

In slum urban areas, vertical or horizontal column photobioreactors could be established to cultivate algae as they can utilize vertical space effectively (Villalba et al. 2023). On the other hand, in barrel urban and peri-urban regions, as well as rooftops, the open pond cultivation setup and column photobioreactor could both be manipulated (Villalba et al. 2023). The column photobioreactors are composed of tubes or panels that are made of transparent or translucent materials that allow light to pass through the culture, and an open pond could be considered a shallow pool containing algal culture (Assunção and Malcata 2020;

Nwoba et al. 2019). Both cultivation systems could efficiently recycle urban wastewater by using it as cultivation media along with sequestration of atmospheric CO_2 and flue gases and release of O_2 in the atmosphere (Malik et al. 2022b; Usman et al. 2023; Amin et al. 2022; Abdel-Raouf et al. 2012). Urban wastewater typically contains various organic and inorganic carbon and nitrogen compounds, which can be effectively used for microalgal cultivation (Abdel-Raouf et al. 2012). The trophic mode for microalgal cultivation in the presence of carbon could be heterotrophic or mixotrophic. Microalgae can grow using different metabolic routes depending on the environmental conditions (Proietti Tocca et al. 2024). One is phototrophic metabolism, in which CO_2 is used as a carbon source, and light is used as an energy source when no substrate is available. When an organic substrate such as glucose, acetate, or other organic compounds is present instead of CO_2, microalgae can utilize heterotrophic metabolism, where the organic substrate is used for both carbon and energy sources. If the organic substrate is present simultaneously with CO_2 and light, microalgae can use both phototrophic and heterotrophic metabolism at the same time. This is a mixotrophic condition (Proietti Tocca et al. 2024). When using wastewater to cultivate microalgae, the most suitable mode of cultivation is mixotrophic. Using a mixotrophic approach allows microalgae to enhance growth by taking advantage of the energy from light and the organic carbon in wastewater, leading to higher biomass productivity and more efficient nutrient uptake (Khan et al. 2023).

Flocculation-based harvesting followed by air drying of biomass could be performed in the same closed environment (Malik et al. 2020). Dried biomass could be used as biopolymers, biogas, and biofuel feedstock. Additionally, algae biomass can also be used to fertilize green belts and lawns of parks, and recycled water can be used in washing roads and irrigating lawns, green belts, and parks in the urban environment (Amin et al. 2022; Usman et al. 2023). So, this setup will improve the environment and generate new market and employment opportunities for rural migrants to the cities.

There are multiple examples/models of algae cultivation in urban areas. Futuristic algae farms have been developed at the roadside in Geneva, Switzerland (Futuristic Algae Farm Cleans the Air in Geneva; cameralabs.org), Urban Algae Canopy, and Urban Algae (*Spirulina*) Folly developed by London-based ecoLogicStudio. A success story was presented at "Feeding the Planet Expo" in Milan in 2015 (Futuristic Urban Algae Folly Grows Food, Fuel, and Shade; zmescience.com). Moreover, The BIQ house in Hamburg, Germany, is an actual case study that uses 200 m^2 of closed photobioreactors in 120 façade-mounted boards to produce algal biomass as a renewable energy source in a low-energy multifamily residential structure (Biloria and Thakkar 2020). Furthermore, one study reported that open pond-based cultivation of *Spirulina* in peri-urban areas is an economically lucrative process. It can generate high revenue ($148.41 million-$1.62 billion annually) with an annual biomass productivity of 8600 mg/m^2/d (Richard Kingsley et al. 2023). According to Allied Market Research, there is a high demand for *Spirulina* in the market. *Spirulina's* market size was valued at $0.56 billion in 2022 and is expected to reach $1.14 billion by 2030 with an annual growth rate of 9.28% (marketresearchfuture.com). Another study examined the techno-economic feasibility of wastewater-grown *Chlorella* sp. biomass (from the cultivation process to biofuel production) and demonstrated that algae-based biofuel could be sold at the rate of $2.23/gallon, which is a feasible cost and near to an acceptable level (Xin et al. 2016).

So, it is concluded that cultivating algae in urban and peri-urban areas can have significant benefits such as pollution mitigation, biofiltering, and improving water quality and concomitantly provide feedstock to small and medium enterprises (Fig. 3). Furthermore, they can offer sustainable solutions to urban ecosystems, provide job opportunities to unemployed agricultural laborers, and stimulate economic growth through algae-based entrepreneurial initiatives in peri-urban systems.

4 Role of algae farming to cope the climate change-triggered food security challenges

The rising population needs improved soil fertility for enhanced crop productivity. Additionally, identifying and incorporating underutilized soils (marginal lands, urban and peri-urban areas) into current agricultural systems should be prioritized, while the changing climate is adding to the uncertainty of sustainable production of food/feed from the current agricultural

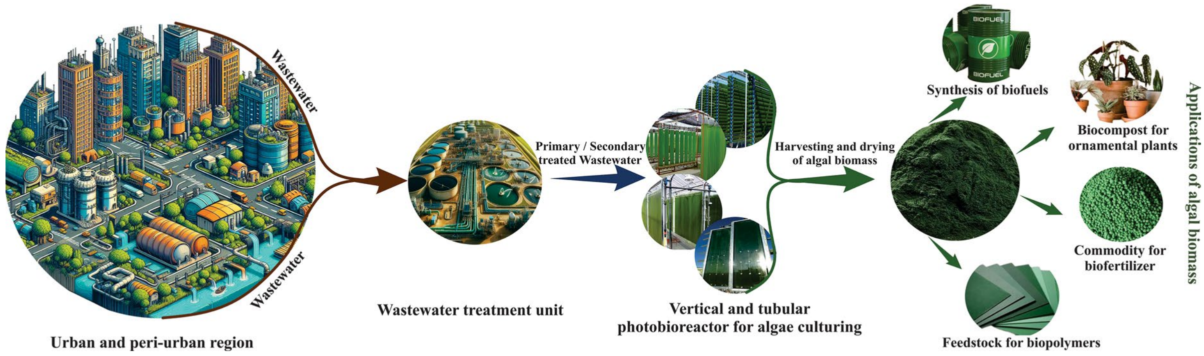

Fig. 3 Overview of algae cultivation in urban and peri-urban regions by integrating biomass production for industrial applications coupled with wastewater treatment and recycling

systems, leading to rising food insecurity. Therefore, alternative, sustainable, and cleaner sources of soil fertility and reclamation should be explored and assessed on a priority basis. The following sections highlight the role of algae biomass in improving soil fertility and reclaiming poor soils for their subsequent inclusion into agriculture systems.

4.1 Improving crop productivity through enhanced soil nutrition

Soil fertility is determined by various physical parameters such as soil aggregation, water-holding capacity, soil aeration, soil nutrient recycling, and soil drainage ability. The structure, fertility, nutrient flow, and productivity of agricultural soil may all be impacted by soil erosion, tilling, and overuse of heavy machinery. Maintaining the right amounts of organic matter and soil structure is essential for successful agriculture to obtain high crop yield and increased soil fertility. Usually, synthetic fertilizers are applied to conserve soil nutrition, but these fertilizers can affect the indigenous microbiota of the soil, thereby negatively affecting the soil nutrition (Fatmawati et al. 2023). Several algae species produce EPS (extracellular polymeric substances) in their cell surroundings, which have the potential to improve soil organic carbon, aid in particle aggregation, improve soil structure, and significantly reduce soil erosion due to the adhesive characteristics of EPS (Xiao and Zheng 2016). For instance, the addition of *Nostoc* strains to soil led to the creation of soil aggregates made of filaments and EPS, which enhanced aggregate stability six weeks after inoculation in comparison to the uninoculated control (Malam Issa et al. 2007). Poor soils are often highly compacted, low in fertility, saline or sodic, poorly aerated, and retain less water (Nichols et al. 2020). Algal biomass addition to the soil improved the water holding capacity, water infiltration, seed germination, aeration, and nutrient cycling. Soil aggregation was increased by 85%, 130%, and 160%, respectively, when *Nostoc* sp. and *Anabaena* sp. were applied to loam, silty clay loam, and sandy loam soils. Other algal species, such as *Phormidium ambiguum* and *Scytonema javanicum,* were found to increase soil aggregation and EPS content, lowering soil water repellence from silt loam to sandy soils (Chamizo et al. 2018).

Sustainable agricultural practices have significantly benefited from using biofertilizers, specifically algae-based fertilizers. These biofertilizers use the strength of beneficial microorganisms to enhance soil fertility and aid plant nutrient uptake (Fig. 4). Algae-based biofertilizers lower the environmental effects due to low energy consumption and release of transportation gases when compared to chemical-based fertilizers. They can play an essential role in nutrient regulation and availability, reducing the possibility of soil and water contamination and promoting a healthy ecosystem (Massey and Davis 2023). Algal biofertilizers provide a well-balanced nutrient profile, focusing on nitrogen and phosphorus. With their ability to fix nitrogen, cyanobacteria turn atmospheric nitrogen into ammonia, giving plants a ready-to-consume nitrogen source to fulfill their nitrogen needs (Kuraganti et al. 2020). Cyanobacteria colonize plant roots and intercellular spaces (Lee and Ryu

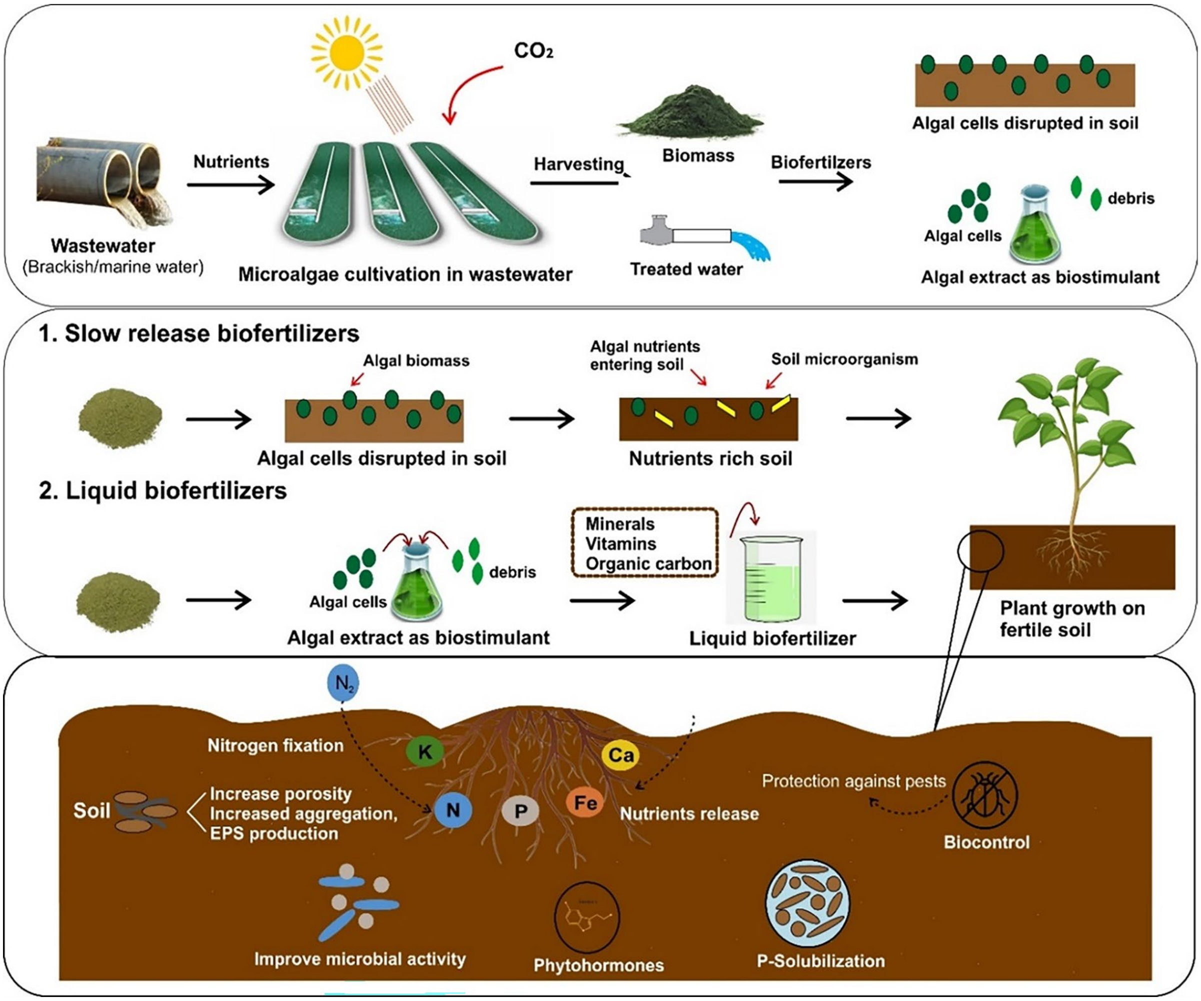

Fig. 4 Schematic diagram showing using brackish and seawater as cultivation media for algae. The treated water can be used for the irrigation process. In contrast, the algal biomass or their extract can be used as a bio-stimulant to improve plant growth by improving soil fertility

2021). Some instances have shown the invasion of rice roots by *Nostoc* spp. and the roots of wheat and cotton by *Anabaena* spp. and *Tolypothrix* spp. (Babu et al. 2015). Algae are administered into the soil as a source of N_2, either as a dried biomass or suspension for green algae or as a living culture of cyanobacteria (Alvarez et al. 2021). Adding living cyanobacteria improves soil nutrition, enhancing nutritional value for food crops. For instance, *Anabaena* sp. and *Nostoc* sp. have been used to replace conventional nitrogen fertilizers, resulting in higher levels of Fe (19.33 µg/g), Zn (8.75 µg/g), and K (1.92%) in wheat and rice grain (Prasanna et al. 2013). Grain and straw yields were improved when live consortia of cyanobacteria, such as *Anabaena* sp. and *Nostoc* sp., were used *in lieu* of 50% conventional nitrogen fertilizer in rice production (Prasanna et al. 2015a). Although algae biomass improves the soil nutrient availability, their impact on plant growth and yield may vary. For instance, compared to the control group, the inoculation of *Anabaena* sp. and *Providencia* sp. in the soil produced lower values of the cob weight in maize (Prasanna et al. 2015b). Even if less than 5% of the N content in the algae biomass is mineralized, it has the additional benefit of having less probability of leaching or loss as runoffs when compared to chemical-based N fertilizers (Mulbry et al. 2005).

Moreover, unlike urea or other manures, NH3 volatilization is not a significant problem when applying dried algal biomass (Castro et al. 2017).

Additionally, algae are excellent at solubilizing phosphorus (P), making sure that this vital mineral is readily available to crops through pH modification. Cyanobacteria may solubilize bound P in two different ways: either by releasing organic acids that encourage solubilization or by releasing chelators that bind Ca^{2+} ions (Alvarez et al. 2021). Phthalic acid is secreted by cyanobacterial species, including *Anabaena variabilis* and *Westiellopsis prolifica*, to solubilize P from phosphate rock and tricalcium phosphate (Yandigeri et al. 2011). Mineralization of P from organic P sources is another mechanism by which algae use P. Besides, algae produce specific enzymes, including alkaline phosphatases, phosphodiesterases, 5'-nucleotidases, and phytases (Markou et al., 2014), improving P availability in the soil. The accumulation of polyphosphate granules inside the cells of microalgae and cyanobacteria is executed by the absorption mechanism for P (Powell et al. 2009). This absorption is further promoted through membrane lipid remodeling, which reallocates P inside the cell according to its availability in the surrounding medium (Çakirsoy et al. 2022). Few fast-growing, high-P-uptake microalgae species, including *N. oceania, N. gaditana,* and *Tetraselmis suecia*, have been observed to accommodate additional P from the surrounding medium or reallocate P during P deficiency via polar lipid remodeling (Cañavate et al. 2017). Microalgae's opportunistic absorption of P might be used to provide plants with soluble P. Utilizing algal species that can sequester P as polyphosphate inclusions and recycle these species as biofertilizers for the slow and moderate release of P presents a sustainable approach for biological recovery of P from waste and effluent (e.g., parboiled rice mill effluent) (Mukherjee et al. 2015).

Alongside the whole biomass, applying an algal extract may positively affect the biochemical characteristics of fruits and crops and encourage crop development and yield. Foliar spraying with *Spirulina platensis*'s extracts boosted fruit output in *Foeniculum vulgare* spp. from 9920 to 12,330 mg/plant (Wafaa et al. 2017). The use of an algal extract foliar spray might affect some metrics, such as shoot length, root length, total height, weight, steam diameter, moisture content, leaf area, fruits/plant ratio, and fruit weight (Ramya et al. 2015; Díaz-Leguizamón et al. 2016). Furthermore, algae-based liquid fertilizers improved the biochemical properties of fruits and crops (Ramya et al. 2015). In maize fertilized with 6,000 mg/L of *S. platensis* extract, the protein and lipid contents were raised by 9.50–9.75% and 5.01–5.33%, respectively, compared to only 9.08–9.18% and 4.68–4.82% in the control group (El-Moursy et al. 2019). Foliar fertilization with algal extract boosted fruit juice percentage, decreased fruit acidity, and enhanced fruit ascorbic acid content in *Valencia orange* (Amro 2015). Not to mention, foliar fertilizers containing algal extracts may sometimes benefit cellular metabolisms in plants. Foliar fertilization with *Microcystis aeruginosa*, *Anabaena* sp., and *Chlorella* sp. enhanced the stomatal conductance, transpiration, intensity of net photosynthesis, stability of cytomembranes, and chlorophyll content in willow (*Salix viminalis*) (Grzesik et al. 2017). In comparison to the control treatment, the plants (*Hordeum vulgare*, *Cucumis sativus*, *Glycine max*, *Licopersicon esculentum*, *Nasturium officinale*, *Triticum aestivum*) showed an overall positive effect on plant roots when suspension (500 mg/L) of different algal species (*Synechocystis sp., Tetradesmus obliquus, C. protothecoides,* and *C. vulgaris*) was applied. The germination index of *Cucumis sativus* (140–170%) and *Licopersicon esculentum* (~130%) were also improved due to algal suspensions (Ferreira et al. 2021). Saccharide molecules from algae have already been shown to support stress tolerance, nutrient absorption, and plant development (Ferreira et al. 2021; El-Naggar et al. 2020; Farid et al. 2019). Applying *S. platensis* (0.88%) to papaya roots improved the quality of papaya seedlings and boosted growth. At the same time, applying *S. platensis* suspensions on leaves did not affect the development and quality of papaya seedlings (Guedes et al. 2018). Additionally, by enhancing nutrient and water intake, bio-stimulants may impact the process of root development, which in turn improves plant growth, health, and nutritional content. These findings imply that different algae species may impact crop development differently. Therefore, a thorough assessment of the individual impacts of algae species on crop yields is necessary before their utilization as a fertilizer.

4.2 Environmental benefits of applying algae biomass as a soil amender

Algae-based biofertilizers positively impact the environment and help alter agricultural practices toward enhanced sustainability (Mutale-Joan et al. 2023). Unlike chemical fertilizers, which require energy-intensive manufacturing processes and considerably increase emissions, biofertilizers work within the natural nutrient cycles. Utilizing biofertilizers can help lower the carbon footprint to combat climate change by reducing emissions from agriculture (Guo et al. 2020).

Chemical fertilizers frequently seep into groundwater or run off into neighboring rivers and lakes when used in excess or during heavy rain. This runoff has the potential to damage aquatic habitats by creating nutrient contamination and eutrophication (Win and Fu 2018). Contrarily, biofertilizers gradually release nutrients, lowering the chance of nutrient runoff. This protects water quality and supports initiatives to maintain biodiversity and fragile aquatic habitats. Utilizing biofertilizers also encourages soil health and biodiversity preservation. These organic compounds stimulate soil microbial activity, which is essential for the cycling of nutrients, the breakdown of organic matter, and the ability to store nutrients for longer time (Massey and Davis 2023). Additionally, biofertilizers support soil-friendly organisms, such as earthworms, insects, and other soil-dwelling creatures, thus increasing soil biodiversity and contributing to ecological balance (Osorio-Reyes et al. 2023). Hence, biofertilizers promote the long-term sustainability of agricultural landscapes as well as improved crop yields while ensuring sustainable farming practices to meet the rising food/feed demands (Rani et al. 2019).

5 Algae biocrusts for reclaiming non-arable lands to ensure food security

With the increasing population, land degradation also increases because of human activities, mainly deforestation and overcropping, to meet the living and feeding demands of growing bodies (Yirdaw et al. 2017). This is alarming for human beings and the whole ecosystem, so there is a need to restore the fertility of degraded soil (Rossi et al. 2022). For this purpose, different chemical and biological technologies are applied, including adding organic and inorganic substances to stabilize the soil chemically or utilizing wheat/rice straws for biological soil fixation (Chi et al. 2020; Rossi et al. 2022). External inoculation of microbes, specifically algae in the soil, promotes the growth of indigenous microbial communities, leading to improved soil structure and fertility (Rossi 2020).

Algae and bryophytes develop associations with fungi, bacteria, and archaea to develop biological communities in the soil crust (a few upper centimeters of soil), forming biocrust (Chamizo et al. 2020b; Grover et al. 2020). Among these, cyanobacteria are abundantly present both in terrestrial and aquatic ecosystems due to their higher adaptability to different climatic conditions (Whitton and Potts 2012). Additionally, cyanobacteria secrete EPS (exopolysaccharide), which helps them make significant associations with other communities and soil particles (Chamizo et al. 2020b). The self-secreted matrix of EPS from cyanobacteria entraps the filaments of microbes to make a stabilized microbial structure and increase the soil holding capacity by firmly holding the loose residues and aggregates in their place (Mugnai et al. 2020). EPS only provides physical stability to biocrust, while cyanobacterial filaments are significantly involved in soil fixation (Mugnai et al. 2020). However, the stability of soil biocrust is not always the same with all cyanobacterial species, which may be because of some processing factors like the inoculum size, varying traits of the species, and, most importantly, varying growth stages of biocrust (Li et al. 2015; Mugnai et al. 2020). Stable biocrust is significantly responsible for maintaining soil sustainability and restoring degraded land (Fig. 5).

5.1 Soil stabilization

The nutritional balance of the soil is being threatened due to changing climatic conditions (heavy rain and bushfires) and human activities (overcropping and deforestation). Ensuring soil stabilization is meant to regain the nutritional, microbial, and water balance of the soil. Therefore, rehabilitation of soil stability and incorporation of the reclaimed soil has become essential to ensure food security in the future. A study investigated the impact of algal biocrust on the soil stability of the rainfall-affected land and observed only 400 g/m^2 sediment loss; however, lichen-associated biocrust kept soil sediments firmly in their place and resulted in almost

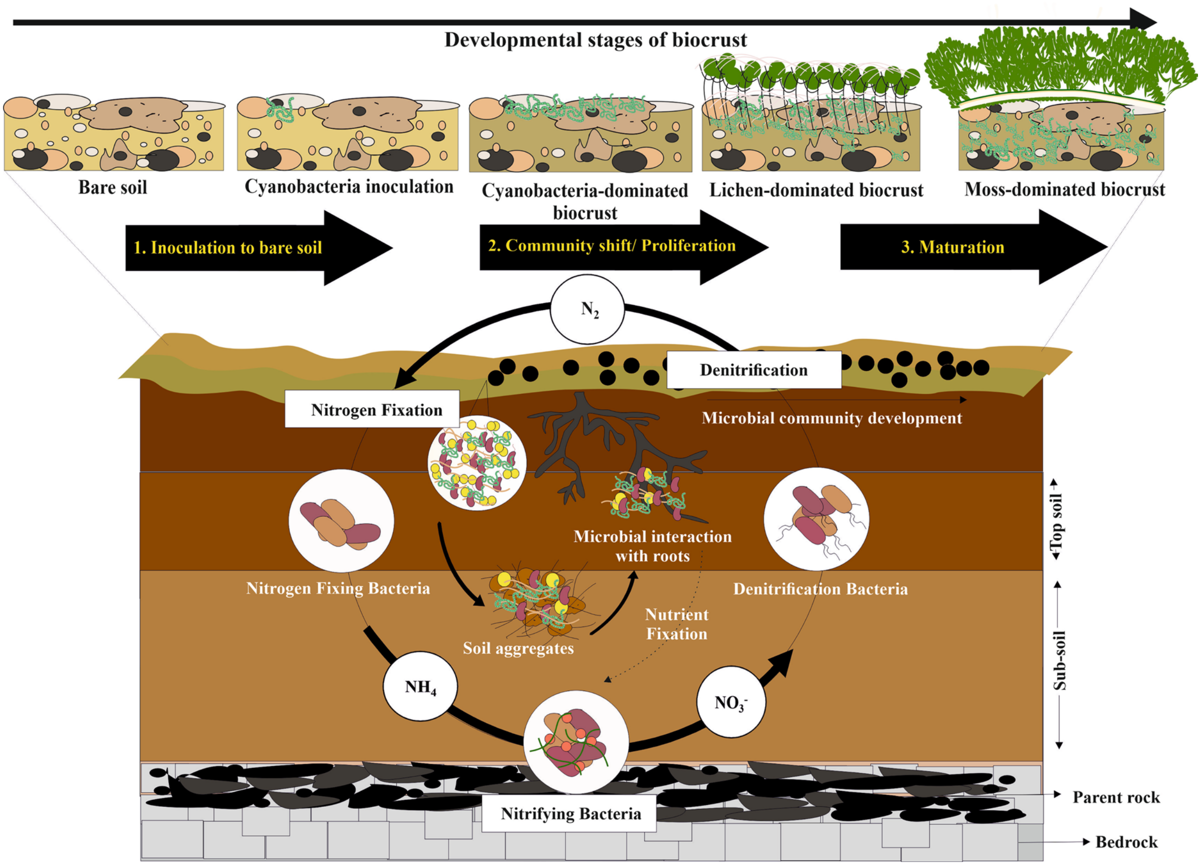

Fig. 5 Schematic diagram of biocrust development stages and its role in reclamation of poor soils

no loss of sediment (Belnap et al. 2013). Similarly, some other studies evaluated the influence of different types of biocrust on soil stability by analyzing the erosion rate of that soil. The results showed that the algal biocrust with lichen and mosses association was more effective, i.e., reduced even 100% soil erosion compared to algal biocrust alone (Liu et al. 2017; Zhao and Xu 2013). Other than components and types of biocrust, soil stability is directly affected by the inoculum sizes and bonding of the microbes. A lab-scale study used cyanobacteria to generate the biocrust without any associating microbes. The impact of inoculum size was evaluated on the physical stability of the biocrust structure, stability of the soil aggregates, and water-holding capacity of the soil. After a 30-day soil incubation assay, it was found that initially, a larger inoculum size was required for the thick layer of biocrust, which keeps sand aggregates stable and is, in turn, responsible for the stability of biocrust (Mugnai et al. 2020).

Although algal biocrust becomes more effective when it comes in association with other microbes like fungi, algae, and bacteria, during the initial stages of biocrust formation, algae play a decisive role due to their EPS sheath that not only entangles filaments but also attaches soil residues to provide physical stability to biocrust and soil stability respectively (Garcia-Pichel and Wojciechowski 2009; Nelson et al. 2021). Other microbes later help in the maturation of the biocrust. So, inducing artificial biocrust formation using algae seed culture could be an effective tool in transforming non-arable lands into arable ones to meet the future needs of agri-food systems.

5.2 Nutrient fixation

Nutrient balance is maintained by the activity of the microbial communities where, again, algae play a significant role by providing microbes with cell-to-cell attachment through EPS (Nelson et al. 2021). When microbes co-exist in clusters by interacting symbiotically, they adopt the act of community shift for nutrient fixation while growing in the biocrust. This is how microbes make nutrients available and regain the nutritional balance of soil by replacing one community with another (Lan et al. 2021). Community shift for nutrient fixation is the process in which different developmental stages of biocrust are involved. The driving component of the biocrust is cyanobacteria, as they cluster the filaments of microbes inside the EPS sheath and hold the soil aggregates. Initially, they dominate and start carbon fixation with a higher photosynthetic rate associated with microalgae (Lan et al. 2021). As time passes, the need for nitrogen fixation increases as enough carbon has been fixed; this is where community shift happens. The carbon-fixing cyanobacteria are slowly replaced by the nitrogen fixers (bacteria) and will dominate in the biocrust; similarly, further development will dominate another microbial community, such as lichens or mosses, that finally leads to biocrust towards maturation. A study investigated the nutrient fixation ability of biocrust by inoculating two different cyanobacterial species in various soil types, one with non-nitrogen fixing (*Phormidium ambiguum*) and the other one with nitrogen-fixing ability (*Scytonema javanicum*) and results showed that soil type significantly impacts the nutrient restoration cycle of cyanobacteria in non-arable land by directly effecting their EPS secretion and composition (Lan et al. 2022).

Other than community shift, nutrients could also be fixed by artificially inoculating soil with a small amount of the nutrient source, enzyme, or microbes to induce their production in the soil. A study adopted a bio-mineralization technique to fix nutrients in the soil for its stability. Calcium carbonate was precipitated in the eroded soil by inoculating a small amount of calcium and hydrolyzing urea via inoculating the urease enzyme or the microbes that produce the enzyme. Hydrolysis produced ammonium and carbonate that started soil enrichment to restore its fertility. However, microbial activity induced calcium precipitation that made bridges between soil particles to raise the soil strength (Patil et al. 2023, 2021; Raveh-Amit and Tsesarsky 2020). Therefore, the optimized inoculum size of cyanobacteria and their associated microbes and the inoculation of any nutrient or enzyme slowly induce microbial activity in degraded soil. This slow transformation of the degraded soil into stabilized soil by regaining its nutritional balance has yet to be demonstrated on a large scale. Still, it can be considered and evaluated in the future to assess its anticipated potential.

5.3 Microbial community development

Biocrust is always shaped by the symbiotic contribution of different microbes that interact to develop biological communities for survival in the soil ecosystem. Cyanobacterial biocrust is therefore induced or generated artificially in the non-arable land to transform it into fertile land by slowly activating the microbial activity there. Like soil stabilization and nutrient fixation by cyanobacterial biocrust, microbial community development starts with laboratory-level experimentation by using different inoculum sizes of microbes on various soil types to optimize community development conditions. Cyanobacteria play a significant role in microbial community development while biocrust formation by specifically generating micro and macro assemblages of filaments to physically attach soil residues and produce a sheath of EPS for biochemical interaction (Mager and Thomas 2011; Patil et al. 2023). Microbial communities can be developed by inoculating the optimum number of microbes or by enriching the soil with artificially generated biocrust.

The inoculation will induce the microbes' activity, production, and interaction to develop biocrust. Additionally, by excreting amino acids, indole 3-acetic acid, and other growth-promoting substances into their immediate surroundings, cyanobacterial species (*Calothrix ghosei*, *Hapalosiphon intricatus*, and *Nostoc* sp.) promote the development of microbial communities in soil (Karthikeyan et al. 2009, 2007). When the wheat plant was inoculated with consortia of unicellular microalgal cells (*Chlorella* sp., *Scenedesmus* sp., *Chlorococcum* sp., *Chroococcus* sp.), it improved the soil biomass (38.1–67%), grain's nitrogen content (3.56%), dry weight (7.4–33%), and spike weight (10%) (Renuka et al. 2016). Therefore, it is believed that the rise in cyanobacteria and other soil microbe populations is responsible for the increase in microbial biomass and carbon content in soil (Fig. 5). However, transforming non-arable lands to the arable ones through induced biocrust formation, inoculating the soils with carefully selected consortia of microbes (algae, cyanobacteria, fungi) would be needed.

6 Greening deserts and rehabilitation of bushfire-damaged soils to ensure food security

Desertification is a type of land degradation where soil loses its microbiota and water-holding capacity, possibly due to destructive human activities, improper agricultural practices, climate change, and some natural factors like drought (Xue et al. 2022). Desertification not only degrades soil but also has a direct detrimental effect on the economy because it damages the cultivation system. Reforestation seems to be the best way to get green deserts. However, it still contains limitations, as the competitive behavior of plants compromises their growth due to limited nutrients and minerals in the non-fertile soil. Therefore, based on all the information about developing plants and other crops in the desert, most studies have tried to make them fertile via microbial inoculation and activation.

Fire-affected lands remain under the long-term influence of degradation, loss of biocrust, and overall soil biodiversity (Kelly et al. 2020). The detrimental effects of fire are the structural loss of post-fire soil that completely changes the composition of soil microbiota, hydrological dysfunctioning, and, most importantly, increases the erosion rate that may cause mortality of the fertile soil (Pereira et al. 2018). This damage causes an increase in the non-arable lands, contributing to rising concerns about food security. However, in algal biocrust, algal activity depends upon the pH and nutrient availability of the fire-damaged soil for its reclamation (Muñoz-Rojas and Bárcenas-Moreno). Biocrust formation, by inducing microbial growth and activity in the degraded soil, can slowly improve the soil structure by restoring soil biodiversity and water-holding capacity.

The improvement of the structure of fire-damaged soil is again about the soil stability that is effectively restored by algae and other microbes with the successional growth of biocrust. As the oxygenic nature of algae increases their abundance in biocrust, similarly, their self-regenerating ability in post-fire soil makes them great contributors to the process of soil structure improvement (Bowman et al. 2020; Muñoz-Rojas et al. 2021). Cyanobacteria inoculants are abundantly used worldwide for ecological restoration or improvement of the structure of degraded soil, not only as biocrust but also as bio-fertilizers because of their adaptive potential in extreme climatic conditions (Singh et al. 2016). A few studies have attempted to reclaim the burnt soil using cyanobacterial slurries, resulting in a significant improvement in soil structure without affecting the soil microbiota (Clair et al. 1986). Two cyanobacterial species, namely *Phormidium ambiguum* and *Scytonema javanicum*, were employed to reclaim the highly burnt soils, which increased the resistance of surface water penetration and overcame the water-repellent effect of soil for its structure restoration (Chamizo et al. 2020a).

Algae can contribute physiochemically to the health of desert and semi-arid soils by helping to form and stabilize soil aggregates, which improve soil's pore size and continuity. Greening deserts could be best performed by inoculating different microbes along with some chemical stabilizers in such a way that they generate symbiotic associations in the soil and form biocrust to establish a microbial ecosystem. A study used aquatic cyanobacteria inoculants along with nano stabilizers to treat the problem of desertification (Chi et al. 2020). The nano stabilizers provided aquatic and desert cyanobacteria a suitable environment for their proliferation and helped them get over the soil for its stability and strength. The positive effect of the association of aquatic cyanobacteria with nanocomposite on soil crust development was observed (Chi et al. 2020).

Desertification can effectively be handled, and deserts can be transformed into green landscapes by simply utilizing the aquatic blooms considered waste or environmental pollutants in marine ecosystems when their growth exceeds a specific limit. That's why cyanobacteria are considered soil or ecological engineers; they can potentially regenerate degraded soils. Deserts contain microbial communities, but here they entrap within the soil roots; however, the biocrust formation because of the growth of fungi, microalgae, and other bacteria associated them with soil particles can mitigate desertification (Dhawi 2023). However, it would require the selection of suitable cyanobacterial strains, frequency, and size of inoculation with fungi and bacteria. In addition, the possible impact of large-scale induction of biocrust on the desert ecosystem and biodiversity should be carefully assessed through carefully planned multidisciplined studies.

7 Perspectives and recommendations

Algae farming offers a potential solution for nutrient transformation into organic biomass, which is used as a biofertilizer and improves soil nutrition with a circular economy and sustainable environmental advantages; the substantial startup and maintenance expenses provide considerable obstacles. Financial incentives and technological developments are essential for ensuring the economic feasibility and desirability of algae farming for entrepreneurs and small enterprises. Providing sufficient assistance via subsidies, tax incentives, and research and development funding will be crucial for the expansion and long-term viability of this industry.

A complete environmental evaluation should incorporate algae farming's drawbacks, notwithstanding its low carbon and water footprints. The water footprints can be lowered by using brackish wastewater or seawater; however, algal blooms may deplete oxygen and emit poisons, disrupting ecosystems. Non-native algal species may also cause invasive species, harming biodiversity and natural environments. Algae farming must be managed and regulated to stay sustainable and ecologically friendly.

Based on the literature review and analyses, the following recommendations are made for researchers, companies, enterprises, and entrepreneurs.

- Scenario-I: Algae farming using seawater and brackish water

  Owing to their ability to tolerate high salt concentrations and having higher biomass productivity in saline waters, the algae species, namely *Chlorella vulgaris*, *Isochrysis galbana*, *Tetraselmis suecica*, *Nannochloropsis salina*, *Chlorella salina*, *Spirulina platensis*, and *Dunaliella salina* could be the species of choice. At the same time, large-scale solar-powered open pond cultivation systems could be used to produce biomass. The biomass produced can be used as feed supplements in animal feeds to improve the quality or as functional foods for human consumption. In a biorefinery system, these cultivation systems can also be integrated with animal farming, producing fodder, milk, meat, and biogas. For example, fish farms may include algal ponds that use the nutrient-rich water from fish tanks to improve water quality and decrease the need for external feed inputs. This will also help establish a parallel food production system with low carbon and water footprints without competing with land for food and feed.
- Scenario-II: Algae farming under urban and peri-urban environments

  Owing to their higher growth and lipid productivity, the algae species, including *Chlorella vulgaris*, *Spirulina platensis*, *Scenedesmus* spp., *Chlamydomonas reinhardtii*, *Euglena gracilis*, and *Nannochloropsis* spp. have come forward as the best species to be employed in urban and peri-urban environments. Meanwhile, the cultivation systems of choice could be tubular column reactors and small-scale open ponds. The biomass produced can be used to store carbon in the soil or anaerobic digestors to produce biogas, produce biomaterials for packaging and infrastructures, or be pyrolyzed to produce energy.
- Scenario-III: Soil reclamation using algae biomass

  Owing to their ability to fix atmospheric nitrogen and carbon and positive interactions with the soil's indigenous microbiota, the algae species, namely *Chlorella vulgaris*, *Spirulina platensis*, *Scenedesmus* spp., *Azolla filiculoides*, *Euglena gracilis*, *Dunaliella salina*, *Microcystis aeruginosa*, *Anabaena* spp., *Nostoc* spp., *Tolypothrix* spp., *Calothrix* spp., *Scytonema* spp., and *Microcoleus vaginatus* could be employed for improving soil health for improved agricultural practices. This will not only help reduce the environmental burden of synthetic fertilizers but will also add more land into agri-food systems to meet the growing demands for food and feed.

8 Prospects and outstanding questions

Algae cultivation and bioprocessing offer incredibly high hopes for carbon capture, wastewater recycling, food/feed production, and myriad applications in various directions. However, several bottlenecks between the expectations and practical applications must be addressed through global and regional collaborative research efforts and resource-sharing programs.

- What legal and economic policies shall support, monitor, and regulate the large-scale algae cultivation to produce, prepare, transport, export/import, and process the biomass? Which government departments should be involved in developing the needed policies?
- Who and how will produce the algae biomass? Who will buy it? What industries are there to process the biomass for promised applications? How can we develop a producer-to-consumer supply chain by fully educating/training the farmers to harness the algae's potential as a low-carbon feedstock?
- Considering the needs, availability of land/water resources, and biosafety risks, how much area should a country spare for algae cultivation?
- Considering the specific biotic and abiotic factors of algae cultivation, shouldn't the most suitable geographical regions for algae cultivation be identified for establishing algae-based industries through global comparative studies, including techno-economic and life-cycle impact analyses?
- How is large-scale cultivation of algae going to affect the biodiversity of ecosystems? Could it bring some unexpected environmental challenges?
- How will we tackle the market acceptance and consumer perspectives for algae-based food and feed products?

9 Conclusion

Finding sustainable bioresources that can help fight climate change-driven food insecurity challenges by establishing an alternative agri-food system that uses non-arable lands with low water and carbon footprints is the need of the hour. Algae are a viable and sustainable alternative for tackling food poverty because of their considerable nutritional content, fast growth rates, and minimum resource needs. They are used directly to improve soil nourishment. They are essential due to their high adaptability and survivability, straightforward nutrient requirements, and the production of ecologically viable diversity of bioactive products and recycling resources. They can be grown using brackish and seawater owing to their ability to withstand salt stress, which can reduce the burden on freshwater resources. Algal biomass produced using the coastal, salt-affected lands and under urban/peri-urban environments can be utilized for various applications, including food, feed, industrial feedstock, biofertilizer, and soil amender (to reclaim the poor/marginal or salt-affected soils). Nevertheless, the potential for algae farming to expand in size must consider the potential negative impacts on the environment. The introduction of non-native algae species into local ecosystems has the potential to disturb the current aquatic life and compromise water quality. In addition, the administration of large-scale farming systems must be meticulous to avoid contamination and ensure the implementation of sustainable methods. However, a global cooperative program should be launched to harness the full potential of algae after carefully assessing the economic, environmental, technical, social, and regulatory aspects of large-scale algae farming.

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