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Role of Algae in Built Environment and Green Cities: A Holistic approach towards Sustainability

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ABSTRACT

The changing lifestyle, urbanization, and depletion of non-renewable resources to match the ever-increasing energy demand are causing a pessimistic impact on the environment. The cities are responsible for 75% of carbon emissions and about 60-80% of the energy consumption globally, causing a precarious situation because they only constitute 3% of the earth's land. Urbanization makes the cities vulnerable due to the changing climatic conditions and possibilities of natural deserts disasters, thereby compelling the researchers to go for planning building green and resilient cities. Green cities are imperative in resisting the environmental crisis and assure a sustainable future for the upcoming generations. The pivotal role for the green cities is played by the renewable sources of energy. Therefore, solar and wind energy systems were employed, but eventually these renewable energy systems are associated with cost and pollution issues. This led to the paradigm-shifting towards algae as a third-generation feedstock and it is expected to become a potential source of green energy and environment due to the following advantages: (i) sequestration of CO2 and other greenhouse gases (GHGs), (ii) they can be easily and rapidly cultured and bioengineered, (iii) they can utilize the wastewater as a source of nutrients for its cultivation, (iv) their growth does not depend upon the geography and climate, and (v) algal biomass can be processed into biofuels (biodiesel, bioethanol, biogas etc) and other useful bioproducts (biofertilizer & biochar). This review paper incorporates the role of microalgal bioreactive façades (algae powered buildings) in the simultaneous mitigation of environment and energy production, contributing to green cities. Since the importance of Urban Green Space (UGS) is imperative for green cities, its functions and role during the critical period of the pandemic are also explained together with the efficient and viable biofoundry approach of converting algal blooms in urban water bodies to energy and useful products.

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1. Introduction

Urban expansion is taking place globally at a faster rate, creating a disbalance in the sustainable climate mechanisms which may result in natural disasters, causing acute social and economic losses. Rapid urbanization will also result in the depletion of natural resources (especially fossil fuels) due to the rising energy demand propelled by industrialization. It is reported that the total energy utilization in the domestic sector is expected to get increased by 1.5% every year from 2012 to 2040. Furthermore, disproportionate usage of fossil fuels is contributing to environmental pollution by the release of harmful greenhouse gases (GHGs). It is reported by World Health Organization that 90% of the population in urban areas is breathing polluted air according to the air quality guidelines. The cities are responsible for 75% of carbon emissions and about 60-80% of the energy consumption globally, causing a precarious situation because they only constitute 3% of the earth's land (Kutty et al., 2020). About 70% of the GHG emissions are coming out of urban agglomerated centers (Chew et al., 2020). Mega cities like Tokyo, Delhi, and New York are individually responsible for generating much more GHGs as compared to a cluster of states in underdeveloped countries (Clark II and Cooke, 2016). The current vulnerable situation o the cities compelled the researchers to go for planning, designing, and building green and resilient cities.

Green cities are imperative in resisting the environmental crisis and assure a sustainable future for the upcoming generations. The pivotal role for the green cities is played by the renewable sources of energy. Solar energy has been experimented as the source of renewable energy but it cannot be used for large scale production due to the following disadvantages, (i) extremely dependent on the weather conditions; (ii) large area is required to produce solar power in abundance (solar power with 1 MW capacity having 18% efficiency requires about 16,187 m^2 of land); and (iii) solar energy is having very high installation cost (3.7$/watt and the total cost is 13000$ for providing 5KW for a household) (Kabir et al., 2018).

Wind power contributes to reducing CO_2 emissions by acting as an alternative to fossil fuels but simultaneously releasing CO_2 during the construction of wind turbines. Another limitation associated with wind turbines is the noise pollution, where it was reported that for a 10-meter height and wind speed of 5.1 meter per second (m/s), the noise from the wind turbine is 48.5 dB, which was about 9 dB higher than the ambient sound limit (Kaldellis et al., 2012). This has led to the advent of algae as an efficient and attractive source of renewable energy.

Microalgae are chlorophyll-containing eukaryotic organisms found in freshwater and marine water habitats. The main composition of microalgae are proteins, lipids, carotenoids (i.e., astaxanthin), and nucleic acids (Khoo et al., 2020). The specific percentage of individual constituents depends upon the strain of microalgae and the type of cultivation system. Microalgae convert energy from sunlight/artificial light, and it gets stored as lipids or carbohydrates when it undergoes a photosynthetic process.

Algae are expected to become a potential source of green energy due to the following advantages: (i) sequestration of CO_2 and other greenhouse gases (GHGs), (ii) they can be easily and rapidly cultured and bioengineered, (iii) they can utilize the wastewater as a source of nutrients for their cultivation, (iv) their growth does not depend upon the geography and climate, and (v) algae façades contribute to the green-space ratio by carbon bio fixation and release of oxygen (Chew et al., 2020).

Globally, buildings account for 40% of energy and material use, 33 % of CO_2 emissions, 25 % of wood harvesting, and 17% of freshwater usage (Say and Wood, 2008). Therefore, it is of utmost importance to plan and design new buildings and cities on the precept of sustainable development features, such as self-sustainability, zero waste/zero emissions, environmental safeguarding, and green fuel and energy exercise (Watson, 2019). Hence, there is a need for some stringent building codes and standards to stabilize these components. The implementation of these standards depends on the climatic and economic condition of that very nation. Generally, green buildings have a higher capital cost, which is about 2% more than conventional buildings, but in return, they give a life cycle savings of 20 % (10 times more than the initial investment). Various benefits of green buildings are shown in Figure 1. Due to the significance of green space in the cities, there is a trend of studying and working on the aspect of Urban Green Space (UGS). The importance of UGS in the survival of healthy cities during the pandemic is summarized in section 4. While some of the trends of green buildings and cities are depicted in Figure 3.

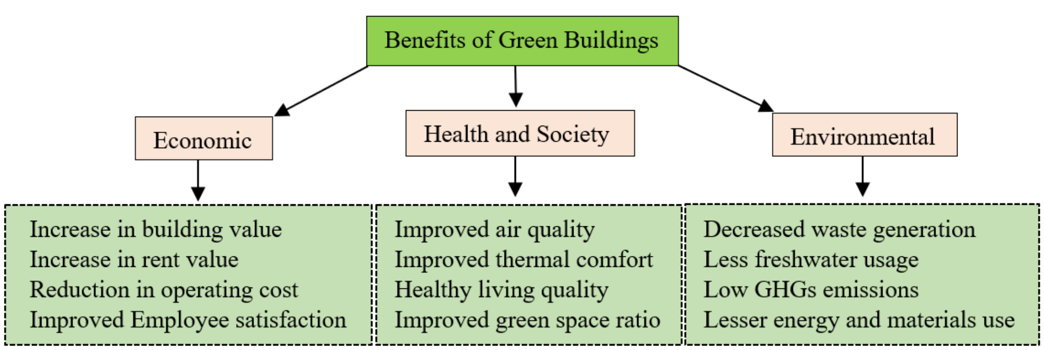


Figure 1 Benefits of green buildings

There is unanimity between the nations in the recent approaches for sustainable design regulations based on the concept of green buildings and cities. The leadership in energy and environmental design (LEED) and the US Green Building Council (USGBC) are the two examples of leading institutions in energy design (Beauregard et al., 2011).It is indeed crucial to get their certification as the building should be qualified in all the aspects like recycling of waste, water, and energy conservation, indoor environmental quality, outdoor greenery. World green building was founded in 1998 and now it has spread its establishments to 12 countries. Green buildings contribute to 9 out of 17 SDGs, as shown in Figure 2. However, in the establishment of green buildings and cities, it is important to integrate the aspects of energy production and treatment/recycling of wastewater/CO_2. This will lead to multi- benefits in terms of sustainable energy, environment, and individual well-being. In this regard, researchers have been studying the suitability of algae to be the potential contender for the same purposes.

Figure 2 Sustainable development goals contributed by Green Buildings (Council and Council, 2016).

Figure 3 Revolutionizing trend of green buildings and green towns in Kuala Lumpur (Photo taken by Authors).

Algal-based green communities are trending and introduced in many countries, while it is predicted that algae are having immense potential to suffice long-term future demand of energy and food in an environmentally sustainable manner (Vassilev and Vassileva, 2016). Algal green communities will lead to the mitigation of pollution (greener environment), conservation of natural resources (fossil fuels), and a vibrated economy. This study is based on the literature review of the recent research and review articles from ScienceDirect, Taylor and Francis, and Springer by searching the keywords algae, built environment, green buildings, green cities, sustainability, and Covid-19. This review paper summarizes the state of the art technology of microalgal bioreactive façades (MA-BRF) in the simultaneous mitigation of environment and energy production. MA-BRF provides resilience and sustainability to the building and makes them environmentally and aesthetically suitable to its dwellers.

The exclusive feature of algal façades is that they are an integral part of the structure. The subsequent section provides the contribution made by microalgae in terms of the production of biofuels (biodiesel, bioethanol, biogas) and production of biofertilizer for sustainable agriculture and treatment of wastewater by utilizing it for the cultivation of microalgae. The green spaces in the urban areas are of paramount significance as they provide a haven in the otherwise polluted environment. The scenario of urban movements has changed a lot due to the effects of Covid-19 and its associated restrictions. But since the importance of Urban Green Space (UGS) is imperative for the green cities, its functions and role during the critical period of the pandemic is also explained together with the efficient and viable biofoundry approach of converting algal blooms in urban water bodies to energy and useful products. In a world that is severely affected and afflicted by the pandemic (Covid-19), this paper gives the understanding to re-establish and rehabilitate the world by providing a possibly viable and sustainable solution.

2. Algal Façades Or Buildings Powered By Algae

Microalgal bioreactive façades are considered as state of art technology, since they are contributing to reduce the fossil fuel depletion and carbon footprint of the buildings. The coupling of bioreactors with the building can considerably reduce the buildings' energy demand. Microalgal cultivation is performed in open and closed systems. The advantages and superiorities of closed systems (tubular or flat panel photobioreactors, PBRs) over open systems (open raceway ponds) are high efficiency for biomass production, lower risk of contamination, better light distribution, avoidance of the evaporation of culture medium, better resistance to climatic fluctuation, and convenient sterilization and maintenance of reactors (Ahmad et al., 2021b).

One of the important factors in the cultivation of microalgae is the thermal regulation of PBRs because the variation in temperature can affect microalgal growth (Hindersin, 2013). Extremely high as well as low temperatures may lead to the death of microorganisms. Hence, heating and cooling are required to attain the optimum thermoregulation of PBRs. Simultaneously, the light intensity should also be closely monitored as the excessive intensity can cause photoinhibition, causing cell death (Burns, 2014). On the other hand, the shading effect in dense cultures is considered imperative in preventing cells from absorbing light. To avoid both problems, efficient circulation and mixing of the cells in PBRs are necessary. For the optimized production of biomass, the duration of light and dark cycles plays a crucial role during the cultivation of microalgae in PBRs. Therefore, the intensity, penetration strength, wavelength of the light, and the duration of light and dark cycles-all contribute to the overall light regime inside PBR (Matthijs et al., 1996).

2.1 Functions and Advantages Of Microalgal-Bioreactive Façades

Integrated microalgae bioreactive façades (MA-BRF) provide some exceptional benefits in terms of energy and environmental sustainability. For instance, (i) BIQ house in Hamburg, Germany which was the first BRF in the world popularly known as the solar leaf is utilized to produce biofuels, generate heat, shading, and reduce CO_2 emissions (CO_2 sequestration rate of 6tons/year for 200 m^2 MA BRF). (ii) The potential of PBR-BRF includes daylight and thermal performance, visibility potential, better acoustical performance, environmental and economic viability, and improvising aesthetics (Genin et al., 2016). (iii) PBR-BRF has the additional capability of contributing to wastewater remediation, heat dissipation, and end-stage production of valuable derivatives for the building dwellers. (iv) Furthermore, the medium of microalgae can act as an adaptive shading screen, which helps to control the thermal regulation of the building. (v) Some of the anecdotal theories suggest that PBRs can act as sound buffers for the sound isolation in the buildings. (vi) The biomass produced by microalgae during photosynthesis is considered a major source of biofuels and other value-added products (Talaei et al., 2020). Therefore, the incorporation of PBRs into the building façades establishes a live factory that provides thermal regulation and energy generation at the buildings. The thermal and energy outcomes and advantages of MA-BRF are summarized below.

2.2 Thermal Functioning And Roles Of Microalgal Bioreactive Façades

MA-BRF can suffice building's thermal requirements by playing the role of solar thermal collectors, photosynthetic biomass converters for biofuel production, thermal insulation materials, and flexible shading devices (Casini, 2016). Studies found that the exchange of energy between PBRs and buildings can help to regulate thermal load. This symbiotic relationship works on a two-fold basis, as it averts PBR from overheating by providing filtration and shading of thermal loads in the hot weather while it helps the PBR in maintaining the growth of microalgal biomass in cold weather (Pruvost et al., 2016). If the MA-BRF is coupled with solar collection and PV integrated shading mechanisms, then this collection system can provide dual benefits of electricity generation and shading (Al Dakheel and Tabet Aoul, 2017). MA-BRF also contributes to thermal insulation in the building leading to thermal comfort for the occupants (Öncel et al., 2016). ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) defines thermal comfort as the mental condition revealing satisfaction with the thermal environment surrounding the observer and evaluated based on subjective assessment (ANSI/ASHRAE Standard 55- 2013). Study was conducted on different PBR prototypes integrated with different kinds of walls to evaluate their insulation performance. The study revealed that the heat transfer was reduced in all the cases, thus contributing towards energy saving. MA-BRF has the potential for energy saving because the thermal insulation and acoustic performance of the façade were enhanced by water medium in microalgae and the temperature was reduced due to the shading, solar absorption, and parasol effect generated by the photosynthesis taking place during microalgal cultivation (Sardá and Vicente, 2016).

2.3 Microalgal Bio Reactive Façades As Energy Generation

The main function performed by MA-BRF is to photosynthetically converts light into heat and biomass, which can be later transformed into biofuels (Ahmad et al., 2021c). Microalgal biomass is not only capable of producing biofuels but can also become a source of energy in the form of electricity and heat. Microalgae are having the upper hand on first- and second-generation biofuels because of higher oil yield productivity (Naik et al., 2010), lipid storage (Buzalo et al., 2015), and photosynthetic efficiency.

The crucial parameters in the designing of flat panel façade coupled PBR that affect the microalgal growth and biomass productivity are intensity of light, orientation, materials utilized, CO_2, nutrients, pH, thickness, temperature, and contaminants (Elrayies, 2018). The thickness of the PBR should be less than 6 cm, while the most suitable and efficient materials to be used for BRF are transparent acrylic, plexiglass, polycarbonate, polyethylene, and ethylene tetrafluoro ethylene (ETFE) (Marsullo et al., 2015, Pagliolico et al., 2017).

In the Bio-Intelligent Quotient (BIQ) system, there is a central building control at the core of the microalgal PBR circuit that removes biomass from the medium by employing an algae separator, and the wastewater is discharged to the municipal sewage system. Besides that, the extra heat from the system is dissipated by the heat exchanger to heat the building and water through underfloor heating, while a portion of it is stored in geothermal borehole wells. All these processes are automatically and sequentially done (Wurm, 2013b). However, converting biomass to biogas by the hydrothermal process to generate electricity is performed in an external biogas plant. The produced energy is transferred to the cities in the last stage. The efficiency and energy performance of the BIQ system as the first microalgae-powered building has been intensively monitored. The photographic imagery of the BIQ system is shown in Figure 4. The output of biomass and heat of 200 m^2 of algae façade is 26,165 kWh per year (biomass: 4539 kWh, and heat: 21,626 kWh) while the electricity consumption is 13,471 kWh. The system generates about 30 kWh/m^2a energy from biomass and 150 kWh/m^2a energy from heat and reduces CO_2 emissions by 2.5 tons/year (Wurm, 2013a). The rate of sunlight energy conversion into heat and biomass are 21% and 4%, respectively. This rate is about half of what was modeled at the design stage (Wurm and Entwhistle, 2015). The coupling of microalgal bioreactors into the building façades is a groundbreaking technology as it transforms an ordinary building into a standing, self-reliant, renewable energy-producing, and sustainable structure contributing towards the development of green cities. Various places where the MA-BRF system is established experimentally either at a small or large scale are incorporated in Table 1.

Figure 4 MA-BRF in BIQ house, Hamburg Germany, zoomed image of PBR panels being used as façade (Biloria and Thakkar, 2020).

2.4 Contribution towards green space ratio

Green space ratio can be defined as the ratio of an area occupied by greenery (vegetation) to the whole area in which vegetation is being calculated (Susaki and Komiya, 2014). It is an important parameter for adapting to climate change and sustainable development of the cities. It directly affects the health, quality of life, and comfort of the people living in the cities (Lõhmus and Balbus, 2015). The technologically advanced algal façades contribute towards CO_2 mitigation, the release of oxygen, the production of biofuels, and other value-added green products. Thus, augmenting the Urban Green Spaces (UGS) and subsequently the green space ratio. The multiple tasks performed by an algal-powered building are shown in Figure 5.

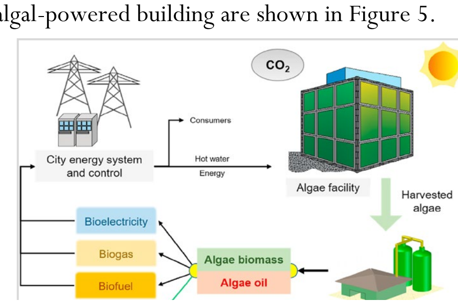
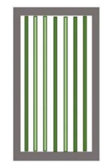
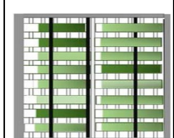
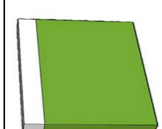
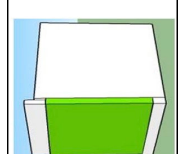


Figure 5 Multi-utility benefits of an algal façade or algal powered building (Chew et al., 2020).

Table 1 Different places where microalgae bioreactor façades are established (experiment and simulation).

Place	Methodology	Type of PBR	Thermal functions of PBRs	Contribution/Conclusion	Orientation	PBRs panel schematics	Ref
Germany (Hamburg)	Full-Scale Experimentation	Vertical flat-panel bioreactor	Solar-thermal, shading,	Photobioreactors energy per m^2 of biomass production is 15 g TS/m^2/day (900 kg/ year) The production of energy from biomass is 345 kJ/m^2/day Biogas produced from algal biomass 10.2 liters methane/m^2/day	Southwest and Southeast		(HAMBURG, 2013)
U.S.A (Lincoln)	Experimentation	Vertical tubular bioreactor	Shading	Increase in microalgal culture density resulted in reduced light penetration and inner luminance.	South, East, West		(Elnokaly and Keeling, 2016)
Israel (Tel Aviv)	Experimentation	MPBR Macroalgae closed vertical photobioreactor	Solar-thermal (biomass production) Solar-thermal (biomass and energy production	Max. energy from biomass =0.081 Wh L^{-1}d^{-1} (*Ulva compressa linnaeus* species) Maximum values for energy efficiency and energy return on investment for MPBR are 0.012 and 0.22, compared to a range of 0.05–8.34 and 0.013–0.327 for microalgae PBRs integrated with building façade.	South/East		(Zollmann et al., 2018)
Turkey (Izmir)	Experimentation	Flat panel bioreactor	Thermal insulation	There is considerable interaction between all main factors (reservoir, air layer, and reservoir wall thicknesses) and U value.	-----		(Umdu et al., 2018)
Indonesia (Bandung)	Simulation and Experimentation	Flat plate bioreactor	Shading Shading and thermal insulation	The maximum value of illuminance in the outdoor (at 11.52 a.m.) was 110,800 lux while the indoor (at 3.22 p.m.) was 5189 lux. The consumption of energy cooling (district cooling) for the building-integrated algae bioreactor is less than the energy consumption of the façade applying horizontally fixed shading device and *brise-soleil*.	West		(Martokusumo et al., 2017)

3. Applications of Microalgae In The Development Of Green Cities And Reduction Of Carbon Footprint

A city is termed as a green city or carbon-neutral if the impact of GHG emissions can contain global warming below the alarming threshold of 2°C (Clark II and Cooke, 2016). Microalgae can contribute to the production of green energy such as bioethanol, biodiesel, biogas, together with that, it also provides CO_2 sequestration, wastewater treatment, nutrient uptake, and land-water conservation (Ahmad et al., 2021a). Therefore, microalgae can provide clean and sustainable transportation, greener cities (algal façades), making the city life more livable, and helping to resolve the global climate crisis. Algae has a considerable potential to absorb CO_2 and contribute towards tremendous greenhouse gases uptake. The biofuels produced from algae release oxygen as a byproduct, thus, adding fresh oxygen to the otherwise polluted cities. The vitality of oxygen can be understood from the acute crisis of oxygen in various cities of India during the peak of Covid-19 in May 2021. Algae can convert a larger amount of CO_2 to biomass, thereby, releasing oxygen photosynthetically. Algae can produce JP-8, biodiesel, and jet fuel having about 40% greater energy per gallon than gasoline due to its immense efficiency in energy conversion via photosynthesis (Khan et al., 2017). A study conducted by the US Energy department estimated that there are about 3000 microalgal species, which can be exploited for the production of biofuels (Sheehan et al., 1998). The first motive to exploit microalgal biomass was to produce biofuels in an economically viable and environmentally sustainable manner and a lot of researches have been conducted for the purpose, however, there are still a lot left (Chen et al., 2017). The potential of some microalgae species in the sequestration of CO_2 and their biomass yields are shown in Table 2.

Table 2 Potential of microalgae in CO_2 sequestration and biomass yield.

Microalgal genera	**Cultivation system used**	**Initial CO_2 (%)** *(v/v)*	**CO_2 bio-fixation rate (g/L/d)**	**Biomass yield (g/L)**	**References**
Botryococcus braunii	Fermenter	5	0.5	3.11	(Sydney et al., 2010)
Chlorella vulgaris	Membrane-sparged helical tubular bioreactor	0.09	3.45	0.90	(Fan et al., 2008)
Scenedesmus obliquus	Glass-made vessel	10.0	0.55	3.51	(Ho et al., 2012)
Chlorella vulgaris	Glass bubble column	6.0	2.22	10.02	(Anjos et al., 2013)

3.1 Biodiesel

Due to increasing urbanization and industrialization, the transportation fleet is having an upsurge, causing CO_2 and GHG emissions to be at alarming rates. Algal-based green cities will be shifting towards sustainable mass transit (environmentally friendly and efficient), reducing the usage of vehicles, and incorporating algal fuels instead of fossil-based fuels (Abdallah, 2017). Biodiesel derived from microalgae is having the potential to replace petroleum-based fuels as an alternative and renewable green fuel. Animal fats, microalgal lipids, and vegetable oils containing mono-alkyl esters triglycerides are termed biodiesel (Chia et al., 2018). The biomass produced from some of the microalgal species contains about 80% of oil per unit of dry mass (Yaşar, 2018). However, microalgal-extracted oil has high viscosity that is further reduced by the process of transesterification, making it suitable for the vehicles engines. A study revealed that the biodiesel produced from microalgae releases reduced concentrations of CO and NOx during combustion as compared to fossil fuels when recirculation of the exhaust gases was carried out (Mat Aron et al., 2020).

Hence, the incorporation of algae in the transportation system by replacing petrol and diesel with algal-based biofuels will contribute in two ways: (i) by releasing oxygen and cleaner by-products, and (ii) the sequestration of CO_2 from the atmosphere. Studies revealed that algal-powered vehicles are currently being researched and have a bright future. Toyota designed and manufactured the Toyota Prius (plug-in-hybrid) named *Algaeus* because it runs on the 5% blend of algal fuels. Japanese researchers and the government are working together to develop buses that will be powered using algal oil. In 2011, United Airlines conducted a first-ever passenger flight (Chicago-Houston) that used a blend of aviation biofuel made from algal oil (40%) and petroleum-based jet fuel (60%). This shows that the practices had already taken momentum, but still a lot of work need to be done (Chew et al., 2020). As air pollution is mainly caused by vehicular emission comprising of GHG gases, the replacement of fossil-based fuels by the algal-based biofuels will lead towards environmentally clean and green cities, a primary requirement in the post-Covid-19 era, as most of the complications of this deadly disease are associated with the breathing.

3.2 Bioethanol

Bioethanol is an internationally accepted biofuel because of its significant features: (i) ability to reduce the usage of gasoline by 4%; (ii) mitigation of CO_2 emissions by about 35 Metric tons/year, when used as an octane booster for gasoline; and (iii) high efficiency with internal combustion engines. Ahmad et al., (2021c) has extensively differentiated between biodiesel and bioethanol in their review article. Bioethanol can be obtained from microalgae through a chain of processes, i.e., the production and harvesting of biomass, pretreatment to derive the fermentable sugars, sugar fermentation to get ethanol, and finally, the purification of ethanol. The yielded microalgal biomass contains carbohydrates and proteins in the form of starch, proteins, and polysaccharides, serving as the source of carbon during fermentation (Chew et al., 2019).

Chlorococcum infusionum can produce 0.26 g ethanol/g of algae and the content of carbohydrates in the biomass was about 32%, while *Chlamydomonas reinhardtii* produced a yield of 0.35 g ethanol/ g of algae and a high proportion of carbohydrates, that was 60%. The production of bioethanol consumes less energy as compared to the production of biodiesel, as the energy consumption in fermentation is less (Yaşar, 2018).

3.3 Biogas

Biogas (methane and hydrogen) produced from microalgae can be used for various industrial activities and consumers living in the green cities by converting it into heat energy and electricity. Methane can be obtained from algae by the process of anaerobic digestion, gasification, and pyrolysis. Anaerobic digestion involves the degradation of organic matter in the absence of oxygen, while in gasification and pyrolysis, methane is derived under the effect of high pressure and temperature. Hydrogen can be obtained from algae by different biological processes carried upon algal biomass like anaerobic fermentation, dark fermentation, bio photolysis, and photo fermentation, or via more than one of these processes (Gupta et al., 2017). It was reviewed that the process of anaerobic digestion has shown great potential in the conversion of algal biomass into biogas (Ahmad et al., 2020)

3.4 Biofertilizer and Biochar

The condition of soil also plays an important role in the development of green cities. Food security, together with the nutritional composition of food should ensure that there is enough food for the population and is healthy too for better living (Al-Dailami et al., 2020). To achieve this feat, the cities and villages should practice sustainable agricultural techniques, which are efficient and environmentally safe. After the extraction of biofuels, the wasted biomass is further processed to obtain biofertilizers. Biofertilizers can boost the phyco-chemical properties, such as the mineral nutrients, thereby enhancing the fertility of the soil. A chemical known as aminolevulinic acid (ALA) can also be generated from algae, which can be used in agriculture as a natural insecticide and catalyst for plant growth.

When biomass is heated (300-1000°C) with limited or no supply of oxygen, then an organic recalcitrant carbon compound or biochar is formed (Yu et al., 2017). Wet algal biomass can be transformed into algal biochar by utilizing batch processing conditions in a comparatively shorter span of time (Lam et al., 2012). Microalgal biochar has larger aggregates with irregular porosity in their molecules. Biochar is believed to contribute a lot to the betterment of soil as it contains great proportions of nutrients such as ash, nitrogen, and other inorganic constituents. Since it has high pH, therefore it can generate a more balanced acidic environment for plant growth. Biochar is having the potential for the sequestration of about 12% GHGs from the cities affected by smog pollution. Biochar can also help in the bioremediation of organic and inorganic pollutants present in wastewater as it is a strong bio adsorbent (Yu et al., 2017).

3.5 Wastewater Treatment Using Algae

With the unprecedented expansion of cities, there is a pressing issue of wastewater generation and its appropriate treatment. Generally, physical and chemical methods are employed for wastewater treatment. They require large amounts of chemicals, costly, and not eco-friendly. There is a dire need to introduce a wastewater treatment method that is sustainable and economically viable. Microalgal treatment or bioremediation of wastewater is currently the subject of interest for scientists because of its flexible metabolism and efficiency in the treatment of various wastewaters types (Aron et al., 2021). Microalgae can act effectively in the removal of nutrients as they require ammonia, nitrogen, phosphate, and other trace elements for their growth (Manirafasha et al., 2019). Hence, using wastewater as the medium for microalgal growth will reduce the reliance on fresh water and fertilizers/synthetic mediums. Moreover, microalgae also help in the bioremediation of wastewaters containing toxic chemicals and heavy metals from textile, pharmaceutical, and agro-industrial wastewater. Furthermore, due to the biorefinery approach of microalgae, we can obtain biofuels and other value-added products together with the wastewater treatment. A study revealed that algal-based wastewater treatment and bioenergy production are more environmentally sustainable and economically viable to fit in the wastewater treatment loop of green cities (Ganeshkumar et al., 2018). *Chlorella sp*. was grown in winery and piggery wastewater and it was found that it resulted in the removal of pollutants, production of lipids, and a high yield of biofuels (Alam and Wang, 2019).

4 Role of Urban Green Space (UGS) in the Development Of Sustainable Green Cities And Covid-19 Pandemic Management (Green Spatial Measure) And Biofoundry Approach For Algal Blooms

Covid-19 is considered as a pandemic that strikes once in a century and has a catastrophic impact on socio-economic and health aspects of society. That is the reason WHO impulses the collective approach of the whole society to combat this pandemic. Since a major chunk of the population lives in urban areas/cities, therefore urban green space (UGS) plays a vital role in the transformation of smart and sustainable cities. UGS promotes improved living quality providing a haven from hectic and tiring life trends, encourages physical activities, augments social well-being, and improves health and mental fitness (Haines-Young and Potschin, 2018). UGS contains diverse structures having biophysical nature and their ecological relations together contributing towards stabilizing the framework of green and sustainable cities and better pandemic management. UGS serves as a smart urban design to match the needs and demands of humans, which are aesthetic and functional. The concept of UGS is comprehensively studied and implemented to achieve holistic green infrastructure in a city. The terms open space and urban green space are quite close but, they are not the same. UGS can be construed as an area of land covered by greenery/vegetation irrespective of its size, type, and pattern of plants/trees and other utilities. While open space delineates all the land excluding the built environment which implies that urban green space is the subset of the open space (Wolch et al., 2014). UGS and open space can be understood from Figure 6. The severe problem arising due to the input of excessive nutrients in the urban water bodies (ponds and lakes) is the formation of harmful algal blooms (HABs). These algal blooms can be tapped for their hidden potential and can become a resource for sustainable energy and the environment.

4.1 Covid-19 Impact On Social Well Being

Many epidemics have struck the globe in the past decades (i.e., MERS, SARS), but the pandemic of Covid-19 has given a catastrophic impact on the world with unprecedented scale and scope. National government-imposed measures such as social distancing, movement control orders, and different types of quarantines are aiming to break the chain of Covid-19. These control measures have affected the well-being and mental state of the people. Therefore, to counter these issues, UGS will be a resource of relief and relaxation to all those residing in urban areas (Ugolini et al., 2020). This is due to the Covid-19 pandemic that has disrupted urban/city life and the risk was high in the overcrowded places.

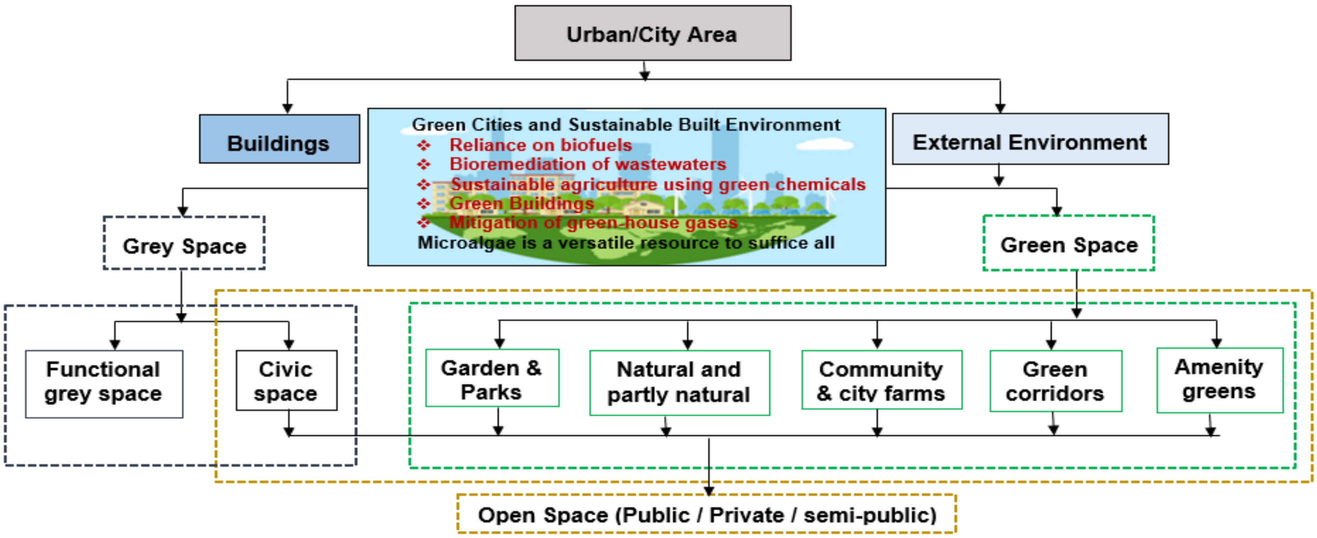


Figure 6 Urban Green Space (UGS) a blessing in Covid-19 pandemic.

4.2 UGS a blessing in the pandemic of Covid-19

Studies revealed the sheer importance of UGS in stabilizing public health and individual wellbeing in different countries like the USA, Norway, and Spain (Slater et al., 2020). The potential role of UGS is the recurring topic of discussion in promoting public health and individual wellbeing to counteract the stressors of the Covid-19 pandemic. During the Covid-19 pandemic, the demand and necessity of green spaces have increased drastically as they are the only options other than home to provide respite and solace from the sufferings like depression and anxiety for the urban population during this crucial time of lockdown and restricted social gatherings. It was reported that despite the risk of transmission, the number of visitors to the UGS showed an eventual increase as compared to the pre-Covid-19 period (Ugolini et al., 2020).

The convenience of the people accessing the green spaces needs to be evaluated as the main aspect by the designers and planners of urban areas. It is reported in previous studies that there is a close connection between the built environment and the transmission of infectious diseases (Dietz et al., 2020). The association of public health with the built environment can be explained by the influence of the built environment on infectious diseases. The planning and designing of buildings including the parameters such as daylight, drainage, ventilation, and sewer systems are of much importance in controlling and preventing the disease (Pan et al., 2021).

UGS is believed to be the economic form of the built environment that can be altered as per the requirement and contributes to enhance the quality of air, livability of the region, aesthetics, and recreational opportunities in the cities. UGS is the means to alleviate fatigue and stress by providing a sense of peacefulness, comfort, and tranquility, leading to a healthy state of mind (Sugiyama et al., 2018). UGS has a compelling positive impact on public health, individual wellbeing, climatic mitigation, and the conservation of biodiversity, as revealed in previous studies (Sathyakumar et al., 2020, Mehrotra et al., 2020). The approach and reaching out to green spaces are vital factors when assessing the spatial distribution of UGS on public health. It is being reported that during the Covid-19 pandemic, UGS has played a contributory role in the improvement of public health and wellbeing.

4.3 Algal blooms in urban water bodies: a threat or a potential resource

Algal blooms can be defined as accelerated growth and build-up of algae (*Cladophora and Spirogyra*) at the surface of different water bodies, i.e., lakes and oceans under favorable conditions of growth (hydrology, nutrients, and climate) (Lõhmus and Balbus, 2015). HABs cause a deleterious impact on the commercialization of fisheries and recreational activities; financial loss in terms of the cost associated with the continuous observation, management, and cleaning up of HABs (annually they cost the US about 2.4 billion USD) (Wurtsbaugh et al., 2019); decrease the water transparency and oxygen concentration of water bodies; cause harmful impact on the water ecology of the affected areas, also posing a threat to the drinking water (Brookfield et al., 2021).

These threats hinder the functioning of green cities by posing danger to animals, humans, and aesthetics of the affected areas in the urban spaces. Many important freshwater lakes are reported to be severely struck by HAB pollution, with significant examples such as Lake Erie (US), Lake Taihu (China), and Lake Victoria (Kenya) (Davis and Gobler, 2016). Nowadays, researchers are working on the simultaneous mitigation of HABs with a biofoundry approach (development of useful bioproducts) (Kim et al., 2015). Therefore, within the domain of circular bioeconomy, biomass production from HABs is fuelled by N, P, and CO_2 from the atmosphere. This provides a sustainable and emerging solution to transform polluted streams into feedstock for further producing various bioproducts. So, biomass produced from HABs can be harvested and further processed to separate its carbohydrates, proteins, and lipid fractions. The extracted biomass can be further exploited to obtain myriad bioproducts like biochar, biofertilizers, animal feed, bioplastics, biofuels, nutraceuticals, and cosmeceuticals, etc (Corcoran and Hunt, 2021). This bio foundry approach can potentially contribute to the establishment of sustainable green cities in terms of energy production and environmental bioremediation.

5. Conclusion

Rapid urbanization and industrialization have resulted in an overwhelming increase in resource depletion and pollution of the cities, thereby creating a compelling need for the development of green cities. To catalyze the sustainable functioning of green buildings and cities, microalgae are studied and emphasized in this paper. Microalgae, contributed by the efficient, innovative, and groundbreaking technology of microalgae bio reactive façades (algal-powered buildings), will simultaneously work on the treatment/recycling of wastewater and the production of bioenergy. As wastewater is used for the cultivation of microalgae, the approach contributes to CO_2 sequestration, minimizing fresh water and land usage, consequently contributing towards sustainability. The microalgal biomass produced can also be utilized to produce biofertilizer and biochar, leading towards sustainable agriculture. Since the role of Urban Green Spaces (UGS) is imperative in green cities, therefore, its functions and role during the critical period of the pandemic are explained in terms of its impact on the environment and social wellbeing. The paper also incorporates the emerging topic of algal blooms in urban ponds and lakes and their potential of causing harm to the environment and humans,subsequently followed by the efficient and viable biofoundry approach of converting algal blooms to energy and useful products. Critical research must be carried out for exploiting different species of algae to avail their hidden potential. Industry-Academia joint work is required to make the use of algae for sustainable and green cities economically viable in the post-pandemic (Covid-19) period. These elements, when integrated together form a sketch (holistic approach) of self-reliant, green, and sustainable city-dwelling, thus providing a healthier and better life to people.

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