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Review Article

Green building future: Algal application technology

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ABSTRACT

In the context of rising global energy demands driven by population growth and urbanization, the construction industry significantly contributes to greenhouse gas emissions during the construction phase and subsequent energy consumption. Fossil fuel dependency for heating and energy needs exacerbates climate change, necessitating urgent solutions. Algal technology emerges as a promising strategy for green building practices, addressing energy efficiency and emissions reduction. Algae's unique ability to absorb carbon dioxide (CO_2) through photosynthesis is harnessed by deploying photobioreactors on building exteriors. Studies indicate that each kilogram of dry algae consumes 1.83 kg of CO_2 while offering applications as organic fertilizer, oil, and protein sources. This technology not only diminishes CO_2 emissions but also transforms wastewater and generates bioenergy, catering to building energy requirements. Algal technology's economic and environmental significance becomes evident through carbon capture, energy generation, and circular waste management, aligning with sustainability principles. This study highlights the potential of algal technology to shape the future of environmentally conscious construction practices, providing avenues for reduced emissions, efficient energy utilization, and sustainable development.

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1. INTRODUCTION

Urban expansion is taking place globally faster, creating a disbalance in the sustainable climate mechanisms, which may result in natural disasters, causing acute social and economic losses. With the recent population growth and increasing urbanization and industrialization, more energy is needed [1]. During the 19th and 20th centuries, man learned to use focused points such as fossil fuel [2]. With industrial development and increased production, some problems have arisen on the planet and become more severe daily. Some consequences are increased disease and mortality caused by environmental pollution, acid rain, and the destruction of ecosystems and ozone [3]. Rapid urbanization will also cause the depletion of natural resources, particularly fossil fuels, due to the increase in energy consumption brought on by industrialization [4]. World Health Organization reports that 90% of the population in urban areas is breathing polluted air according to the air quality guidelines [5]. About 70% of Greenhouse emissions come from urban agglomerated centers [6]. Globally, buildings account for 40% of energy and material use, 33 % of CO_2 emissions, 25 % of wood harvesting, and 17% of freshwater usage [7]. However, it is projected that shortly, emissions from buildings in countries that are rapidly industrializing will surpass emissions from structures in wealthy nations. Historically, most emissions originated from developed countries [8]. Therefore, it is important

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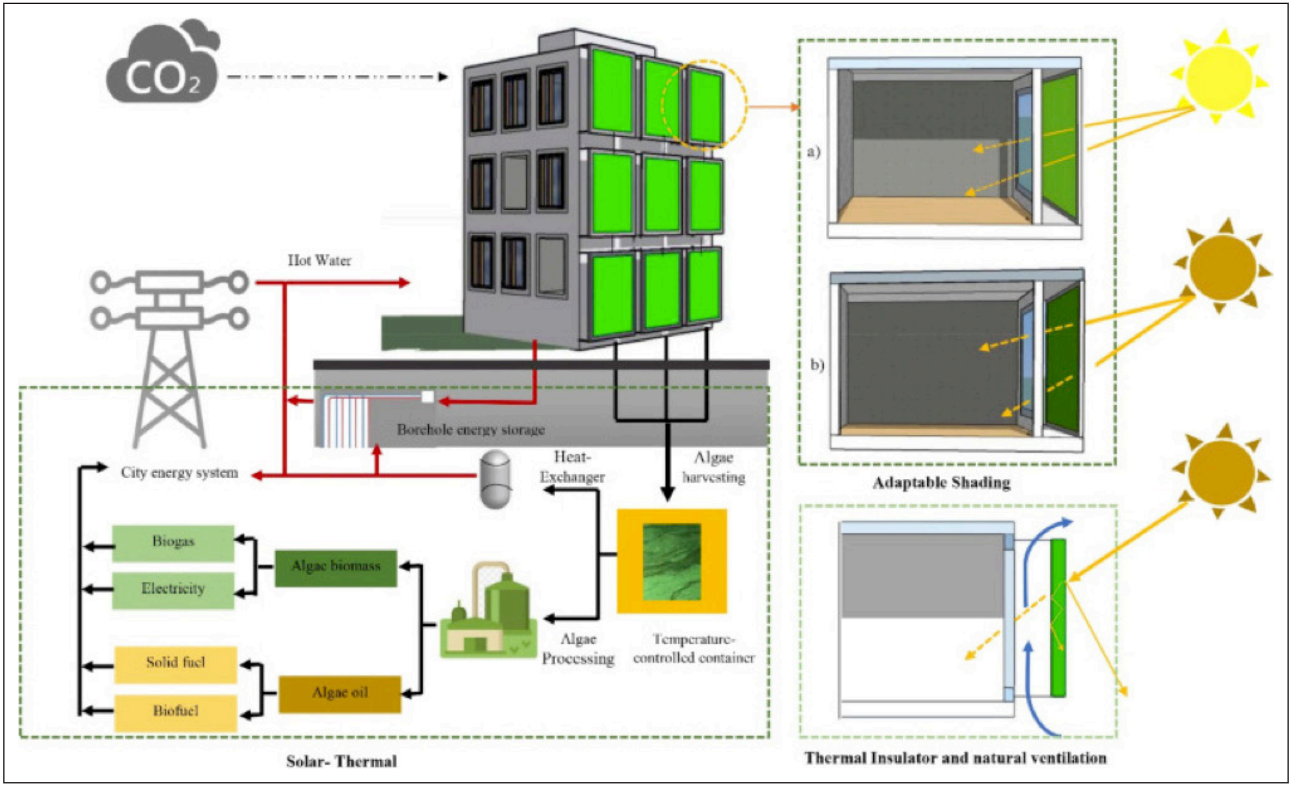

Figure 1. Algae can be grown in various settings, including closed-loop [22].

to plan and design new buildings and cities based on sustainable development features, such as self-sustainability, zero waste/zero emissions, environmental safeguarding, and green fuel and energy exercise [9]. Algae integration into buildings' external façade can sustain buildings and reduce energy consumption [10]. Incorporating algae into building exteriors promotes sustainability in the built environment and acts as a source of renewable energy [10]. Utilizing algae as a renewable energy source to produce electricity or offer other energy-related advantages inside buildings is called algae energy production for buildings [10]. Algae, photosynthetic organisms encompassing diverse species, play a crucial role in various ecological processes. They have garnered increasing attention for their potential applications in sustainable development, particularly in green building technology [11, 12]. Providing a detailed understanding of algae in the context of this discussion is paramount. Algae from the kingdom Protista exhibit various morphological and physiological characteristics. They can be unicellular, colonial, or multicellular, and their size can vary from microscopic to macroscopic scales [13]. Additionally, algae exhibit remarkable diversity in pigmentation, allowing them to thrive in diverse aquatic and terrestrial environments. Classification of algae is based on various criteria, including pigmentation, cell structure, and mode of reproduction. For instance, algae are commonly classified into several groups, such as Chlorophyta (green algae), Rhodophyta (red algae), Phaeophyta (brown algae), and Cyanobacteria (blue-green algae), each with distinct characteristics and ecological roles [14]. The types of algae relevant to green building applications encompass a broad spectrum, ranging from microalgae to macroalgae. Microalgae, such as Chlorella and Spirulina, are valued for their high photosynthetic efficiency and rapid growth rates, making them suitable candidates for biomass production and biofuel generation. Macroalgae, including kelp and seaweed, offer potential as sustainable construction materials due to their abundance, renewability, and unique mechanical properties. Harvesting algae involves various techniques tailored to the specific characteristics of the target species and intended applications [14]. These methods encompass traditional approaches, such as manual collection from natural habitats and innovative technologies like photobioreactors and biofilm cultivation systems. Advancements in harvesting methodologies aim to optimize biomass yield, minimize energy consumption, and enhance overall efficiency in algae cultivation processes. In summary, a comprehensive understanding of algae, encompassing their definition, characteristics, classification, and harvesting techniques, is essential for elucidating their role in green building technology. By integrating scientific knowledge with practical applications, researchers and practitioners can harness the potential of algae to promote sustainability and resilience in the built environment and functional food [15]. Algae-based alternative energy sources provide sustainable possibilities that can help solve pressing global problems such as resource depletion, pollution, and climate change [16]. With global warming, the importance of bioclimatic comfort has increased. An extremely promising strategy that substantially contributes to sustainability and the goal of a greener future is using algae as a source of electricity [17].

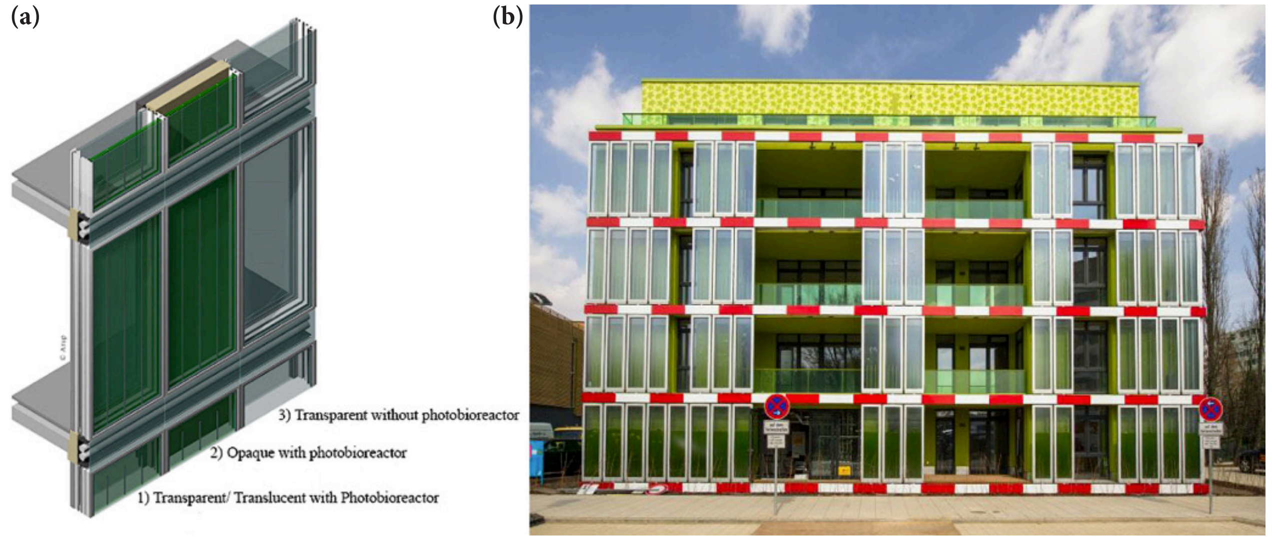

Figure 2. **(a)** Bio-panels [35] **(b)** Building façade in the algae application technology [36].

2. WHAT IS ALGAE APPLICATION TECHNOLOGY?

Algae application technology for buildings, commonly referred to as "bioarchitecture" or "algae-based building systems," includes incorporating algae and associated microorganisms as functional elements into the design and maintenance of buildings. In renewable energy, generating power by combining algae onto building façades is an eco-friendly and long-lasting solution [10]. There are essential applications for environmental sustainability, such as the biotechnological use of algae to purify harmful paints [11]. With the help of algae, energy can be produced directly on the exterior surfaces of buildings, as opposed to the standard photovoltaic systems, such as solar panels, which are mounted on building rooftops or open spaces to convert solar energy into electricity [18]. This developing field investigates algae's potential role in constructing and maintaining sustainable and energy-efficient buildings. A procedure known as transesterification can be used to turn the lipids (oils) that algae produce into biodiesel. Due to its ability to be generated responsibly and the fact that it does not compete with food crops for land, biodiesel made from algae is seen as a possible replacement for conventional fossil fuels [19]. The adaptability of algal energy production is one outstanding feature. Algae can be grown in various settings, including closed-loop photobioreactors and large-scale open ponds (Fig. 1) [20]. Because of their versatility, we can incorporate algal systems into multiple environments, including buildings [21]. For instance, it is possible to embed algae culture systems into building exterior façade designs, converting them into surfaces that produce energy [22].

Algal Application Technology offers a promising avenue for reducing dependence on finite fossil fuels and mitigating greenhouse gas emissions [12, 23]. Through algae cultivation, atmospheric CO_2 is utilized for photosynthesis and biomass accumulation, facilitating carbon capture and storage. Algae's rapid growth rates and adaptability to diverse environmental conditions enable efficient biomass production with minimal land and water requirements and provide information about water quality. Contributes to ecological protection in studies carried out within remote monitoring systems [24, 25]. This versatile biomass resource can be utilized across various sectors, including energy production, construction materials, biofuels, bioplastics, pharmaceuticals, space exploration, climate change causing human migration, and wastewater treatment, contributing to sustainability goals [26, 27].

Furthermore, algal cultivation systems facilitate nutrient recycling and wastewater remediation, reducing environmental pollution. However, the high initial capital investment and operational costs, coupled with energy-intensive extraction and processing processes, pose challenges to the widespread adoption and scalability of Algal Application Technology [28]. Technical obstacles such as contamination risks, nutrient imbalances, and environmental fluctuations necessitate ongoing research and development efforts. Additionally, large-scale algae production may compete with land and water resources needed for food production or natural ecosystems, potentially leading to environmental conflicts. Despite significant advancements, widespread commercialization faces barriers to economic viability, regulatory constraints, and market acceptance. Overall, addressing these challenges is crucial for realizing the full potential of Algal Application Technology in achieving sustainable development objectives.

3. PLACING ALGAE ON THE FACADE OF BUILDINGS

The process of placing algae outside of buildings includes these steps.

A growth medium or substrate would be created to support the growth and adhesion of the algae to the façade surface. This medium might provide algae's nutrients and a steady environment [29]. Specialized bioreactors or bio-panels would be created and built to house the algae on the building face. These bioreactors, which offer a regulated environment for algae growth, must be securely installed onto the façade (Fig. 2a) [30]. The building façade surface

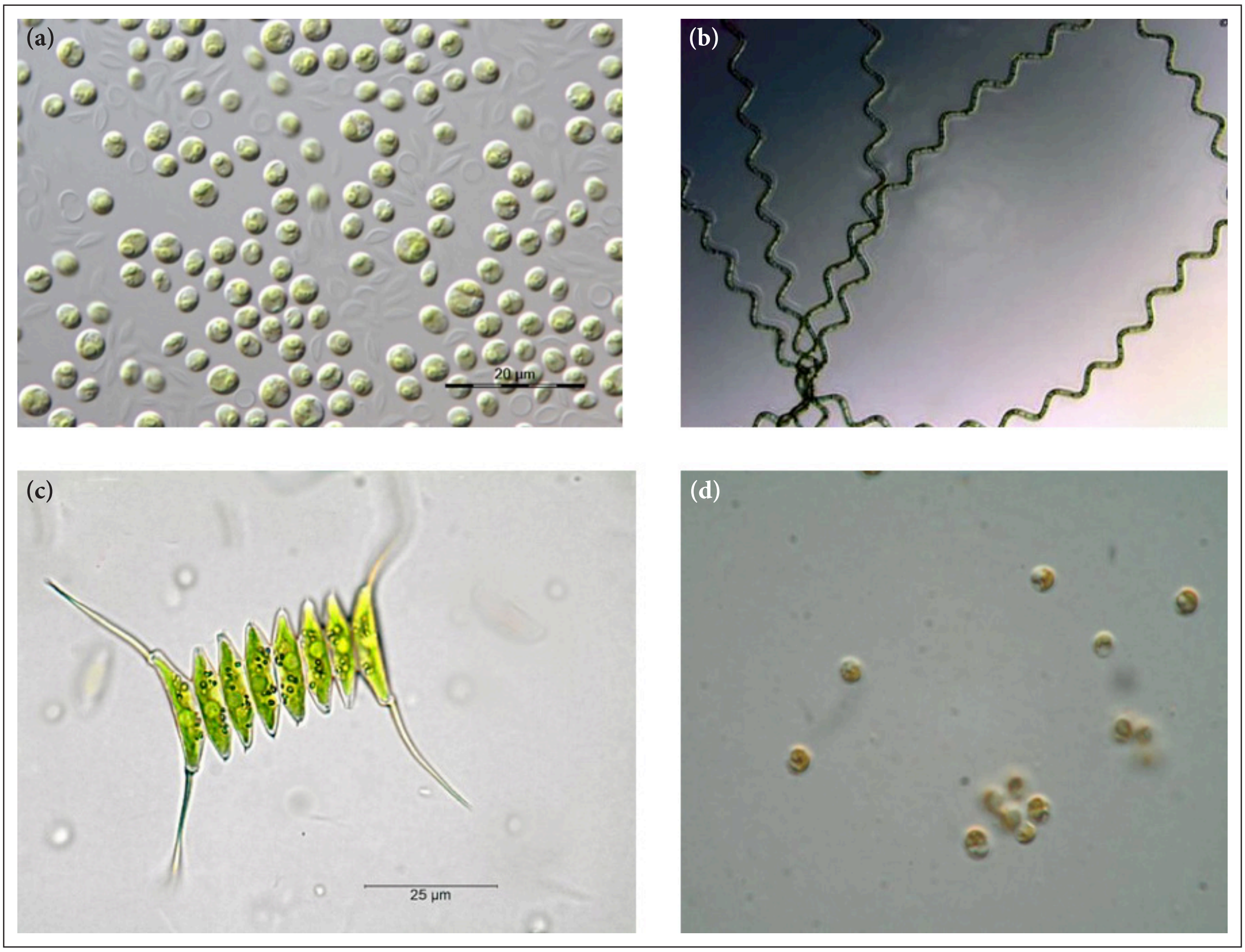

Figure 3. Some algae with high potential energy: **(a)** Chlorella sp. [44], **(b)** Spirulina sp. [45], **(c)** Scenedesmus sp. [44], **(d)** Nannochloropsis sp. [46]

must be ready to allow for algae growth. A character with suitable algae adhesion and development characteristics may be installed, or a suitable coating may be applied (Fig. 2b) [31]. In bioreactors, a few species of algae will probably be planted or seeded on the prepared façade surface. The algae will then utilize the available sunlight to expand and photosynthesize [32]. Algae growth requires water and vital nutrients. Bioreactors can incorporate a controlled fertilizer and water supply system depending on the type of algae being grown there and the surrounding environment [33]. Harvest Energy: As they develop and photosynthesize, algae create biomass, and high-energy chemicals can be gathered and transformed into usable energy by creating biogas or biofuel extraction [34].

Algae bioreactors integrated into building exteriors can be utilized for several things, including energy production and environmental sustainability [22]. Algae bioreactors are devices that use sunlight to grow algae and are capable of photosynthesis on the exterior surfaces of buildings [30]. Many algae species may be utilized depending on the bioreactor's demands and goals [37]. Chlorella sp. use in biofuel production can provide an energy-efficient source and aid in lowering greenhouse gas emissions. The oil extracted from Chlorella sp. can be used to make biodiesel. As a more environmentally friendly substitute for fossil fuels, biodiesel is a renewable fuel. From an environmental sustainability standpoint, producing Chlorella sp. is desirable (Fig. 3a). Because of their high oil content, Chlorella sp. species have the potential to be helpful in the manufacture of biofuel and bioplastic. Chlorella sp. is well known for having a high lipid content per cell, making these lipids an essential source for biofuel manufacture [38]. Spirulina sp. could be used to produce biofuels, which could replace fossil fuels with a more sustainable energy source. Spirulina sp. can use photosynthesis to harvest solar energy. In photosynthesis, oxygen is produced as a byproduct, while carbon dioxide and water are converted into organic compounds (such as glucose). The carbon cycle and energy generation depend on this mechanism [39]. Effective use of microalgae such as Spirulina sp. for energy and nutrition is becoming increasingly important due to biofuel production and the increasing demand for sustainable energy sources (Fig. 3b) [40]. Spirulina sp. is a nutrient-rich form of algae, and because of its high oil content, it has a significant chance of being used to produce biofuel. The oils extracted from spirulina can be transformed into various biofuels, including jet fuel and biodiesel [32]. Scenedesmus sp. uses photosynthesis to absorb carbon dioxide and produce energy. To combat global climate change, this method can help reduce the amount of greenhouse gases released into the environment. Scenedesmus sp has a significant amount of oil per cell, which can be used to make biodiesel. A more sustainable fuel with lower greenhouse gas emissions than fossil fuels is biodiesel, which can be used instead. Scenedesmus sp. and similar microalgae can be grown in special bioreactors under carefully regulated conditions. The manufacturing process can be optimized in these facilities and the surrounding environment (Fig. 3c) [41]. Using photosynthesis, Nannochloropsis sp. takes carbon dioxide (CO_2) from the air and creates oxygen. The amount of greenhouse gases linked to global warming can decrease and decrease the carbon footprint. It is an essential algae species for biofuel. Like other microalgae, Nannochloropsis sp. has much oil in each cell. These oils can be used to make biodiesel. With its ability to replace fossil fuels and cut greenhouse gas emissions, biodiesel is a sustainable fuel that is better for the environment. Nannochloropsis sp. is a helpful algae for energy production because of its quick reproduction rate and ability to quickly generate a significant quantity of biomass (Fig. 3d) [42, 43].

4. REAL-WORLD EXAMPLES OF ALGAE IN BUILDINGS

Algae have been increasingly utilized in various real-world applications within the built environment, showcasing their potential to contribute to sustainable architecture and construction practices [10]. For instance, in the architectural realm, the use of algae in façade systems has gained traction to integrate renewable energy generation and bioremediation into building design. One notable example is the BIQ House in Hamburg, Germany, which features a reactive façade of glass panels filled with microalgae [47]. These algae photosynthetically convert sunlight and CO_2 into biomass, generating renewable energy while shading the building interior and enhancing thermal insulation. Also, the algae help regulate indoor air quality by absorbing CO_2 and releasing oxygen, contributing to a healthier indoor environment. Another pioneering project is the Algae Dome, showcased at the Expo Milano 2015, which demonstrates the potential of algae cultivation in architectural settings. Designed as a self-sustaining ecosystem, the Algae Dome utilizes sunlight and wastewater to cultivate algae, which can be harvested for various applications, including biofuel production, food supplements, and wastewater treatment. The modular design of the Algae Dome allows for scalability and adaptability to different environmental conditions, making it a versatile solution for urban sustainability challenges [10]. In addition to façade systems, algae-based materials have been explored for interior finishes, insulation, and structural elements in building construction. For example, research initiatives such as the Algae Brick project aim to develop bio-based building materials using algae as a critical component, offering renewable alternatives to traditional construction materials. These real-world examples underscore algae's potential to revolutionize how we design, construct, and inhabit buildings, offering innovative solutions that integrate renewable energy generation, bioremediation, and biomimicry principles into architectural practice. However, further research and technological advancements are needed to overcome technical challenges and scale up algae-based building solutions for widespread adoption in the construction industry [10].

5. PHOTOBIOREACTORS: TOOL FOR SUSTAINABLE DESIGN

Integrating photobioreactors (PBRs) in buildings holds significant promise for sustainable design, offering a renewable source of biomass while simultaneously enhancing environmental performance [48]. To effectively incorporate PBRs into buildings, several technical requirements must be considered. Firstly, adequate space and access to sunlight are essential for successfully operating PBRs. Buildings must be designed or retrofitted with suitable rooftop or façade configurations to optimize sunlight exposure for algal cultivation. Additionally, orientation, shading, and nearby obstructions must be evaluated to maximize solar irradiance. Secondly, PBRs require a controlled environment to support optimal algae growth. This includes maintaining suitable temperature, pH levels, nutrient concentrations, and CO_2 supply within the reactor system. Building systems must incorporate temperature regulation, nutrient dosing, and CO_2 capture mechanisms to ensure favorable conditions for algal cultivation [48]. Furthermore, effective nutrient management is critical to sustain algae growth in PBRs. Nutrient sources like wastewater or organic effluents should be readily available and compatible with the cultivation system. Proper nutrient cycling and monitoring protocols must be established to prevent nutrient depletion or excess, which can adversely impact algae productivity and system stability. Moreover, the design of PBRs should prioritize operational efficiency and ease of maintenance. Accessible components, automated monitoring systems, and remote control capabilities can streamline operations and facilitate timely maintenance activities. Additionally, consideration should be given to selecting durable, corrosion-resistant materials suitable for long-term use in the building environment. In summary, successfully integrating PBRs into buildings requires careful consideration of technical requirements related to sunlight exposure, environmental control, nutrient management, and system reliability [48]. By addressing these aspects in the design and implementation phases, photobioreactors can emerge as a viable, sustainable building design tool, contributing to energy production and environmental stewardship [48]. These can use sunlight to convert carbon dioxide into biomass, oxygen, and essential bioactive chemicals. They allow for the production of bioenergy and carbon capture. In photobioreactors, photosynthetic microorganisms may take in carbon dioxide from the environment as they grow [34]. This procedure acts as a carbon capture and storage method, lowering greenhouse gas emissions. Additionally, the biomass produced can be transformed into bioenergy using a variety of processes, including the creation of biogas, bioethanol, or biodiesel. Various transparent and leak-proof

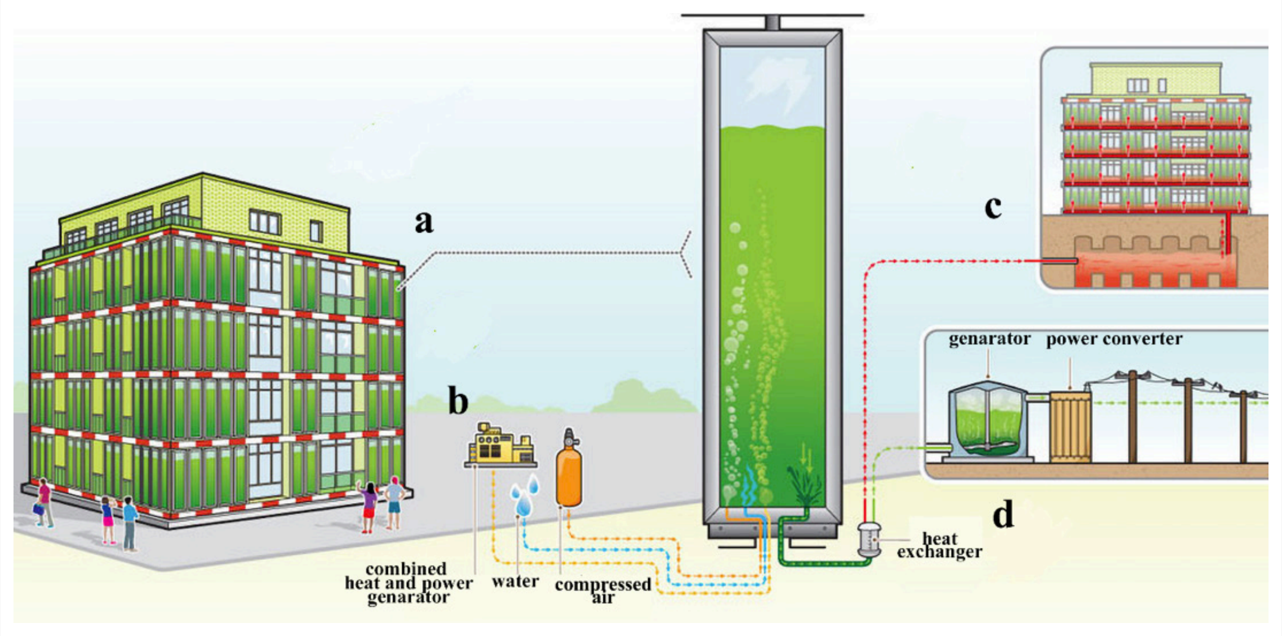

Figure 4. Bioreactor working principle [52].

containers are used in photobioreactors [30]. To efficiently harness solar energy for bioenergy production from algae, most photobioreactors have large surfaces exposed to sunlight (Fig. 4). The efficient facilitation of bioenergy generation should be a goal of photobioreactor design [49]. To accomplish this, they need a mixing system that guarantees adequate agitation of the algal culture and a high mass transfer rate. To maximize light exposure, it is essential to consider efficient light utilization and a suitable surface-to-volume ratio [50]. Thanks to the design, high CO_2 transfer rates should be possible, which should be with high-density algae cells. Solar energy should be maximized when it is deployed in outdoor settings. Furthermore, it's essential to ensure that accumulated O_2 is removed effectively [51].

Figure 4a represents that the bioreactors at BIQ are fastened to the south-facing walls of the structure and are made to function with a minimum of maintenance by humans. Between laminated safety glass panels, each bioreactor is around six gallons of water thick, more than eight feet high, and three inches wide [53]. Figure 4b represents that water, phosphorus, and nitrogen are pushed through the bioreactors by a sophisticated circulatory system that keeps the algae alive. Carbon dioxide, the food source, is produced by a generator on the first floor (In the future, the algae might consume CO_2 released from other structures.) While tiny beads scratch the glass and prevent the organisms from adhering to it, compressed air blasts keep the algae from becoming too thick [54]. Figure 4c represents that the water in the bioreactor can reach 100°F on a bright day because algae emit heat when they reproduce. To heat the rooms or to pre-heat the water used in the kitchen and showers, that water passes through an exchanger and heats a second supply of water that flows through pipes set into the floors. Eight boreholes under the structure that are more than 260 feet deep are used to store extra hot water. The algae from the bioreactors collectively generate enough energy to heat four apartments all year round [52]. Figure 4d represents that the algae are filtered from the water and trucked three kilometers to a university, where they are processed for methane and hydrogen. This procedure happens at least once a week. They might be burned to produce power, but this may be an expensive and unproductive solution to reduce carbon emissions [16].

6. CHALLENGES SETTING UP THIS SYSTEM

The façades of buildings can be used to generate energy by installing algae bioreactors, but this process is complex and may present several challenges. Algae can produce oxygen and biomass using photosynthesis in algae bioreactors, which are devices involved in energy production. These systems are very effective in terms of sustainability but in terms of challenges [55]. In bioreactors, technical elements, including an appropriate environment, water flow, light, and temperature, must be carefully controlled for algae to grow and produce energy effectively [34]. Potentially insufficient at this time are reliable data and technology that demonstrate the biological activity of algae in outdoor conditions [56]. Choosing the kinds of algae that are most suited for bioreactors and making them climate-change resistant might be challenging at the same time [56]. Erratic weather and environmental pollutants can negatively impact Algae's ability to function effectively [57].

6.1. Environmental Impacts and Benefits

The environmental crisis we face today necessitates innovative solutions that can address multiple challenges simultaneously [58]. Algal application technology, especially in the context of green buildings, presents multifaceted environmental advantages [10]. This section delves into the specific environmental impacts and benefits of this technology.

6.1.1. Carbon Sequestration Potential

One of the most promising attributes of algae is its ability to absorb and store carbon dioxide (CO_2) from the atmosphere, a process known as carbon sequestration. When deployed on building façades, the algae interact directly with ambient air, capturing CO_2 as they undergo photosynthesis. This not only helps mitigate urban air pollution but also actively reduces the carbon footprint of the building itself [59]. Algae's efficiency in capturing CO_2 surpasses many traditional terrestrial plants. For every kilogram of dried algae, there's an absorption of approximately 1.83 kilograms of CO_2 [40]. As urban areas grapple with high CO_2 concentrations, integrating algae application technology in construction could present a tangible solution for atmospheric carbon reduction [60].

6.1.2. Reduction in Greenhouse Gas Emissions

Beyond just CO_2, the construction and operation of buildings are responsible for various greenhouse gas emissions, including methane (CH4) and nitrous oxide (N2O). By transitioning to algal-based energy solutions for buildings, there's a potential to displace some fossil fuel usage, thus decreasing greenhouse gas emissions from energy consumption. Moreover, when used for heating or other building needs, the energy produced by algal biomass releases only the amount of CO_2 initially absorbed by the algae, creating a closed carbon loop. This ensures no net increase in atmospheric CO_2 levels [21].

6.1.3. Wastewater Treatment and Purification

Algal technology's lesser-known but equally vital advantage is its role in wastewater treatment [61]. Algae thrive in nutrient-rich environments, and when exposed to wastewater, they can effectively absorb pollutants, including nitrogen and phosphorus compounds [62]. This not only purifies the wastewater but also prevents the release of these compounds into natural water bodies, which could lead to problems like eutrophication [63].

6.2. Economic Implications and Considerations

Incorporating algal technology within the construction and architectural realm is not solely an environmental undertaking; it intertwines deeply with the economic fabric of the industry [10]. Understanding the economic implications is pivotal for decision-makers, investors, and other stakeholders in gauging the viability and scalability of this technology.

6.2.1. Cost-benefit Analysis

While the initial installation costs of algal application systems, including photobioreactors, might be higher than traditional building materials or systems, it's crucial to consider the long-term savings and benefits. Operational Savings: By generating bioenergy, buildings can offset some energy costs, leading to significant savings over the building's lifecycle [64]. The harvested algae can be processed to produce valuable by-products such as biofuel, organic fertilizers, and proteins, creating additional revenue streams. Algal systems can reduce wastewater treatment and purification costs, providing dual functionality. With growing emphasis on carbon trading and credits, buildings employing algal technology may qualify for credits or incentives, further improving the financial model [16]. Considering the cumulative savings and potential revenue streams, the return on investment over time can be considerably positive, making the technology economically attractive in the long run [65].

6.2.2. Market Potential and Growth Forecast

The global demand for sustainable and energy-efficient buildings is on the rise, driven by regulatory pressures and consumer demand. As awareness about the multifaceted benefits of algal technology spreads, its market potential is expected to witness an uptrend. With increasing urban population densities, there's a pressing need for solutions tackling air quality issues and carbon emissions. As countries commit to the Sustainable Development Goals, technologies that offer solutions for both energy and the environment will be in high demand [66]. As research continues and innovations in the algal application field evolve, the efficiency and applicability of the technology are likely to improve, driving market adoption.

6.2.3. Stakeholder and Industry Reception

The construction and architectural industry's reception of algal technology has been cautiously optimistic. While many laud the environmental and economic potential, others express concerns regarding maintenance, aesthetics, and long-term durability [53]. Several collaborations between biotechnologists and architects are emerging, pointing towards a growing interest in integrating biology with building design. As green technology investments gain traction, venture capitalists and green funds have shown notable interest in algal startups and initiatives [10]. Encouragingly, some governments and local municipalities offer incentives or grants for sustainable construction practices, boosting the adoption of such technologies [67].

6.2.4. By-products and their Utility

Algae, given their prolific growth and diverse composition, are not just valuable for their primary roles in carbon capture or bioenergy production. Their biomass offers myriad by-products, each with its utilities that promise for various sectors. Delving into the potential by-products and their applications showcases the multifaceted benefits of cultivating algae on building façades [68].

6.3. Algal Biomass as Organic Fertilizer

One of the significant advantages of harvested algal biomass is its potential use as an organic fertilizer [69]. Algae are known to be high in essential nutrients, such as nitrogen, phosphorus, and potassium, making them an excellent source of plant nourishment [70]. The organic matter present in the algal biomass can stimulate beneficial soil microbes, enhancing soil health. Using algal biomass reduces the need for chemically synthesized fertilizers, reducing the environmental damage these chemicals often inflict. By integrating this by-product into agriculture, we could witness increased crop yields, healthier soils, and reduced chemical pollutants infiltrating our natural ecosystems.

6.4. Production of Algal Oil and its Uses

Algal oil extraction has gained significant attention due to its myriad of applications. One of the most renowned applications of algal oil is its conversion into biodiesel. This biofuel is more sustainable than fossil fuels and emits fewer greenhouse gases upon combustion [71]. Algal oil contains omega-3 fatty acids, eicosatetraenoic acid, and docosahexaenoic acid [72]. These compounds benefit cardiovascular health, making algal oil a sought-after ingredient in dietary supplements. The unique composition of algal oil, loaded with antioxidants and fatty acids, finds its way into various cosmetic products, offering hydration and anti-aging benefits [73].

6.5. Protein Extraction and its Potential

Beyond oil, the algal biomass is a protein powerhouse, opening doors to several promising applications. The protein-rich algal biomass can be processed into poultry, fish, and livestock feed, providing a sustainable alternative to traditional feed sources. Some algae species have been explored for their potential as protein supplements in human diets. Given the global demand for alternative protein sources, algae offer an exciting potential. Specific algal proteins have bioactive properties, making them candidates for drug development and other medical applications [74]. To conclude, the range of by-products derivable from algal biomass underscores the versatility and potential of this organism. From fueling our vehicles with biodiesel to nourishing our soils and feeding our livestock, algae stand out as a promising pillar in the march towards a more sustainable and eco-friendly future.

7. CHALLENGES AND FUTURE DIRECTIONS

While algal application technology in green buildings is promising, adopting a balanced perspective is crucial to adopting both its potential and challenges. Understanding the existing solutions in the pipeline and anticipated future trends provides a comprehensive view of the road ahead for this innovative integration of biology and architecture. When integrated with buildings, pPhotobioreactorsequire regular maintenance. Ensuring the health of the alga when integrated with buildings, cleaning the systems, and managing potential contamination are concerns. Algal growth rates and productivity can be significantly affected by changing climatic conditions. Inconsistent sunlight, extreme temperatures, or unpredictable weather patterns can impact system efficiency. Algal systems can change in appearance over time. Concerns about the visual appeal of green-tinted façades and potential public perception can be barriers to broader adoption. The upfront investment required for integrating algal technology can be high, deterring some stakeholders.

7.1. Potential Solutions and Ongoing Research

Research is ongoing to develop self-cleaning and more durable photobioreactor systems, which can minimize maintenance demands. Biotechnologists optimize algae strains for specific climatic conditions, enhancing resilience and productivity. New business models and financial incentives are being explored to make the initial investment in algal systems more feasible for builders and property owners. Combining algal systems with technologies like solar panels or wind turbines can address some energy variability issues and enhance overall building efficiency [21].

7.2. Future Trends and Predictions

Beyond building façades, the future might see dedicated urban algal farms catering to dense urban populations' energy, food, and other by-product needs. As the world moves towards stricter climate targets, governments might offer more incentives or mandates for green construction practices, propelling the adoption of algal technologies. Research hints at the possibility of using algae directly in building materials, like bricks or panels, allowing for carbon sequestration and insulation benefits. With algal systems' potential in wastewater treatment, future buildings might adopt a more decentralized approach to waste management, enhancing sustainability. In summary, while the path of integrating algal technology into green building practices is riddled with challenges, the solutions on the horizon, combined with the potential future trends, paint an optimistic picture. As technology advances and the urgency for sustainable solutions increases, algal applications in architecture could become commonplace in tomorrow's cities.

8. CONCLUSION

In the contemporary epoch characterized by rapid urbanization juxtaposed with climatic vicissitudes, the synthesis of biological innovations, notably algal technology, within sustainable architectural methodologies emerges as a potential panacea. This discourse endeavors to encapsulate the salient attributes and inherent challenges of this avant-garde amalgamation. At the environmental forefront, algal applications underscore a multifaceted approach, adept not merely at diminishing carbon dioxide efflux but also instrumental in wastewater rectification, ambient purification, and sustainable energy genesis. Economically, transcending its environmental prowess, the algal paradigm augments the edification domain, offering fiscal efficacies, engendering innovative revenue avenues, and catalyzing sectoral growth. Moreover, the diverse array of by-products, spanning biofuels to organic enhancers and proteomic adjuncts, underlines the holistic benefits of this integrative venture. Yet, the journey to ubiquitous adoption is riddled with tangible constraints. However, the present scholarly landscape, marked by relentless research, technological evolutions, and strategic fiscal models, appears poised to surmount these hurdles. Regarding architectural and energy implications, the algal foray heralds a paradigmatic shift from conventional design philosophies towards ecologically synergistic modalities. The edification arena, invigorated by algal derivatives, presents a cornucopia of novel commercial prospects, alliances, and revenue trajectories. Concurrently, algal-equipped infrastructures epitomize the zenith of energy diversification, curbing traditional power reliance and accentuating resilience. The difficulties for stakeholders encompass the necessities of academia-industry confluences, an intensification of public cognizance initiatives, regulatory incentivization, and robust financial endorsements of boundary-pushing endeavors within the algal architectural sphere. To conclude, integrating such pioneering modalities is no longer a discretionary endeavor but a cardinal collective mandate at the intersection of ecological imperatives and technological ascendancy. In light of this, further research should focus on elucidating optimal integration methodologies, refining cultivation techniques, and assessing long-term environmental and economic impacts to facilitate the seamless integration of algal technology into mainstream architectural practices.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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REFERENCES

1. Çelekli, A., Yeşildağ, İ., Yaygır, S., & Zariç, Ö. E. (2023). Effects of urbanization on bioclimatic comfort conditions. *Acta Biol Turc, 36*(4), 1–10.
2. Dincer, I., & Rosen, M. A. (2001). Energy, environment and sustainable development. *Appl Energy, 64*(1–4), 427–429. [CrossRef]
3. Singer, S. F. (1985). Global environmental problems. *Eos Trans AGU, 66*(15), 164–165. [CrossRef]
4. Mudakkar, S. R., Zaman, K., Khan, M. M., & Ahmad, M. (2013). Energy for economic growth, industrialization, environment and natural resources: Living with just enough. *Renew Sustain Energy Rev, 25*, 580–595. [CrossRef]
5. World Health Organization. (2016). Ambient air pollution: a global assessment of exposure and burden of disease. *Clean Air J, 26*(2). [CrossRef]
6. Yu, X., Wu, Z., Zheng, H., Li, M., & Tan, T. (2020). How does urban agglomeration improve the emission efficiency? A spatial econometric analysis of the Yangtze River Delta urban agglomeration in China. *J Environ Manag, 260*, 110061. [CrossRef]
7. Say, C., & Wood, A. (2008). Sustainable rating systems around the world. *CTBUH J, 2008*(2), 18–29.
8. Li, K., & Lin, B. (2015). Impacts of urbanization and industrialization on energy consumption/ CO_2 emissions: Does the level of development matter? *Renew Sustain Energy Rev, 52*, 1107–1122. [CrossRef]
9. Wang, Z., Zeng, J., & Chen, W. (2022). Impact of urban expansion on carbon storage under multi-scenario simulations in Wuhan, China. *Environ Sci Pollut Res, 29*(30), 45507–45526. [CrossRef]
10. Sedighi, M., Pourmoghaddam Qhazvini, P., & Amidpour, M. (2023). Algae-powered buildings: A review of an innovative, sustainable approach in the built environment. *Sustainability, 15*(4), 3729. [CrossRef]
11. Zariç, Ö. E., Yeşildağ, İ., Yaygır, S., & Çelekli, A. *Removal of harmful dyes using some algae*. 10.5281/zenodo.8190776.
12. Çelekli, A., & Zariç, Ö. E. (2024). Plasma-enhanced microalgal cultivation: A sustainable approach for biofuel and biomass production A. In Shahzad & M. He (Eds.), *Emerging Applications of Plasma Science in Allied Technologies* (pp. 243-263). IGI Global. [CrossRef]
13. Corliss, J. O. (2002). Biodiversity and biocomplexity of the protists and an overview of their significant roles in the maintenance of our biosphere. *Acta Protozool, 41*(3), 199–219.
14. Round, F. E. (1984). *The ecology of algae*. Cambridge University Press.
15. Çelekli, A., & Zariç, Ö. E. (11–13 October, 2023). *Assessing the environmental impact of functional foods. 6th International Eurasian Conference on Biological and Chemical Sciences*. Ankara, Türkiye.
16. Chew, K. W., Khoo, K. S., Foo, H. T., Chia, S. R., Walvekar, R., & Lim, S. S. (2021). Algae utilization and its role in the development of green cities. *Chemosphere, 268*, 129322. [CrossRef]
17. Benedetti, M., Vecchi, V., Barera, S., & Dall'Osto, L. (2018). Biomass from microalgae: The potential of domestication towards sustainable biofactories. *Microb Cell Fact, 17*(1), 173. [CrossRef]
18. Sepehri, F. (2016). Lighting and energy supply for heating in building using algae power. *J Fundam Appl Sci, 8*(3), 1021–1036 [CrossRef]
19. Bisen, P. S., Sanodiya, B. S., Thakur, G. S., Baghel, R. K., & Prasad, G. B. K. S. (2010). Biodiesel production with special emphasis on lipase-catalyzed transesterification. *Biotechnol Lett, 32*(8), 1019–1030. [CrossRef]
20. Hossain, N., & Mahlia, T. M. I. (2019). Progress in

physicochemical parameters of microalgae cultivation for biofuel production. *Crit Rev Biotechnol, 39*(6), 835–859.

21. Elrayies, G. M. (2018). Microalgae: Prospects for greener future buildings. *Renew Sustain Energy Rev, 81*, 1175–1191. [CrossRef]
22. Talaei, M., Mahdavinejad, M., & Azari, R. (2020). Thermal and energy performance of algae bioreactive façades: A review. *J Build Eng, 28*, 101011. [CrossRef]
23. Çelekli, A., & Zariç, Ö. E. (2023). From emissions to environmental impact: Understanding the carbon footprint. *Int J Environ Geoinf 10*(4), 146–156. [CrossRef]
24. Zariç, Ö. E., Çelekli, A., & Yaygır, S. (2024). Lakes of Turkey: Comprehensive review of Lake Çıldır. *Aquat Sci Eng, 39*(1), 54–63. 10.26650/ASE20241353730.
25. Çelekli, A., & Zariç, Ö. E. (2023). *Utilization of herbaria in ecological studies: Biodiversity and landscape monitoring*. Advance Online Publication. [CrossRef]
26. Çelekli, A., & Zariç, Ö. E. (2024). Breathing life into Mars: Terraforming and the pivotal role of algae in atmospheric genesis. *Life Sci Space Res, 41*, 181–190. [CrossRef]
27. Çelekli, A., & Zariç, Ö. E. (11–13 October, 2023). *Hydrobiology and ecology in the context of climate change: The future of aquatic ecosystems. 6th International Eurasian Conference on Biological and Chemical Sciences*. Ankara, Türkiye. https://doi.org/10.5281/zenodo.10021473
28. Murthy, G. S. (2011). Overview and assessment of algal biofuels production technologies. *In Biofuels*. Elsevier. [CrossRef]
29. Ramaraj, R., Tsai, D. D.W., & Chen, P. H. (2015). Carbon dioxide fixation of freshwater microalgae growth on natural water medium. *Ecol Eng, 75*, 86–92. [CrossRef]
30. Kükdamar, İ. (2018). Cephelerde fotobiyoreaktör kullanımının binaların sürdürülebilirliğine etkisi. *Tesis Mühen, 2018*(166), 34–48.
31. Tran, T. H., & Hoang, N. D. (2016). Predicting colonization growth of algae on mortar surface with artificial neural network. *J Comput Civ Eng, 30*(6), 4016030. [CrossRef]
32. Mata, T. M., Martins, A. A., & Caetano, N. S. (2010). Microalgae for biodiesel production and other applications: A review. *Renew Sustain. Energy Rev, 14*(1), 217–232. [CrossRef]
33. Parmar, A., Singh, N. K., Pandey, A., Gnansounou, E., & Madamwar, D. (2011). Cyanobacteria and microalgae: A positive prospect for biofuels. *Bioresour Technol, 102*(22), 10163–10172. [CrossRef]
34. Sarwer, A., Hamed, S. M., Osman, A. I., Jamil, F., Al-Muhtaseb, A. H., Alhajeri, N. S., & Rooney, D. W. (2022). Algal biomass valorization for biofuel production and carbon sequestration: A review. *Environ Chem Lett, 20*(5), 2797–2851. [CrossRef]
35. Buchheister, C. Bioenergy façade 2.0 presented at Glasstec. https://www.arup.com/news-and-events/bioenergy-facade-20-presented-at-glasstec
36. Loomans, T. (2013). *The world's first algae-powered building opens in Hamburg*. Inhabitat.
37. Walker, T. L., Purton, S., Becker, D. K., & Collet, C. (2005). Microalgae as bioreactors. *Plant Cell Rep, 24*(11), 629–641. [CrossRef]
38. Rai, M. P., Nigam, S., & Sharma, R. (2013). Response of growth and fatty acid compositions of Chlorella pyrenoidosa under mixotrophic cultivation with acetate and glycerol for bioenergy application. *Biomass Bioenergy, 58*, 251–257. [CrossRef]
39. Milano, J., Ong, H. C., Masjuki, H. H., Chong, W. T., Lam M. K., Loh, P. K., & Vellayan, V. (2016). Microalgae biofuels as an alternative to fossil fuel for power generation. *Renew Sustain Energy Rev, 58*, 180–197. [CrossRef]
40. Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renew Sustain Energy Rev, 14*(2), 557–577. [CrossRef]
41. Farronan, B., Carrasco, R., Flores, J. W. V., Olivera, C. C., Lopez, J., & Alfaro, E. G. B. (2021). Microalgae scenedesmus sp as a clean technology in reducing greenhouse gas carbon dioxide. *Chem Eng Trans, 86*, 445–450.
42. Sarkar, A, "Algae-Based Carbon Capture System: Modelling Photosynthesis for Carbon Dioxide Reduction," Algae, 2020.
43. Tran, N. A. T., Seymour, J. R., Siboni, N., Evenhuis, C. R., & Tamburic, B. (2017). Photosynthetic carbon uptake induces autoflocculation of the marine microalga Nannochloropsis oculata. *Algal Res, 26*, 302–311. [CrossRef]
44. AlgaeBase. (2024). *Listing the world's algae*. http://algaebase.org/
45. UTEX. (2024). *UTEX culture collection of Algae at UT-Austin*. https://utex.org/
46. Nordic Microalgae. (2024). *Nannochloropsis granulata Karlson & Potter, 1996*. https://nordicmicroalgae.org/taxon/nannochloropsis-granulata/
47. Nowicka-Krawczyk, P., Komar, M., & Gutarowska, B. (2022). Towards understanding the link between the deterioration of building materials and the nature of aerophytic green algae. *Sci Total Environ, 802*, 149856. [CrossRef]
48. Chisti, Y. (2006). Microalgae as sustainable cell

factories. *Environ Eng Manag J, 5*(3), 261–274. [CrossRef]

49. Schenk, P. M., Thomas-Hall, S. R., Stephens, E., Marx, U. C., Mussgnung, J. H., Posten, Kruse, O., & Hankamer, B. (2008). Second generation biofuels: High-efficiency microalgae for biodiesel production. *BioEnergy Res, 1*(1), 20–43. [CrossRef]
50. Rezvani, F., & Rostami, K. (2023). Photobioreactors for utility-scale applications: Effect of gas–liquid mass transfer coefficient and other critical parameters. *Environ Sci Pollut Res, 30*(31), 76263–76282. [CrossRef]
51. Zittelli, G. C., Rodolfi, L., Bassi, N., Biondi, N., & Tredici, M. R. (2013). Photobioreactors for microalgal biofuel production. In Algae for biofuels and energy (pp. 115–131). *Springer*. [CrossRef]
52. Ferris, D. (2013). *Algae Haus*. https://www.sierraclub.org/sierra/2013-6-november-december/innovate/algae-haus.
53. Poerbo, H. W., Martokusumo, W., Koerniawan, M. D., Ardiani, N. A., & Krisanti, S. (2018). Algae facade as green building method: Application of algae as a method to meet the green building regulation. *IOP Conf Ser Earth Environ Sci, 99*(1), 012012. [CrossRef]
54. Kendrick, M. (2011). *Algal bioreactors for nutrient removal and biomass production during the tertiary treatment of domestic sewage* [Doctoral Thesis, Loughborough University].
55. Kunjapur, A. M., & Eldridge, R. B. (2010). Photobioreactor design for commercial biofuel production from microalgae. *Ind Eng Chem Res, 49*(8), 3516–3526. [CrossRef]
56. Peter, A. P., et al. (2022). Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: Current status and future challenges. *Renew Sustain Energy Rev, 154*, 111852. [CrossRef]
57. Singh, R. N., & Sharma, S. (2012). Development of suitable photobioreactor for algae production–A review. *Renew Sustain Energy Rev, 16*(4), 2347–2353. [CrossRef]
58. Dincer, I. (2000). Renewable energy and sustainable development: A crucial review. *Renew Sustain Energy Rev, 4*(2), 157–175. [CrossRef]
59. Kumar, K., Dasgupta, C. N., Nayak, B., Lindblad, P., & Das, D. (2011). Development of suitable photobioreactors for CO2 sequestration addressing global warming using green algae and cyanobacteria. *Bioresour Technol, 102*(8), 4945–4953. [CrossRef]
60. Huseien, G. F., & Shah, K. W. (2021). Potential applications of 5g network technology for climate change control: A scoping review of Singapore. *Sustainability (Switzerland), 13*(17), 9720. [CrossRef]
61. Ahmad, A., Banat, F., Alsafar, H., & Hasan, S. W. (2022). Algae biotechnology for industrial wastewater treatment, bioenergy production, and high-value bioproducts. *Sci Total Environ, 806*, 150585. [CrossRef]
62. Gondi, R., Kavitha, S., Kannah Y. R., Karthikeyan, O. P., Kumar, G., Tyagi, K. V., Banu, J. R. (2022). Algal-based system for removal of emerging pollutants from wastewater: A review. *Bioresour Technol, 344*, 126245. [CrossRef]
63. Abdel-Raouf, N., Al-Homaidan, A. A., & Ibraheem, I. (2012). Microalgae and wastewater treatment. *Saudi J Biol Sci, 19*(3), 257–275. [CrossRef]
64. Wilkinson, S. J., & Stoller, P. (2018). Algae building technology energy efficient retrofit potential in Sydney housing. Proceedings of the 10th International Conference in Sustainability on Energy and Buildings. In Kaparaju, P., Howlett, R., Littlewood, J., Ekanyake, C., Vlacic, L. (eds) *Sustainability in Energy and Buildings*. Springer. [CrossRef]
65. Yulistyorini, A. (2017). A mini review on the integration of resource recovery from wastewater into sustainability of the green building through phycoremediation. *AIP Conf Proc, 1887*(1), 020048 [CrossRef]
66. Ahmad, I., Abdullah, N., Koji, I., Mohamad, S. E., Al-Dailami, A., Yuzir, A. (2022). Role of algae in built environment and green cities: A holistic approach towards sustainability. *Int J Built Environ Sustain, 9*(2–3), 69–80. [CrossRef]
67. Chan, A. P. C., Darko, A., & Ameyaw, E. E. (2017). Strategies for promoting green building technologies adoption in the construction industry-An international study. *Sustainability (Switzerland), 9*(6), 969. [CrossRef]
68. Talebi, A. F., Tabatabaei, M., Aghbashlo, M., Movahed, S., Hajjari, M., Golabchi, M. (2020). Algae-powered buildings: A strategy to mitigate climate change and move toward circular economy. In S. Patnaik, S. Sen, M. S. Mahmoud. (Eds.). *Smart village technology* (pp. 353–365). Springer. [CrossRef]
69. Khan, S. A., Sharma, G. K., Malla, F. A., Kumar, A., Rashmi, Gupta, N. (2019). Microalgae based biofertilizers: A biorefinery approach to phycoremediate wastewater and harvest biodiesel and manure. *J Cleaner Prod, 211*, 1412–1419. [CrossRef]
70. Ammar, E. E., Aioub, A. A. A., Elesawy, A. E., Karkour, A. M., Mouhamed, M. S., Amer, A. A., El-Shershaby, N. A. (2022). Algae as bio-fertilizers: Between current situation and future prospective. *Saudi J Biol Sci, 29*(5), 3083–3096. [CrossRef]
71. Adeniyi, O. M., Azimov, U., & Burluka, A. (2018). Algae biofuel: Current status and future applica-

tions. Renew. *Sustain Energy Rev, 90*, 316–335. [CrossRef]

72. Topuz, O. K. (2016). Algal oil: A novel source of omega-3 fatty acids for human nutrition. *Sci Bull Ser F Biotechnol, 20*, 178–183.
73. Çelekli, A., Özbal, B., & Bozkurt, H. (2024). Challenges in functional food products with the incorporation of some microalgae. *Foods, 13*(5), 725. [CrossRef]
74. Zhang, S., Qamar, S. A., Junaid, M., Munir, B., Badar, Q., & Bilal, M. (2022). Algal polysaccharides-based nanoparticles for targeted drug delivery applications. *Starch-Stärke, 74*(7–8), 2200014. [CrossRef]