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Review

Algae-Powered Buildings: A Review of an Innovative, Sustainable Approach in the Built Environment

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Abstract: Environmental pollution, global warming, energy consumption, and limited natural resources are some key factors from which today's built environment faces interrelated problems and their management plays a vital role in sustainability. The building sector is involved in 35% of global energy usage and 40% of energy related CO_2 emissions. Application of bioactive elements on buildings' façades is a novel approach for solving the above-mentioned problems. Management of some important factors such as thermal comfort, energy efficiency, wastewater treatment, and CO_2 capture is positively affected by bioactive façades because of their environmentally friendly nature. They also have positive effects on global warming, pollution control, social wealth, and sustainable development on a larger scale. The buildings integrated with photobioreactors (PBRs) can meet their thermal needs due to thermal insulation, shading, solar collection, and light-to-biomass conversion. Energy savings up to 30% are estimated to be met by PBR-integrated buildings due to reduced heating, cooling, ventilation, and lighting loads. The above amount of energy saving results in less CO_2 emission. Moreover, the algae-integrated buildings can sequester CO_2 with an average sequestration rate of 5 $g/ft^2/day$ when optimum growing environments and operation modes are implemented. This study is an overview of microalgae intervention and PBR-adapted buildings as an innovative approach for energy efficiency in the built environment with regard to implemented or speculative cases, pros and cons, challenges, and prospects.

Keywords: bioactive-façade; algae-powered buildings; energy efficiency; green walls; carbon neutral

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1. Introduction

The energy crisis, beginning in 1970s, and climate change due to the emission of greenhouse gases (GHGs) have directed attention to renewable energy sources and their related supporting policies [1,2]. The construction sector is among the major GHG producers either during the construction process or during the energy use of buildings, especially through air conditioning and ventilation. Energy consumption in the built industry has increased in recent decades due to population growth, urbanization, and industrialization, resulting in increased demand for energy derived from fossil fuels [3–5]. Apart from being energy intensive, this sector has drastically produced large amounts of GHGs due to burning non-renewable resources along with waste landfilling [6]. Approximately, more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions are attributed to the construction sector. It is expected that GHG emissions from buildings will be doubled over the next 20 years; thus, designing more energy efficient buildings is important to achieving a low carbon future [7–10]. Energy efficient buildings are "buildings that need less energy with the precautions taken during the design phase, meet the energy they need from renewable sources and make minimum emission by using the energy in the most efficient way" [11,12]. Of the required stock for 2050, 87% is expected to have already been built; therefore, concentrating on retrofitting can have a more significant effect than new construction [13,14].

Green building standards and rating systems for buildings, such as the American LEED [15,16] and the British BREEAM [17], provide practical tools for designers with the aim of achieving high quality architectural solutions on one hand, and making it easy for consumers to identify product quality and encouraging the demand for green buildings on the other hand [18]. Elements such as solar panels and small wind turbines are incorporated in the next generation of buildings to generate local clean energy; however, they are not able to supply 100% of the energy demand, and additional renewable technologies are required to back up and supplement these systems [8,19]. The conversion of algal biomass produced on buildings' façades into bioenergy is a new approach to supplying the energy required for a building's need. Different forms of energy such as electricity, heat, and biofuels are produced by conversion of biomass as a promising eco-friendly alternative source of renewable energy. In 2014, it was claimed that bioenergy is no longer in transition due to 88 GW worldwide energy production using biomass [20–22]. The "symbiosis" between a building and a microalgae photobioreactor (PBR) has the potential to reduce the consumption of fossil fuels by the building and consequently to reduce the carbon footprint. This symbiosis is mutually beneficial for algae growth and building performance: on the one hand, the high capital and operating costs of PBRs are reduced by integrating buildings with PBRs; on the other hand, the thermal function of the building will also be improved, reducing thermal loads and the energy and heating requirements of the building through the conversion of algal biomass to biogas for use in the infrastructure, supplying hot water and partially gaining electricity [11,23,24]. Aggravated urban warming and the constant increase of energy use lead us to the intelligent utilization of energy and improvements to its efficiency. Investigating data on temperature effect shows that the energy consumption due to air-conditioning can be reduced up to 30–60% as a result of insulation related to the stagnant air layer created by green walls [25–27]. Alongside the energy saving resulting from increased thermal efficiency, it is claimed that PBR-integrated buildings purify polluted air and wastewater, and consequently provide improved air quality [11,28,29]. The PBR's function includes dynamic shading, thermal insulation, solar thermal collector, and biomass production. A balance between climates, building space, window-to-wall ratio (WWR), aesthetics of microalgae growth, energy savings, and occupants' satisfaction should be considered in the design and placement of microalgae enclosures. According to the expansion of renewable energy use, these buildings are both more energy efficient and sustainable and can offer environmental, economic, and commercial opportunities [23,24].

In this review, we explore the algae building technology (ABT) as an innovative approach to energy efficiency in the built environment, refer to conceptual designs and real-world examples of a microalgae system in the area of architecture interventions, and discuss the advantages and disadvantages of buildings retrofitted with this technology.

2. Microalgae and Their Intervening Role in Buildings' Design

Microalgae are photosynthetic microorganisms which convert water and CO_2 into organic compounds and oxygen using light energy. As the oldest resident of our planet, they have an important role in building our atmosphere. Due to their fast growth rate and high content of nutritional and bioactive compounds, they can be cultivated for various applications in bioenergy, cosmetics, pharmaceutical, agricultural, and food industries. Various factors including cultivation systems, the type of algal species, environmental conditions, and algae–bacteria interaction can affect the biomass productivity of microalgae and the biochemical composition. The algae theoretical efficiency of solar energy conversion to biomass is 9%, which is at least three times higher than the amount related to C_4 plants. Microalgae are known as carbon mitigators due to their high capacity of CO_2 sequestration by uptaking 1.8 kg of CO_2 per 1 kg of biomass. The decarbonization and oxygenation (more than 75% of the oxygen needed is produced by microalgae) through photosynthesis could be a cost-effective and sustainable way to address global environmental issues [30–33].

Microalgae have a promising role in the bioremediation of anthropogenic pollutions to air, soil, and water. Their environmental benefits consist of atmospheric decarbonation through photosynthetic carbon capture, wastewater treatment through taking nutrients and organic wastes from the wastewater, and soil decontamination through biosorption and bioaccumulation of heavy metals. On the other hand, the use of agricultural land with a limited area capacity and a limited capacity of fuel obtained from agricultural products which form the basis of fuel products, makes algae more productive among other types of biomasses [34–36].

There are different systems for microalgae cultivation, including an open cultivation system, a closed cultivation system, or a hybrid of both. Open cultivation systems including different configurations of open ponds have the advantages of low initial and operational cost and low operational energy, but they need larger ground areas for light availability and are more susceptible to contamination, water evaporation, and unfavorable weather conditions. On the other hand, the closed cultivation systems, including different configurations of PBRs, have overcome these limitations by minimizing the required space and better controlling the growing conditions. However, they incur more costs and energy consumption for installation, operation, and maintenance. It is reported that PBRs yield 13 times more productivity compared with open raceways. The feasibility study of a microalgae-integrated system is vital for understanding the key cultivation technologies and environmental growth parameters such as nutrients, pH, temperature, light intensity, salinity, and carbon concentration, and also production conditions such as aeration, mixing, dilution rate, and harvesting frequency [37–39].

Recently microalgae-integrated buildings have been considered by architects and designers. The multifunctionality of microalgae, such as phycoremediation and the production of biomass as feedstock, offers advantages for integrating microalgae system into urban green buildings [40,41]. Microalgae can grow in different aquatic habitats and tolerate a wide range of environmental conditions. They become a part of building materials or service systems in a microalgae-integrated building. Due to their rapid growth (a key factor of their superiority), microalgae can reach high densities and cover the façade in a short time. They also can be cultivated all year round [25]. By remediating wastewater coupled with capturing CO_2, generating O_2, and producing renewable energy potentials, they benefit the building and the occupants. They also reduce the building energy consumption due to providing effective shading in summer, solar heating in winter, and year-round daylighting penetration. These multi-functionalities and multiple benefits have caused various approaches to be introduced by architects, designers, and engineers for integrating algal systems in different scales of the built environment [42]. Evaluating different types of building envelope technologies in terms of two factors, namely, energy efficiency and compliance with the building, shows that algae bioreactor façades are in the first place in terms of energy efficiency. Biological energy generated in this system results in the reduction of environmental pollution as well as high efficiency. On the other hand, in terms of compatibility with architecture, the highest score goes to the algae bioreactor façade, showing that the algae bioreactor façade, among building-interactive technologies, should be considered a promising example [43].

3. Façade-Integrated Algae

The building-integrated microalgae cultivation system is an innovative technology for high-performance adaptive architecture that offers multiple benefits, including sequestration of CO_2 and production of O_2 to reduce the air pollution, conversion of solar radiation into heat and biomass, providing shading through changes in algal density, and creating sound insulation. It can also make a dynamic exterior vision due to the color changes of the algal culture [44]. Algae façade-integrated buildings as living designs are the result of applying biomimicry in architecture design and planning; they their required energy and water from their location and are adapted to their environment and climate. They also do not pollute the environment. The responsiveness of the building's skin to natural factors including wind, rain, and sunlight, and vital functions including breathing, carbon capture, and water consumptions, should be considered in the biodesign of such buildings [45,46]. In algae façade-integrated buildings, the lifesaving sources of CO_2 and nutrients for microalgae growth are obtained from occupants and building operations. A simulation study of PBR façade-integrated building showed a 13% reduction in CO_2 level compared to a standard building with 200 occupants [27,47]. The high concentration of CO_2 produced by occupants' respiration and nutrients from domestic wastewater increases the biomass productivity. This symbiotic relation causes CO_2 fixation, wastewater treatment, and biomass production for various uses [42].

The microalgae façade is a patent-pending system under development by XTU Architects for many years. There are some conceptual designs or built examples of a microalgae system in the area of architecture interventions. Table 1 summarizes some of these microalgae application in architecture interventions. Green Loop Tower (2011) is a project of retrofitting old building enclosures with green technologies. It is a proposed building intervention of the Marina City Tower where the parking deck and roof top are enclosed with microalgae systems for the purpose of CO_2 reduction, wastewater treatment, bioenergy production, and net zero energy building (ZEB) [42,48]. Process Zero (2011) is a proposed office retrofitting, speculated for the General Services Administration in Los Angeles, where the building is enclosed with microalgae reactors with different densities depending on open view provision and solar availability [42,49]. Algae BRA (2011) is another concept proposal, speculated for a fashion company housing offices and commercial spaces. It is a proposed office building installed with external and internal tubular PBRs, presenting thermal regulation, passive cooling, decarbonation, biomass production, and flexible spatial organization [42,50]. The FSMA Tower (2011) is a project researching the integration of biological systems and skyscrapers. It is a speculative skyscraper enclosed with PBRs dispersed across the vertical surface, supporting social interaction and environmental benefits [42,51]. Algae Therapeia (2011) is a proposed research complex near the coastline, enclosed with PBRs as an external environmental skin to filter light, heat, sound, and air. It is a dome-shaped building, focusing on seawater and algae for medical, nutritional, and industrial usages [42,52]. UrbanLab (2012) is a speculative R&D office building enclosed with plastic PBRs with the aim of developing the microalgae technology for biofuel production along with wastewater treatment. The project will be implemented with the participation of Ennesys, a French-based startup, and Origin Oil, a company dedicated to transforming algae into biofuels in La Defense, France. Using approximately 10,000 m^2 of bioreactor panels, it is expected that the building will be capable of reducing water usage by 80% along with an energy saving of 80% [42]. BIQ (Bio-Intelligent Quotien) house (2013) is a real-world application of flat PBRs installed on a residential building with the purpose of energy saving, carbon sequestration, and biomass production. The building is enclosed by microalgae glass panels on two sides. The solar energy stored in the panel and the grown algal biomass supply the renewable energy required for building operation. The installation sequesters approximately 16 kg of CO_2 per day with a biomass production equivalent to 30 kWh/m^2year and heat production of 150 kWh/m^2year [13,42,53]. The CSTB Prototype (2014) is a technology demonstration project including bioreactor curtain walls installed on an office building in France and focusing on carbon sequestration and air quality improvement. This project is the first real-world application since microalgae façade experiments in 2009 experimenting with different configurations and density effects in daylight penetration [42,54]. In Vivo (2016) is another project with the purpose of attracting social attention and openness toward a sustainable city. It consists of three buildings; each has a unique façade integrated with different biological systems and functions. One grows microalgae for medical research with potential solar energy revival for heat supply and domestic hot water. In Vivo is a design competition-winning project and should increase the visual appeal of a building for advertising its environmental, economic, and social benefits, leading to increased acceptance for general use [42,55]. French Dream Tower (2018) is a speculative mixed-use project, combating glass towers' environmental problems related to quick energy transmission and high energy consumption. It consists of towers enclosed with flat bioreactors for regulating solar energy and thermal insulation, collecting rainwater, and filtering outdoor air [42,56]. Algae Tower (2021) is an office tower in Melbourne, Australia, whose façade elements can be adjusted to the optimal sun angle to maximize shading and biomass production [45,57]. Microalgae Ivy (2021) is a patent-pending project for low-performing windows retrofitting. Its full-scale prototype was installed at the School of Architecture at the University of North Carolina (UNC), Charlotte. It consists of a network of interlocking bioreactors, providing the possibility of cultivating different strains for different uses and aesthetics. The prototype demonstration filled with five strains (*Chlorella*, *Chlorococcum*, *Haematococcus*, *Scenedesmus*, and *Spirulina*) for energy efficiency, biofuel production, and indoor air quality enhancement was able to sequester CO_2 produced by three occupants and output 500 g of biomass per day [42].

Table 1. Conceptual designs of a microalgae system in the area of architecture interventions.

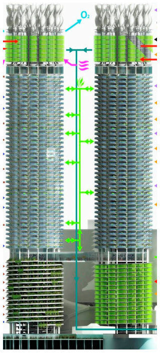
Project		Objective and Design Data	Ref.
Green Loop Tower, 2011 Location: Chicago, Illinois, USA Designer(s): Influx Studio		The concept of this building aims to showcase algae potential connection with new emerging green technologies, to create a whole new CO_2 scrubbing integrated system, contributing to clean polluted air, to create energy onsite, allow food and biofuel production, and ensure wastewater treatment. PBR type: Helical tube PBR Building type: Retrofitted building	[42,48,58]
Process Zero, 2011 Location: Los Angeles, California, USA Designer(s): Sean Williams		Process Zero is a renewable energy system that includes a thin photovoltaic façade system, rooftop photovoltaics, integrated solar thermal panels, and series of transparent tubular bioreactors growing microalgae. This collection of renewable energy systems offsets the energy consumption of the building and serves as an artificial tree, absorbing CO_2 for energy generation and releasing oxygen. PBR type: Modular tube panel PBR PBR façade area: 25,000 ft^2 Energy production: 14 kBTU/sf/year	[42,49,58]
Algae BRA, 2011 Location: Tehran, Iran Designer(s): Benetton Group		An innovative ecological project based on natural ecosystem processes and the traditional Iranian architecture which aims to conduct solar control and screening, passive ventilation, and ground cooling by using water as thermal storage and heat regulator, biomass production, and decarbonation. PBR type: Vertical tube PBR Building type: Retrofitted building	[42,50]

Table 1. *Cont.*

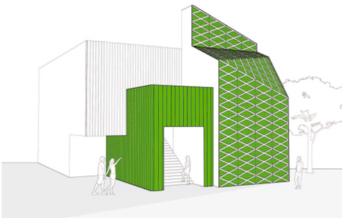
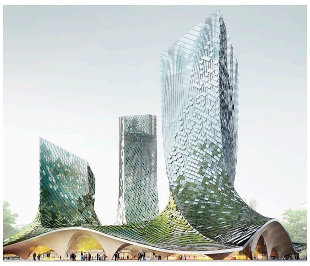
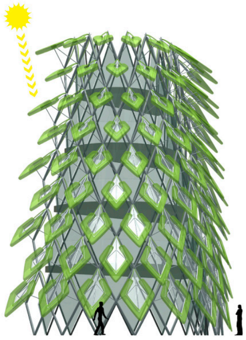
Project		Objective and Design Data	Ref.
FSMA Tower, 2011 Location: London, England Designer(s): Dave Edwards		Mixed-use tower enclosed with bioreactors used for CO_2 sequestration and improving air quality, with algae-absorbing CO_2 emissions which are also harvested as bio-methane to provide heat and power. PBR type: Flat panel PBR Building type: New building PBR façade area: 21,100–44,000 m^2 Absorbed CO_2: 250,000 ton/year Produced biodiesel: 450 ton/year	[51]
Algae Therapeia, 2011 Location: Donostia, Spain Designer(s): Aragonés Balboa, J.		The concept of this design aims to establish a research center of marine algae, typical of the Basque coast, for medicinal, food, and industrial applications. A PBR skin generates the necessary energy for all building operations. PBR type: Tubular PBR Building type: New building	[42,52]
Urbanlab, 2012 Location: Paris La Défense, France Designer(s): Axel Schonert		A speculative building proposal enclosed with microalgae PBR focusing on transforming algae into biofuels, coupled with wastewater treatment. PBR type: Flat panel PBR Building type: New building PBR façade area: 100,000 ft^2 Microalgae yield: 150 ton/year Produced biodiesel: 70 ton/year	[42]
In Vivo, 2016 Location: Paris, France Designer(s): XTU Architects		A speculative building integrating a microalgae-producing PBR bio-façade for medical research. The heat collected by the PBRs is used for domestic hot water and heating. PBR type: Flat panel PBR Building type: New building PBR area: 100,000 ft^2 (932 m^2)	[55,59]
French Dream Tower, 2018 Location: Hangzhou, China Designer(s): XTU Architects		The towers enclosed with PBRs for regulating solar energy and thermal insulation, acoustic insulation, and reducing the building's carbon footprint by absorbing CO_2 and releasing oxygen. PBR type: Flat panel PBR Building type: New building	[56,59]

Table 1. *Cont.*

	Project	Objective and Design Data	Ref.
Algae Tower, 2020 Location: Melbourne, Australia Designer(s): UOOU Studio		The façade system acts as a large-scale PBR transforming a classic façade shading system in an "artificial-leaves-canopy". The canopy protects the building from direct solar radiation, generates energy, and absorbs CO_2. PBR type: Artificial-leaves-canopy	[57]

By using the microalgae as the primary building envelope, the exterior view is ever-changing due to the microalgae grown according to the changes in natural light, air flow, and other environmental factors. For indoor applications, these systems can be effective in good interior microclimates. The microalgae system can also be part of the building service system such as HVAC (heating, ventilation, and air conditioning). It can be concluded that the presence of microalgae in our living and working environments can help occupants to be more productive and healthier and enhance their well-being. However, there are some challenges that make concepts difficult to put into practice, including technical requirements for creating bioenergy infrastructure, CO_2 provision, and high initial cost. There should be an onsite system to supply CO_2, light, water, and nutrients along with harvesting microalgae and extracting bioactive compounds. In addition, there is a requirement to equip the algae-powered building with its own biogas plant to generate its own electricity, which may be difficult to achieve, particularly on a residential scale. The integration of the biorefinery system should also be in agreement with buildings' legal regulations that, accordingly, may require new regulations for building-integrated PBRs. Providing CO_2 and integration of capturing, sequestering, and storing systems into buildings could also be a big challenge. Alongside the aforementioned problems, there are also some important factors that should be pointed out for expanding the design of PBRs on a building scale; these include lightweight and durable materials at reasonable prices, easy maintenance, and balanced cost and payoff [29,54].

4. Algae-Powered Buildings: Energy Efficiency and Environmental Performance

One of the building energy efficiency indicators is energy use intensity (EUI), which explains the level of building energy performance and is determined by dividing total annual energy use by building. Comparing different buildings across energy efficiency is conducted according to this index. A lower EUI indicates lower usage of energy or higher building efficiency. An average primary EUI is around 120 kBtu/ft^2/year and 200 kBtu/ft^2/year for residential and commercial stocks, respectively [42]. Space heating and cooling, lighting, water heating, and ventilation consume more than half of the building's energy usage. Major energy loss has been related to poor building envelope construction and inefficient HVAC systems. Other factors affecting energy consumption include the geometry of the building, energy characteristics of opaque walls and windows, WWR, and microclimate control such as shading, trees, and landscape. Indoor air quality is also affected by building enclosure and some other factors such as off-gassing interior materials, molds/bacteria due to leaks, or lack of ventilation. Energy management in general requires more efficient use of energy, water, and air quality protection, and wastes and pollution control. Energy interventions play an important role in reducing pollutant emissions and energy bills. The energy cost savings due to energy efficiency and on-site energy production can improve living affordability. Integrating climate-responsive design strategies with energy-efficient active systems and renewable energy generation typically increases upfront cost. However, it can lead to faster economic payoff with operational energy savings [42].

The Paris Agreement aims for GHG reduction in the world. Public acceptance to improve building energy efficiency is intensified by greater awareness of climate emergency and economic returns. However, to deal with the climate crisis, both mandatory and voluntary implementations are required. New York City obligates carbon neutrality by 2050 and demands improvement of buildings energy efficiency up to 23% above 2012 levels by 2030. It is targeted to reach 40% GHG reduction by 2025 and 50% by 2030 [42]. At the voluntary level, over 65,000 Passive House (PH) (a voluntary standard for energy efficiency in a building which reduces the building's ecological footprint) buildings are certified around the world, starting in Germany in 1990s. The performance requirements are 15 kWh/m^2 of each heating and cooling demand focus with maximum 60 kWh/m^2/year of renewable primary energy demand (heating, hot water, and domestic electricity use) [42,60,61]. To meet the energy requirements, there are strategies such as high insulative building enclosures, energy-efficient windows, thermal breaks, and air tightness, which are related to high-performance building enclosures, and ventilation heat recovery, which is related to energy-efficient HVAC systems.

Buildings supplying their required energy (heat and electricity) from microalgae (Figure 1) can serve as an alternative building system. The mechanism of the process is as follows: first, water containing nutrients is being filled in the façade PBRs, where daylight and CO_2 are converted to algal biomass through photosynthesis; secondly, the biomass and heat generated by the façade element are transferred through a closed loop system to the plant room, where both forms of energy are exchanged by a separator and a heat exchanger, respectively. For the supply of hot water and heating the building, a hot water pump is used to adjust the temperature levels of the generated heat [62,63].

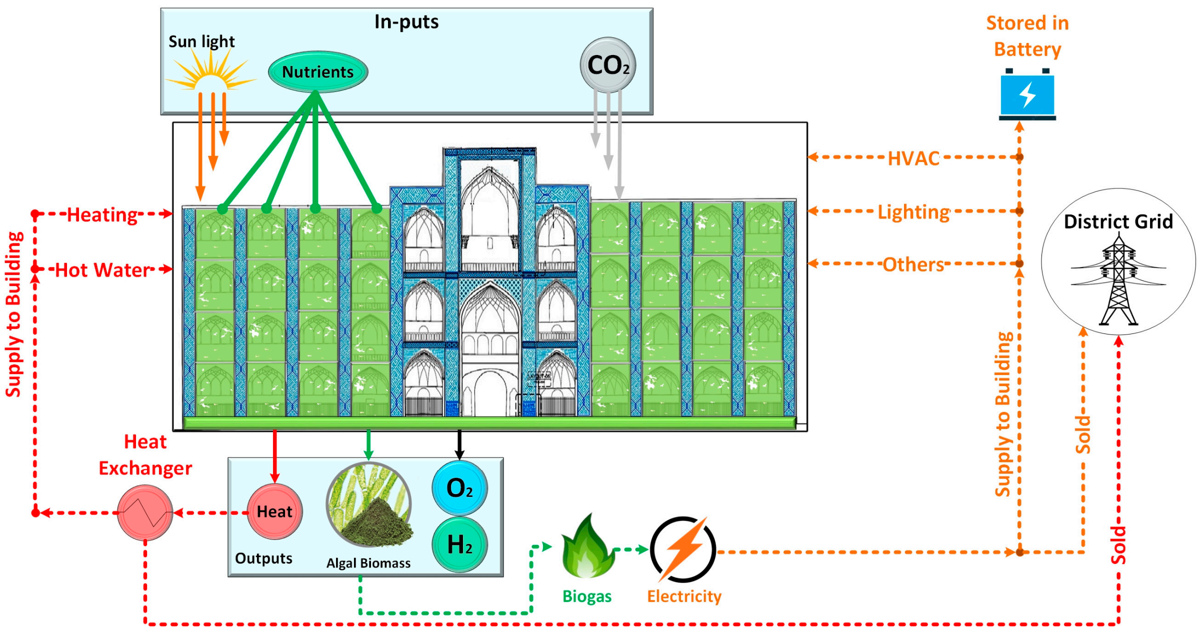


Figure 1. Schematic of algae-powered buildings.

Microalgae enclosures buildings not only generate clean energy but also play a role in GHG mitigation and can be considered as a carbon-neutral power source of energy. Alongside the positive environmental effects, they also have financial profitability due to the reduction of energy and operating costs and taxes which consequently cause lower life cycle costs and increased rental costs without decreasing occupancy [45,64]. These systems are also of interest in the field of net zero energy because of their effectiveness in improving building energy efficiency, renewable power generation, and good air quality.

Resulting in better temperature control, PBR façade-integrated buildings can reduce energy consumption by more than 33% in terms of fuel consumption and 10% in terms of electricity consumption [25,29,54]. There is a micro-community integrated with microalgae systems which restores wastes from buildings and converts them into operational valuable resources; they can achieve off-grid power and water independency along with polluted air decarbonation and wastewater treatment [42,65,66]. In 2013, an algae-powered building was implemented in Hamburg, Germany. Since then, there have not been any implemented real-world applications other than small-scale experiments for testing feasibility [42].

Energy savings and occupant satisfaction in algae-powered buildings is enhanced by geometric configuration along with the cell concentration and color changes of microalgae due to environmental effects. Efficient photosynthetic performance of microalgae enclosures lead to building energy savings by reducing heating, cooling, and artificial light demand, along with CO_2 reduction and indoor air quality improvement. The One World Trade Center in New York City, a 94-story skyscraper enclosed with microalgae windows, was investigated as a study building for estimating the energy savings. The computer simulation indicated that the building would reduce energy usage (heating, cooling, lighting, and ventilation load) by an average 20% annually and save over USD 1 million a year in electricity costs with a seven-year return on investment (ROI) [42,67]. The simulation results for estimating annual EUI of commercial and microalgae buildings in different climate zones shows an average 20% energy saving that can be achieved from microalgae window buildings by reducing heating, cooling, ventilation, and lighting loads. This energy savings also results in an average reduction of 6000 tons CO_2. Alongside the carbon reduction due to energy savings, the study buildings can sequester over 7000 tons of CO_2 annually using a CO_2 sequestration rate of 5 g/ft^2 [42].

There are different parameters including panel size, orientation, and type of microalgae which affect the thermal performance of the PBR façades. Some studies concentrated on the *U*-value of the flat PBRs show that the air layer thickness has the greatest effect on providing effective insulation. The thickness of PBR material and PBR depth are also effective, respectively [11,36,68]. Other studies show that the *U*-value is affected by the growing algal medium inside the PBR due to the lower heat transmittance of the algae zone compared with the vision zone. Thus, algae culture density is another important parameter on thermal insulation [69]. The density of algae is also effective in shading, and the more concentrated culture within the PBR has more prevention against solar and light penetration into the building. In addition, there are other factors such as climatic conditions, orientation, and geography which affects the shading. Comparing three different façade systems as shading elements, Martukusumo et al. showed that PBRs on the west façade had an effective role in protection from excessive solar radiation [70]. As façade, PBRs act as solar collectors, and the heat generated in PBRs is also affected by the above-mentioned factors. The evaluations conducted by Negev et al. showed that as well as the thickness of the unit and the algal concentration, type of algae is also a significant factor [8]. They observed that *Chlorella vulgaris* has less light and heat transmission compared to *Chlamydomonas reinnhardtii*. The produced algal biomass should be stored and then used for heat and energy generation. The biomass productivity is affected by different factors including climatic conditions of the building location, PBR material, PBR size and orientation, the intensity of solar radiation, and the algae type. Studies show that the biomass productivity in PBRs with 45° inclination changes through the year, while it is constant in vertical PBRs [24]. A 28.7% increase in productivity was also observed by using *C. vulgaris* at an inclination of 75° compared to *Dunaliella tertiolecta* at 90°. Optimization of the mentioned factors would increase the energy efficiency of PBR-integrated buildings. Table 2 summarizes the parameters affecting the energy efficiency of the façade integrated PBRs from different aspects and Table 3 summarizes the value of influential parameters affecting the performance of PBR façades according to different studies.

Table 2. Effective parameters for increasing energy efficiency in PBR-integrated buildings.

Influencing Factor	Influential Factors
Thermal insulation	PBR material PBR size Building WWR Algae type Culture medium density
Shading	PBR size Orientation Surface to volume ratio Culture medium density
Biomass production	Regional climatic conditions Algae type Surface to volume ratio Inclination degree Orientation Material thickness Building aspect ratio

For adopting algae façades by building sector, environmental, technical, political, economic, and the social performance of practically implemented algae-integrated buildings should be evaluated in decision-making process. In a common set of buildings, the performance assessment seems difficult before the systems are operated [66,71]. Therefore, for implementing algae façades in buildings, the requirements should be defined and investigated. In a construction project, sustainable design considerations should be conducted as early as possible to make the process time- and cost-efficient [72]. System dynamics (SD) support integrated decision-making and its models are applied for considering repetition and feedback processes. Therefore, SD models can support the decision of applying algae façade systems in the building design and also the multiple subsystems and food–energy–water (FEW) feedback processes [73]. In a study conducted by Chang et al., a framework based on building information modeling (BIM) is presented which helps define the critical factors when applying algae façades in buildings, analyzes energy and waste streams through an SD model, and evaluates the performance considering different building contexts [66]. This framework can be applied to determine feasibility when the algae façade is integrated in a building by running the BIM-integrated SD model simulation.

Table 3. Influential factors affecting the performance of PBR façades.

Recommended PBR Design Parameters						
PBRs Type		**Vertical Bubble Column**	**Vertical Airlift PBR**	**Flat Panels**	**Tubular PBR**	**Ref.**
Material		Glass, Low Density Polyethylene (LDPE), PVC, PMMA (poly methyl methacrylate)	Glass, LDPE, PVC, PMMA	Glass, Plexiglas, Polycarbonate, PVC, PMMA, Polyethylene, Plastic bags	Polypropylene acrylic, Polyvinylchloride, PVC, PMMA, LDPE	[74–77]
PBR dimensions	Thickness/Diameter(D)	D < 20 cm	D < 20 cm	D < 7 cm	5–9 cm	[42,76,78]
	Height/length (H)	H < 4 m	H < 4 m	1.5 m	100–150 m	[42,76,78,79]
	Width	-	-	10 cm	-	[78]
Surface to volume ratio (S/V)		2–8 m^{-1}	2–8 m^{-1}	20–80 m^{-1}	up to 100 m^{-1}	[38,77,79,80]
Type of Mixing		Via gassing (Bubbling of CO_2-enriched air)	Via gassing	Circulation flow, Peristaltic pumps and Via gassing	Circulation flow, Peristaltic pumps	[38,74,77,78]
Oxygen mass transfer coefficient		High	High	Low	Low	[38]
Risk of photo-inhibition		Low	Low	Medium	High	[38]

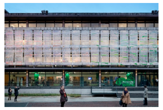
Table 3. *Cont.*

Recommended PBR Design Parameters					
PBRs Type	**Vertical Bubble Column**	**Vertical Airlift PBR**	**Flat Panels**	**Tubular PBR**	**Ref.**
Risk of self-shading of cells	Medium–High	Medium–High	Low (at thin panel thickness)	Low (at thin tube diameter)	[38]
Risk of bio-fouling	Low	Low	High	High	[38]
Investment costs	Low	Medium	Medium–High	Medium–High	[38]
Space occupation	Low	Low	Medium	Medium	[38]
O_2 -release	Easy	Easy	Difficult	Very difficult	[38]
Scalability	Difficult	Difficult	Very easy	Very easy	[38]
Advantages	Compact, good mixing with low shear stress, low energy consumption, easy to sterilize, good for immobilization of algae, reduced photo-inhibition and photo-oxidation		Suitable for outdoor cultures, good light path, high biomass productivities, easy to clean up, low power consumption and shear stress, easy temperature control, low operating cost	Suitable for outdoor cultures, good biomass productivities, improvement of air residence time	[74,81]
Limitations	Construction requires sophisticated materials, stress to algal cultures, decrease of illumination surface area upon scale-up, high cleaning cost		Scale-up requires many compartments, difficulty in controlling culture temperature, some degree of wall growth, possibility of hydrodynamic stress to some algal strains	Gradients of pH, dissolved CO_2 and O_2 gradients, fouling, some degree of wall growth, photo limitation, high capital, and operating costs	[74,81]
Recommended Operational and Environmental Parameters					
	Chlorella	7.5–8			[42,82,83]
	Spirulina	9			[42,84]
	Chlorococcum	8.0–8.5			[42,81,84]
	Haematococcus	7			[42]
Nutrients	Macro nutrients:	Phosphorus and Nitrogen			[82]
	Trace metals:	Fe, Mg, B, Mo, K, Co, Zn, Mb			
Temperature		20–30 °C			[42,81,82]
Light intensity		5000–10,000 Lux (100–200 µmol/(m^2 × s))			[42,82]
Liquid velocity		20–50 cm×s^{-1}			[42,81]
Partial pressure of CO_2 in gas phase		0.2 kPa (0.076 mol × m^{-3})			[80,81]
Aeration (bubble size)		1–7 mm			[42]

5. Real-World Examples of ABT

There are a few real-world applications of algae buildings, summarized in Table 4. The world's first PBR façade project is the BIQ building, which is a part of the International Building Exhibition in Hamburg. BIQ consists of a penthouse plus 15 apartments located on four floors. The integrated PBR system are installed on the southwest and southeast faces of the building, consists of 129 flat panel glass bioreactors with dimensions of 2.5 × 0.7 × 0.08 m, with capacity of 150 kWh/m^2 and 30 kWh/m^{2}of thermal energy and bioenergy production, respectively. The transformation efficiencies of the thermal energy and bioenergy are determined to be 38% (compared with a typical solar thermal source which is 60–65%) and 10% (compared with a conventional photovoltaic (PV) system which is 12–15%), respectively. The produced biomass is harvested in an energy management center where the generated heat is recovered by a heat exchanger to be reintroduced to the system or stored in an underground aquifer. Methane is generated by conversion of approximately 80% of the harvested biomass in an outdoor plant, and is returned to the building for heat and electricity generation [11,13,85,86]. According to Arup, the implemented system on the Hamburg building has high efficiency for growing the algal culture and requires minimal maintenance [45,53,59,87,88]. Currently, the overall energy needs of the building are reduced by 50%, and 100% is expected to be achieved if solar panels are used to power the pumps and heat exchangers [62].

Table 4. Real-world examples of ABT.

Project		Location	Year	Designer(s)	Objective	Data	Ref.
	BIQ Building	Hamburg, Germany	2013	Splitterwerk Architects	The first and most well-known actual enclosed PBR building that uses algal biomass to produce heat and energy, control light and provide shade, sequestrate carbon, and improve building energy savings.	PBR Type: Flat panel (24-L capacity) Number of PBR modules: 129 (2.5 × 0.7 m) PBR façade area: 2500 ft^2 Sequestered CO_2: 16 kg/day Biomass production: 30 $kWh/m^2/year$ Heat production: 150 $kWh/m^2/year$ Cost of PBR's installation: USD 2300 to USD 3200	[45,53,59,88]
	CSTB prototype	Champs-sur-Marne, France	2014	XTU Architects	Microalgae curtain wall system that is integrated with PBRs with the aim of growing biomass, protecting the apartments from both sun and noise, carbon sequestration, and air quality improvement.	PBR type: Flat panel PBR PBR façade area: 200 m^2	[54]
	SYMBIO2	Nantes, France	2014	XTU Architects	The project aims to demonstrate the economic and technical feasibility of simultaneous microalgae production and flue gas partial treatment in a waste processing plant.	PBR type: Flat panel PBR PBR façade area: 300 m^2 Biomass production: 0.7–1 ton/year Sequestered CO_2: 1–1.8 ton/year	[36,89]
	PhotoSynthetica	Dublin, Ireland	2018	ecoLogicStudio	The curtains capture CO_2 from the atmosphere, store is via algae and transform into reusable biomass.	PBR type: Curtain module Sequestered CO_2: 1 kg/day Number of PBR modules: 16 (2 × 7 m)	[90,91]
	AirBubble	Warsaw, Poland	2018	ecoLogicStudio	The world's first biotechnological playground integrated with air-purifying microalgae. The white bubbling noise of the algae gardening system masks the surrounding urban noise to provide a calming atmosphere in which to play and interact.	PBR type: Glass algae reactors Number of PBR modules: 52 Total volume of microalgae: 520 L Flow of polluted air: 200 L/min	[92]
	Microalgae Ivy	Charlotte, NC, USA	2021	EcoClosure + UNC Charlotte	A full-scale prototype to retrofit low-performing window for biomass production and CO_2 reduction.	Full-scale prototype dimension: (8 × 12 feet) Biomass production: 200 kg/year	[42]

The first curtain wall PBR prototypes were constructed by a French consortium in the University of Nantes, which shares the PBR expenses via an efficient building integration through a symbiosis of thermal energy, light quality, and air quality [54]. The CSTB prototype includes a 200 m^2 PBR curtain wall located at CSTB (Scientific and Technical Centre for Building) site in Champs-sur-Marne, a town slightly east of Paris, France. Built on microalgae façade experience since 2009, this project became the first technology demonstration installed in a real-world application, testing different configurations and density effects on daylight penetration. The project capitalizes on high growth rate and superior carbon sequestration, in which 1 m^3 of microalgae absorbs the same amount of carbon dioxide as 80–100 trees. The operation and monitoring system helps the year-round algae growth, and such technological demonstrations help raise awareness of its possibility for benefiting human and built environments [42,54].

SYMBIO2 is another project in France, implemented in Nantes. It integrates a 300 m^2 biofaçade in a waste processing plant for simultaneous microalgae production (0.7–1 ton/year) and partial treatment of flue gas (CO_2 biofixation: 1–1.8 ton/year). It is proposed that the economic and technical feasibility of this new approach for the production of microalgae be demonstrated by this project. The final interest of this concept will be the result of mutual benefits achieved between the buildings and the needs of microalgae; thus, optimization of the symbiosis is critical here [36,89].

Urban Morphogenesis Lab—UCL and Synthetic Landscapes Lab—University of Innsbruck, in collaboration with ecoLogicStudio, a London-based architecture and urban design studio, presented PhotoSynthetica in Dublin during the Climate Innovation Summit, 2018. PhotoSynthetica is a photosynthetic building cladding system which removes CO_2 and pollutants from the atmosphere and produces a valuable food resource in the form of algae, using the algal power. It shows how biotechnology integration with our cities helps to achieve carbon neutrality. Conceived as an "urban curtain", the system captures approximately one kilogram of CO_2 per day, equivalent to that of 20 large trees. The installation on the Irish Revenue and Custom building in Dublin contains 16 custom-made bioplastic containers (2 × 7 m), each of which functions as a PBR. The modules are designed digitally to utilize daylight for feeding the algal cultures and release luminescent shades at night which is very scenic. CO_2 molecules and air pollutants in the inlet air introduced at the bottom of the biofaçade are captured and stored by the algae and grow into reusable biomass while air bubbles naturally raise through the watery medium within the bioplastic PBRs. The harvested biomass can be employed for the production of bioplastic raw material that constitutes the main building material of the PBRs. To culminate the process, freshly photosynthesized oxygen is released at the top of each façade unit into the urban microclimate. In order to hold the carbon for as long as possible, the PBRs are designed in the serpentine scheme so that the algae can process it. As in other ecoLogicStudio projects, the curtain is a form of biomimetic, a design that copies structures and processes from nature [90,91].

AirBubble, a real urban algae greenhouse, invents a new architectural typology and demonstrates the first biotechnological playground in the world integrated with air-purifying microalgae. It consists of a cylindrical wooden structure wrapped in an ethylene tetrafluoroethylene (ETFE) membrane, protecting 52 large glass algae reactors. The reactors are filled with 520 L of *Chlorella* sp. algae culture that can filter 200 L/min of polluted air. The algae actively eat the pollutant molecules, such as carbon dioxide, and then release fresh clean oxygen. The equipment used in this space, such as ropes, foot pumps, and bouncy spheres, makes it possible to use it both as a playground and as an outdoor classroom. The surrounding urban noise is masked by the white bubbling noise of the algae gardening system. As a result, a calming atmosphere is provided in which to play and interact. The architectural morphology of the playground structure is also effective in improving the filtering process. The air circulation and natural ventilation is stimulated by the inverted conical roof membrane, which, in turn, keeps the play area clean. This project, as a real bubble of clean air, creates a purified microclimate for children to play in in the center of Warsaw, Poland, one of the most polluted cities in Europe [92].

The air quality index (AQI) for six main pollutants, namely, fine particulate PM2.5 and PM10, ground level ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and carbon monoxide (CO), are compared through real-time measurements by use of the monitoring system which is integrated with urban air pollution sensors and is connected to a data processing platform. AirBubble is able to absorb nitrogen and the particulate matter in the air up to 97% and 75%, respectively. In May 2021, PM2.5 concentrations within the playground had fallen well within the World Health Organization's (WHO) recommended range (green zone, AQI below 20), with the peak drop rate of 83%. To verify these promising achievements over a longer period of time, the monitoring phase was continued throughout the summer and the autumn, under different climatic conditions and patterns of use. Over these few months, AirBubble served as a test bed of biotechnology application in tackling air pollution and reducing its negative effects on children's health [92].

Microalgae IVY is a patent-pending technology for retrofitting low-performing windows. The system consists of a network of interlocking bioreactors and allows the cultivation of different strains for multi-functional use and aesthetics. Commercial windows are responsible for more than half of a building's energy consumption and emission. The prototype was developed as an alternative to energy-efficient retrofitting for low-performing windows. A full-scale prototype (8 feet tall by 12 feet wide) was developed and installed at the School of Architecture at the University of North Carolina, Charlotte. Five strains (*Chlorella*, *Chlorococcum*, *Haematococcus*, *Scenedesmus*, and *Spirulina*) were cultivated in the system using a semi-continuous production mode. Their biological performance and environmental benefits (e.g., biomass production, CO_2 reduction potentials) were monitored and measured using various environmental sensors and biological measuring tools. By utilizing 26 valves, the microalgae can easily be transported and extracted once the microalgae are ready for harvesting. The system was able to sequester CO_2 produced by three occupants and output 500 g of biomass per day (~200 kg of biomass per year) [42].

6. Algae-Powered Buildings: Drivers and Barriers

Although the algae-powered buildings have multiple advantages, this technology is still in its early life and there are many technological, economic, environmental, social, and regulatory issues which need to be addressed before wide implementation of these systems. Some major challenges include long-term performance in energy efficiency and effective CO_2 sequestration, thermal and acoustic insulation, the indoor color controlling due to variation of algae culture density, algae medium discoloring, algae panels' durability against climate changes, the need for maintenance, construction, and maintenance costs, and negative environmental effects such as potential toxins and odor produced by harmful algae [29,44,71,93]. Of course, the concern about the high cost can be alleviated due to the long-term benefits. Table 5 summarizes the algae-powered buildings pros and cons. Cost is the main barrier to the adoption of the algae system. The real-world ABT buildings are few and there is an insufficient track record of green performance and longevity in real-world applications. The ROI is also unknown and there is a need to be within the lifecycle of 25 years [14]. However, this technology provides the possibility of enjoying the benefits of a low-carbon economy. Energy savings up to 30% in heating, cooling, lighting, and ventilation load can be economically attractive. The scale of installation is effective in making the algae building economically viable. Larger installation may be more economically viable. Moreover, the possible revenue from the sale of biomass or high-value bioproducts, and use of the building waste, may offset the energy costs [14,42,94]. Environmentally, there are clear gains due to the reduction of energy consumption and energy efficiency, onsite production of biomass, generation solar thermal energy, biofuel production, and wastewater treatment. Potential daily productivity is 1–5 $g/ft^2/day$ when optimum growing environments and operation modes are implemented. The adoption of this technology leads to the reduction of GHG emissions; however, there are concerns about the overall carbon footprint. Using the maximum growth rate, a medium-size office building (100 feet $\times$ 100 feet $\times$ 5 stories (65-feet tall)) retrofitted with microalgae envelopes can sequester 17–85 metric tons of CO_2, produce 10–50 metric tons of dry biomass, and 1400–7000 gallons of biofuel. Using the commercial rate of carbon removal in the range of USD 500 to USD 1690 per ton of CO_2, the cost savings according to this case study could be up to USD 145,000 per year [14,42,95]. Microalgae based wastewater treatment is also of interest. Combined with wastewater treatment processes, algal culture efficiency in removing phosphorous and nitrogen is in the range of 80–100% [42]. However, there are considerations about contamination caused by some algae species which contain toxins or generate volatile organic compounds (VOCs) which are harmful to human health [14,96]. From the social aspect, this technology is in harmony with nature and can cause increased health and well-being due to its environmentally positive impacts, but there are also concerns about potential health effects caused by damage or leakage and the need to manage this risk. For large-scale production, educating and informing a wider community about this technology is therefore very important [14,42,71]. There are also technological issues, such as cleaning and periodic replacement of glazing panels and pipes, which arise over production rates. The durability and lifespan of the technology is unknown, and maintenance may be onerous [14,71]. At all stages of the development process, algae panel information and design guidelines are required. Generally, the technological issues are summed up as "complex" due to the novelty of the technology. It should be noted that all identified issues need further research and experimentation, and with the development and advancement of technology, they will be fixed in the future.

Table 5. Advantages and disadvantages of ABT.

Advantages	
➢	Energy savings due to promoting natural cooling process, improving thermal insulation capacity, transmitting natural light; inside the building, and providing shades;
➢	Capturing airborne pollutants and reducing noise;
➢	Reducing CO_2 levels and enjoying the benefits of low-carbon economy;
➢	Providing aesthetic variation and creating visual interest;
➢	Production of biofuels and other high-value bio-products;
➢	Wastewater treatment.
Disadvantages	
➢	High costs;
➢	Health and safety concerns due to odors and toxins may produce by algae;
➢	Requiring highly efficient and specialized maintenance;
➢	Unknown durability of technology and long ROI;
➢	Guidelines needed;
➢	Technology complexity.

7. The Future of PBR-Integrated Buildings

Although the technology of algae-powered buildings is still a relatively new field, it is possible to achieve zero emission buildings, environmental protection, and improved life quality through the algae integrated façades. Algal façades can be integrated in a variety of buildings, especially those which consume large amounts of energy, including hotels, hospitals, laboratories, and office buildings. PBR inclusion in architecture is not restricted to the building's façades, but they can also be used at the urban level with the aim of producing biofuel, admitting light, providing shade, and raising public awareness with regard to alternative fuels. In optimal performance mode, the microalgae enclosure can cause energy savings due to reduced heating, cooling, and artificial lighting loads. Moreover, it can sequester carbon and treat wastewater or other contaminants. The aesthetic aspects of microalgae envelopes can also be a potential driver for public acceptance. The green features can cause higher physical and physiological well-being and school performance in children. A wide acceptance due to financial incentives through carbon credits and the production of value-added products can also lead to the development of this technology in future. Concentrating on the consumption of energy and the energy saving costs, the sustainability and success of the microalgae applications in the built environment will be specified [23,24,29,47]. The bibliographic analysis shows that these systems are an increasingly active and rapidly growing area of research and practice (Figure 2). Application of ABT at precinct and at city scale could contribute to reducing the predicted 3-degree temperature rise we face. With more research, designers will acquire a better understanding of this technology and be able to apply natural patterns to save the planet.

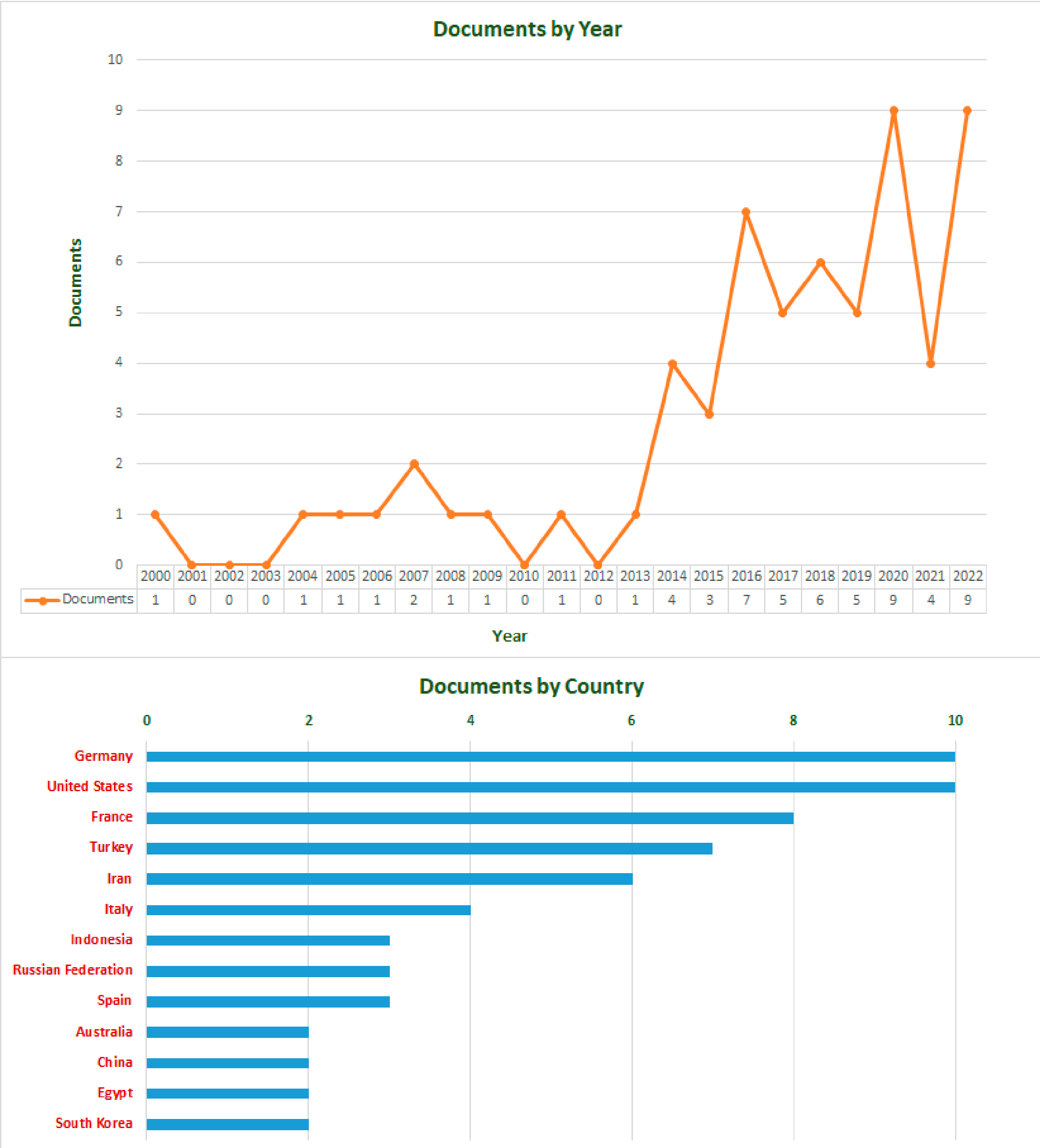


Figure 2. Bibliographic search results of ABT.

8. Conclusions

Green walls and algae façade-integrated buildings as an alternative element in the built environment will have high potential regarding the environment and the carbon footprint if the government support them with new legislation and subsides to inform the public of their benefits. More real-world applications can better attract people; if the market benefits from the environmental and economic advantages, then demand will increase, which, in turn, will act as an accelerator for the developing market. The success of PBR systems integrated with building façades will be directly dependent on the cost and payoff balance in acquiring the chance of application. Other than this bottleneck, there should be an integrated design approach in order that PBRs could be served as an effective building element. Alongside various concepts introduced at the design stage, there are only a few real-life, full-scale proofs, which reflects the fact that this technology is still in its infancy. However, the understanding of the various benefits of microalgae by owners, users, and built environment professionals will be the driving force for future developments.

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Abbreviations

ABT	Algae Building Technology
AQI	Air Quality Index
BIM	Building Information Modeling
BIQ	Bio-Intelligent Quotient
EUI	Energy Use Intensity
GHG	Green-House Gas
HVAC	Heating, Ventilation, and Air Conditioning
PBR	Photo Bio-Reactor
PH	Passive House
PV	Photovoltaic
ROI	Return on Investment
SD	System Dynamics
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WWR	Window-to-Wall Ratio
ZEB	Zero Energy Building

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