ISSN 2729-7640

ARCHITECTURE PAPERS
OF THE FACULTY OF ARCHITECTURE AND DESIGN STU
www.alfa.stuba.sk

2/2023 (Vol. 28)
DOI: 10.2478/alfa-2023-0008

Transdisciplinary collaboration in architecture: Integrating microalgae biotechnologies for human and non-human perspectives

Veronika Miškovičová[1]*

Jiří Masojídek[2]

[1] Academy of Arts, Architecture and Design, Department of Architecture, Studio Architecture III, Prague, Czech Republic

[2] Czech Academy of Sciences, Institute of Microbiology, ALGATECH Centre, Laboratory of Algal Biotechnology, Třeboň, Czech Republic

***Corresponding author**
E-mail: veronika.miskovicova@umprum.cz

Article information
Sent: Apr 14, 2023
Accepted: Jun 12, 2023

Abstract: This article investigates the role of architectural research in addressing the current ecological, geopolitical, and socioeconomic challenges by exploring the potential of symbiotic ecosystems, particularly microorganisms such as microalgae, in architectural and design applications. Microalgae biotechnologies have the potential to offer a wide range of applications in architecture and design, encompassing small-scale objects, living systems on building exteriors, as well as urban and rural scenarios, thereby allowing for systematic research. When using these biotechnologies in architectural designs, it is crucial to consider maintenance requirements, environmental impacts, and the potential for enhancing public spaces and society across various dimensions in both short-term and long-term perspectives, and potential environmental impacts before implementing microalgae-based systems in real-life scenarios. This study describes a collection of interdisciplinary projects and research that involve microbiology, architecture, and design and proposes various experimental scenarios concerning the integration of both human and non-human perspectives. Through collaborative academic efforts, these projects demonstrate the potential for combining microalgae cultivation with architectural applications. The projects include Photosynthetic Landscape, a modular photobioreactor system, Synthesizing/Distancing which addresses coexistence in global epidemics, Biotopia, a permanent interior installation incorporating microalgae, Exchange Instruments, a semi-closed cultivation system, and Cultivated Environment, a small-scale microalgae cultivation apparatus. The article highlights the implication of controlled environments, maintenance, and interdisciplinary cooperation while showcasing the potential for these systems.

Keywords: architectural research, environmental challenges, symbiotic ecosystems, microorganisms, microalgae, interdisciplinary collaboration, biotechnologies, public education, integrated problem-solving

INTRODUCTION

Architectural research in the context of the current ecological, geopolitical, and socioeconomic situation should open new possibilities for coexistence with the surrounding environment on all scales. Today, we can find a direct correlation between the rise of fossil fuel-dependent technology and the degradation of the environment in which humans and non-humans exist (Karyono, 2015). The long-term unsustainability of these sectors results in excessive greenhouse gas emissions, air pollution, and an increase in the overall harmfulness of our environment, which includes ever-increasing global temperature fluctuations (Eurostat Statistics Explained, 2023). A special report published in Nature Climate Change (Raupach, Davis, Peters, Andrew, Canadell, Ciais, Friedlingstein, Jotzo, van Vuuren, Le Quéré, 2014) demonstrates that urgent and rapid system remedy is needed to achieve global emission reductions and slow down associated global warming. According to the above-described systems, processes and their consequences affect the media of air, soil, and water and have a direct impact on all living organisms (European Environmental Agency, 2019).

Given the current technological developments and the impact of industry in all areas of our lives, and the priorities of the European Commission's new Green Deal, which declares achieving climate neutrality by 2050, protecting biodiversity, and developing a circular economy (Araújo, Vázquez Calderón, Sánchez López, Azevedo, Bruhn, Fluch, Garcia Tasende, Ghaderiardakani, Ilmjärv, Laurans, Mac Monagail, Mangini, Peteiro, Rebours, Stefansson, Ullmann, 2021), it is necessary to find new ways of forming and maintaining symbiotic ecosystems and to continually develop their potential. This article focuses on the research and potential of microorganisms, especially microalgae, and their possible application to architectural and design objects and structures. It also aims to analyse and compare different approaches using algal biotechnologies, primarily focusing on them as tools in public education. This understanding is also critical for addressing global challenges such as biodiversity loss, which require a holistic and integrated approach to problem-solving.

Sympoietic interactions

The term "growth" is widely (mis)used and applied with respect to our current socioeconomic models. On the contrary, "de-growth" refers to a paradigm that seeks to reduce the human environmental impact by promoting equitable use of resources. In the context of microbiology, this might involve developing microbial technologies that can help to promote new, non-invasive, and sustainable agriculture scenarios, reduce waste and pollution, and support biodiversity conservation. However, these often presume a conflicting relationship between our society and nature. In the artwork Endosymbiosis: Homage to Lynn Margulis by Shoshana Dubiner, diverse creatures interact with each other, forming organisms, cells and clusters. Sympoietic relationships are characterized by a distributed agency and a shared responsibility for creating and maintaining a system where the parts are not pre-existing but rather emerge through their interactions (Haraway, 2016).

Deconstructing human-centred knowledge and recognizing the company of non-human actors is essential to forming and maintaining relationships between humans and non-humans on our planet (Davis, Turpin, 2014). When we acknowledge that all beings, including non-human ones, are active participants in these processes, we can diverge from the utilitarian view of nature and technology and develop more collaborative relationships with the environment and technologies of use instead. Recognizing the importance of organisms and processes on all scales, it is essential to understand the overall complexity and interconnectedness of Earth's mechanisms. At the micro-scale, single-celled organisms, such as bacteria or fungi, play critical roles in nutrient cycling and decomposition, influencing the biogeochemical cycles that regulate our planet's climate (Lowenfels, Lewis, 2010). These processes have significant impacts on larger-scale phenomena, such as the formation of soils and the maintenance of ecosystem health and biodiversity.

Why microalgae?

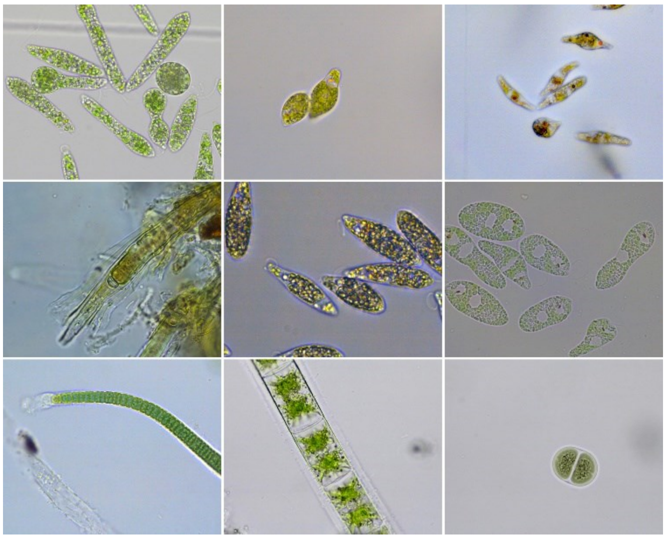

Fig. 1. Various types of cyanobacteria and microalgae. (Source: Lenka Hutárová, Andrej Jedlička, University of Ss. Cyril and Methodius, Faculty of Natural Sciences, Trnava, Slovakia, 2022)

Microorganisms, such as microalgae (including prokaryotic cyanobacteria and eukaryotic and microalgae – Fig. 1) are photosynthetic organisms that can be found in a wide range of environments, from oceans to freshwater systems and even in the soil. They are photosynthetic organisms, similar to higher plants. In economic terms, microalgae can be described as a 'cell factory' having the ability to harness the sun and convert its radiant energy into crucial products (biomass and oxygen) using natural resources, such as nutrients and carbon dioxide. For example, microalga Chlorella (Fig. 2) has a spherical microscopic cell with a diameter of 5-10μm and many plant-like structural elements. Within 24 hours, a single cell of Chlorella and similar green microalgae strains grown under suitable conditions reproduce by dividing, which is the most common asexual reproduction of microalgae. This gives rise to daughter cells, usually two to four inside the mother cell. These processes can involve the interplay between non-human and human, blurring the boundaries by their interaction. As microalgae can also occur and grow in man-made environments, they are intertwined with broader social and environmental issues, such as food and energy security, and climate change.

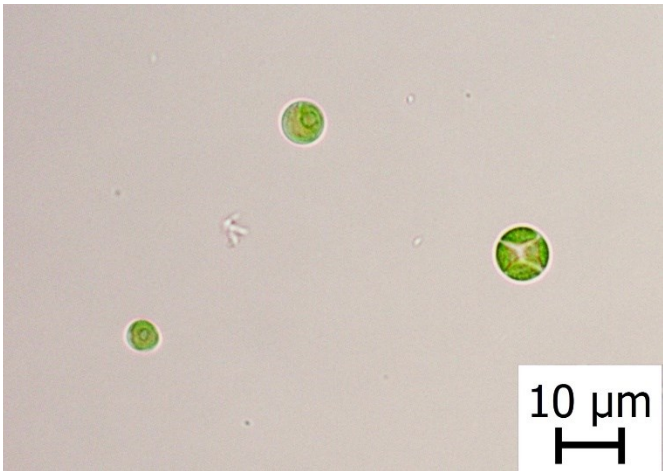

Fig. 2. Chlorella Vulgaris. (Source: Czech Academy of Sciences, Institute of Microbiology, ALGATECH Centre, Laboratory of Algal Biotechnology, Třeboň, Czech Republic, 2020)

Cultivation systems and possible applications

Microalgae can be cultured in various kinds of technological man-made systems – bioreactors, which result in potential applications, aiming to substitute current invasive and destructive industrial sectors. One of these applications is the potential to use refined biomass for the production of biofuels as it contains energetic compounds like lipids and hydrocarbons. Microalgae can be used to produce biodiesel, bioethanol, and biogas, which can (potentially) replace fossil fuels and reduce greenhouse gas emissions. Another sector is nutrient recycling as microalgae can recycle nutrients from wastewater and other sources, reducing pollution and recovering water quality. As concerns carbon capture and storage, microalgae can also catch carbon dioxide from the atmosphere via photosynthesis, reducing greenhouse gas emissions.

Biotechnology can optimize the cultivation process, nutrient recycling, improve the efficiency of harvesting and processing, and develop new methods for converting microalgae biomass into added-value compounds. Detailed exploration and understanding of the natural habitat of various microalgae species can potentially promote interaction between humans and these non-human organisms, leading to innovative solutions in the biotech industry. Microalgae have unique characteristics, such as high growth rate, high lipid content, or versatile cultivation options, that make them suitable for biomass-to-energy conversion. By studying and understanding their natural habitat, including the technical and environmental conditions in which they prospect, we can develop technologies that mimic these features to harness the energy potential of microalgae efficiently.

Several economic models based on fast growth could be relevant to the potential boom of biotechnologies in replacing current industrial sectors. One such model is the "disruptive innovation" model, which posits that new technologies or business models can replace established industries and lead to rapid growth in new sectors. Another potential model based on growth is the "network effect" model, which suggests that the value of a technology or product increases as more people use it. This could apply to biotechnologies because as more people adopt and use them to develop new products and services, their value and potential for growth increase. In the realm of biotechnologies, there lies the potential to revolutionize industrial sectors such as crop agriculture and energy production. The question remains open regarding the scope and timeline for biotechnology's involvement in developing more efficient and resilient new crops or creating biofuels that surpass fossil fuels in terms of their environmental impact.

Who do they work with?

To gain some insights into the behaviour of non-humans, including microorganisms, it is crucial to highlight their potential for existence and resilience within existing systems. For instance, mushrooms and other fungi can help to break down toxins and pollutants in contaminated soil with the potential for bioremediation and other forms of "green" technology that utilize the power of non-human organisms to solve environmental problems (Tsing, 2015). Within this framework, we can recognize microorganisms as active agents shaping our world and potential allies in pursuing more sustainable and equitable life forms. Research into biopolitical citizenship includes human subjects and the many more-than-human actors that shape our lives and environments while questioning the human-centred point of view.

This concept is relevant to collaborating with microorganisms in fields such as design, architecture, and various tech fields because it involves the understanding of how these entities are connected and how they can be worked with to shape our societies and environments. For example, collective work with microorganisms in bioremediation or wastewater treatment can help to decrease environmental pollution, while using probiotics and other microbial supplements can promote overall health. At the same time, it is essential to mention that using microorganisms for profit can also raise questions about power, inequality, and social justice. The development and commercialization of microbial products may disproportionately benefit particular groups or exclude others and raise ethical concerns around safety, consent, and environmental impact. Thus, working with microorganisms requires careful consideration of the ethical, social, and political implications of these technologies, and a commitment to understanding how they intersect with questions of biopolitical citizenship and social justice.

Large-scale cultivation

According to the results of a recent study aimed at mapping microalgae production in Europe (Araújo, Vázquez Calderón, Sánchez López, Azevedo, Bruhn, Fluch, Garcia Tasende, Ghaderiardakani, Ilmjärv, Laurans, Mac Monagail, Mangini, Peteiro, Rebours, Stefansson, Ullmann, 2021) that involved 225 companies in twenty-three countries, about two-thirds of them were found to be focusing on macroalgae cultivation (67%) and one-third on microalgae cultivation (33%). Germany, Spain, and Italy ranked in the top three by the number of microalgae production units. Microalgae have thus become an ideal platform for large-scale biomass production as they are fast-growing in aquaculture, highly efficient, and powered by solar energy. A dense, well-mixed mass culture of microalgae (>0.5g biomass per litre) with sufficient nutrition and optimized growth conditions represents a system whose photosynthetic efficiency is 10-20% compared to 1-2% for terrestrial plants. Some microalgae species can double their biomass in a period of up to 3.5 hours during exponential growth (Singh, Ahluwalia, 2013).

The two main types of large-scale microalgae cultivation are open and closed systems with different technological characteristics and maintenance requirements. Semi-closed or closed systems, the so-called photobioreactors (PBRs), have a significant advantage – the ability to control the entire assembly's carbon dioxide supply, air, and overall individual variables (Koller, 2015). The most common types of PBRs are tubes, columns, or flat panels, made of transparent or translucent materials such as laboratory glass, plexiglass, or foil, positioned horizontally or vertically and arranged in systems of loops, helixes, coils, or fences according to the desired purpose or spatial conditions (Acién, Molina, Reis, Torzillo, Zittelli, Sepúlveda, Masojídek, 2017; Leong, Chang, Lee, 2023). Closed systems have minimal direct contact with the surrounding environment, reducing the likelihood of culture contamination, but making them more maintenance-intensive than open systems.

In open systems, tanks, shallow ponds, raceways (shallow racetracks mixed by paddle wheels) and sloping cascades, the culture is in direct contact with the environment. They are technologically easier to operate and maintain (Narala, Garg, Sharma, Thomas-Hall, Deme, Li, Schenk, 2016). The simplest types of open systems are ponds or air-bubbled containers. Depending on the local climatic conditions and the materials required, optimal cultivation depth can vary. Depending on the size and technological complexity of the units, the mixing and aeration system (enriched with carbon dioxide) can range from local air bubbling to mixing by blades, rotating arms, paddle wheels, or other types. The advantage of this type of cultivation is that, compared to closed systems, they can produce considerable amount of biomass due to the large culture volume.

Application scenarios

Different application scenarios exist depending on the focus and the result, process, or product to be marketed in algal biotechnology. The most widespread is biomass production and its subsequent use within various industry types, such as food supplements, bioplastics, biopesticides, and biofuels, all with active absorption of greenhouse gases or, in some cases, the purification of waste water (Fabris, Abbriano Raffaela, Pernice, Sutherland, Commault, Hall, Labeeuw, McCauley, Kuzhiuparambil, Ray, Kahlke, Ralph, 2020). Algal biotechnologies also offer numerous potential applications in the fields of architecture and design while incorporating these technologies in the built environment on all scales. Microalgae can be incorporated as a living cladding system on building facades. These elements may absorb sunlight and provide natural shading, which helps to control building temperature and generate energy biomass. "Worldwide first façade system to cultivate microalgae" (Arup, 2013) was built in Hamburg, Germany with the concept of bioreactive façade with cultures of microalgae capturing carbon dioxide from the environment and producing biomass.

Urban and rural agriculture scenarios also include growing microalgae on various sites, building walls and rooftops. The harvested biomass can be used to produce food, fodder, biofuels, or other useful bioproducts, boosting local industry and reducing emissions caused by transportation. The installation of Culture Urbaine by Cloud Collective (Peruccio, Vrenna, 2019) implemented closed tubular PBRs as part of a temporary installation over a busy stretch of the motorway. They served to actively absorb carbon dioxide from the air and produce biomass.

Integration of polycultures related to agriculture and water management was implemented within a temporary installation called Floating Fields by architect Thomas Chung (Ezbahn, 2019), which was installed in the area of the mills and flour production. It was a demonstration of the concept of returning agriculture to Shenzhen Bay through the use of floating agricultural fields with various types of installations, including, among others, open cultivation ponds.

This approach raises the question: Could the integration of water areas with non-human life within urban landscapes contribute to the revival of biodiversity in our environment? Water habitats provide a unique ecosystem that can support a variety of flora and fauna, from aquatic plants and invertebrates to fish and birds. Integrating water areas into urban environments also offers opportunities for creating ecological corridors, connecting fragmented habitats, and facilitating the movement of species. It can provide refuge for aquatic organisms, promotes water conservation and purification, and enhances the overall aesthetics and liveability of the urban landscape on every scale – from single-celled microorganisms to complex planning and transformation.

Still under review

Even though microalgae offer a great potential with their applications, there are a few important factors that must be considered. First of all, large-scale microalgae farming in outdoor ponds consumes a lot of water, land, and energy, which could potentially deplete the resources. Moreover, the growth of microalgae with synthetic fertilizers might worsen water pollution and other environmental issues (Christenson, Sims, 2011). Secondly, large-scale microalgae cultivation requires considerable upfront investment in infrastructure, such as photobioreactors or open pond systems, and ongoing expenses incurred for inputs like water, nutrients, and energy. Thus, reducing production costs is crucial for microalgae farming. Lastly, although microalgae are a great source of nutrients, it is important to carefully consider how they might affect both human health and the environment. More research is required to determine how large-scale microalgae cultivation affects biodiversity and aquatic environments (Wijffels, Barbosa, 2010).

Overall, microalgae biotechnologies require a sizeable financial investment to support research, development, and prototype scale-up (Loke Show, 2022). As a result, the distribution of resources frequently favours technologies with the highest anticipated return on investment, potentially moving projects with broader societal implications aside. The bias towards profit maximization may result in research that disproportionally focuses on applications aiming for the needs and interests of a specific segment of society, perpetuating existing socioeconomic disparities. Similar aspects should be considered regarding the application of these biotechnologies in various architectural and design solutions, e. g. the previously discussed building facades (Santos, Mendes, Mendes, 2020).

Project 1: Photosynthetic Landscape

At the Algatech Centre (a part of the Institute of Microbiology of the Czech Academy of Sciences) at Třeboň, Czech Republic, algal biotechnology has been developed since the 1960s. The establishment of cooperation between a research institution and an architecture studio at the Academy of Arts, Architecture and Design in Prague (UMPRUM), Czech Republic, was considered with a focus on microalgae as a key point for expanding theoretical and practical knowledge of the topic. The first direct collaboration with the Algatech Centre was started in 2020. Within the framework of the Photosynthetic Landscape project (Fig. 3, 4), the overlap with microalgae biotechnology was realized by a team of students (Vojtěch Kordovský, Adam Varga, Anna Östlund) of the Architecture III Studio supervised by Prof. Imrich Vaško and Assistant Prof. Shota Tsikoliya at UMPRUM.

As an outcome, a modular PBR system was constructed and placed outdoors. The project's primary objective was to assess the technical aspects of closed cultivation units. To achieve this, the outdoor installation ran continuously for two months, allowing for the evaluation of the overall health and efficiency of the culture. The executive team responsible for the project consisted of researchers and Ph.D. students of architecture as part of the Architecture III Studio at UMPRUM, and the tasks have been regularly consulted with the studio professor. The team explored new spatial configurations for exterior closed PBR units, which could provide shade and enhance the system's performance.

Fig. 3. Photosynthetic Landscape installed in the courtyard of Nevan Contempo Art Gallery in Prague, Czech Republic. (Photo: Eva Rybářová, 2020)

Fig. 4. Photosynthetic Landscape, workshop at the Algatech Centre. (Photo: Veronika Miškovičová, 2020)

At the initial workshop at the Algatech Centre (Fig. 4), supervised by Prof. Jiří Masojídek, the cultivation techniques and practices were worked out. According to that, the initial concept and model for the exhibition project Photosynthetic Landscape was designed and constructed, consisting of an aluminium scaffolding carrying transparent PVC tubes. The idea was tested in various spatial settings and installed at the Landscape Festival 2020 in Prague, Czech Republic, in the exterior of the Nevan Contempo Gallery. Within the installation, 17 pyramid-like loops were connected and intertwined with the tubes. The overall structure demonstrated a manifold PBR system – an interconnected network of tubes exposed to direct sunlight to facilitate photosynthesis (Fig. 5). The system, connected by water and air pumps to the central reservoir (Fig. 6), was maintained continuously for two months. Microalgae from the reservoir were distributed to the transparent tubes through the loops to receive light and circulate.

Fig. 5. Photosynthetic Landscape, detail. (Photo: Eva Rybářová, 2020)

As this was an outdoor installation with daily temperatures of above 30 degrees Celsius, the system was interfaced with a cooling unit to ensure physiological temperatures. By the end of the installation and after optical measurements, the colour and density indicated approximately three times higher concentration of microalgae biomass. Subsequently, the project was reinstalled in a different spatial configuration using three modules in the interior of the Jaroslav Fragner Gallery in Prague, Czech Republic (Fig. 7, 8). Since the gallery space had no natural light, the use of the artificial lighting source had to be investigated and tested. Firstly, estimating the overall light intensity was essential, after which the light source was placed underneath the main reservoir. Due to the sedimentation of microalgae cells, the light source placement was not optimal. Combined with the contamination of the cultures, they separated and proved a colour change, which resulted in the need to clean the system and change the cultures.

The project adopted a methodological approach that involved workshops in developing cultivation techniques, consultation with microbiologists, technicians, electricians, and other PBR specialists, designing and constructing the installation, testing it in different spatial configurations, addressing environmental factors, and implementing sanitation and cleaning protocols to ensure optimal microalgae growth and minimize contamination risks. During the project, the working group consulted with experts from various fields, including microbiologists, engineers, electricians, and other PBR specialists. Their expertise and insights contributed to refining the technical aspects of closed cultivation units. This collaborative approach enabled the project team to learn through on-site experience. One potential limitation of the approach was its seasonality. Chlorella cultures perform well within a temperature range of 15-25 degrees Celsius. Therefore, operating the structure seasonally outdoors is necessary. Running the system during warmer seasons offers enhanced photosynthetic efficiency advantages, as it can utilize natural sunlight instead of relying solely on artificial lighting, which would require additional electricity.

Fig. 6. Photosynthetic Landscape, detail of the culture reservoir and degasser. (Photo: Eva Rybářová, 2020)

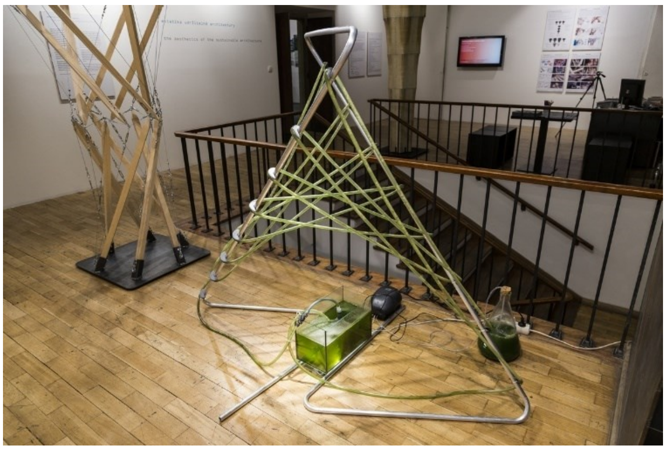

Fig. 7. Photosynthetic Landscape, Jaroslav Fragner Gallery, installation. (Photo: Jiří Straka, 2020)

The goal was to utilize the power of natural sunlight, airflow, and water to facilitate photosynthesis and create an efficient microalgae cultivation system, which would also be capable of being reinstalled by using essential tools and technical knowledge. In conclusion, when cultivating microalgae, it is essential to limit the contact between the cultures (in this case, the main reservoir, which was covered with perforated lid) and the outer environment. As these systems provide a controlled environment for microalgae growth, it is crucial to provide a protective barrier allowing precise control of variables like light exposure, temperature, and nutrient supply. To minimize the possibility of contamination, proper sanitation and cleaning protocols have to be followed, as well as regular monitoring of the cultures and maintaining suitable growth conditions.

Fig. 8. Photosynthetic Landscape, Jaroslav Fragner Gallery, detail. (Photo: Jiří Straka, 2020)

Projects 2 and 3: Synthesizing/Distancing

Referring to the recent questions concerning new ways of coexisting and living in the era of global epidemics, the Photosynthetic Landscape project aimed to address some concerns and offered potential scenarios to the ongoing environmental and epidemiological crisis. To explore the relationship between nature and technology, the same working team undertook the installation for the Ars Electronica 2020 festival in the courtyard of the Pragovka Gallery (Fig. 9). Located in a former industrial area in Prague-Vysočany, Czech Republic, the installation, capable of maintaining photosynthesis, facilitated essential processes, such as oxygen production and carbon dioxide assimilation from its surrounding environment. During the relocation and reinstallation of the modules from the Photosynthetic Landscape project, the team showcased the modularity and reusability of the concept, which also highlighted the project's adaptability and the potential for its application in various contexts. The project still included a phase of continuous evaluation and optimization. The team ran the outdoor installation for one month, monitoring the health and efficiency of the microalgae culture. Data regarding biomass concentration, colour, and density was measured to assess the project's success and identify areas for improvement.

Building on the methodology employed in the previous project entitled Photosynthetic Landscape, the main objective of the new endeavour was to introduce and evaluate the effectiveness of water and air piping systems within different spatial configurations while keeping the culture alive and healthy. The Synthesizing/Distancing and Photosynthetic Landscape projects focused on natural environments and posed practical challenges for algae cultivation and maintenance. The exposure to varying weather conditions and external factors necessitates robust strategies to ensure the health and resilience of the microalgae cultures. This project is a valuable reference for understanding the practical implications and complexities of maintaining algae cultures outdoors. Overall, the Pragovka Gallery courtyard installation symbolized the team's attempt to address the complex relationship between human, non-human, and technology applications as the bridging element. It served as a tangible representation of the need to create cohesive systems that have the potential to coexist with the natural environment and the demands of current societal challenges. The bacterial and fungal contamination, which occurred to the medium in the last week of the installation, also paralleled, as a metaphorical reflection, the vulnerability and fragility experienced during this unprecedented time of social distancing and isolation.

Fig. 9. Photosynthetic Landscape, Pragovka Gallery, installation. (Photo: Eva Rybářová, 2020)

Microflows (Fig. 10) was a site-specific installation during the COVID-19 pandemic as part of the Designblok 2020 event in Gabriel Loci Monastery in Prague, Czech Republic. The team transformed the exhibition room into a fictional forest, utilizing PVC pipes suspended from a ceiling mesh. The installation featured three main reservoirs, one containing the mother culture and the other circulating within the loops of pipes. The overall design of the installation resembled a tree or a forest, aiming to symbolize and represent the photosynthetic efficiency achieved by utilizing a 30-litre medium. The purpose was to highlight the efficiency of this medium compared to that of a mature tree, emphasizing the potential of microalgae-based systems in sustainable and efficient biomass production. While the team reused and developed the same microalgae culture in the Photosynthetic Landscape and Synthesizing/Distancing projects, they faced a setback due to contamination when installing Microflows. As a result, the team had to replace the cultures with new ones cultivated in laboratory conditions at the Algatech Centre. Microflows sought to evoke a sense of wonder and visitors' curiosity by creating a representation of a fictive landscape within the installation while drawing attention to the importance of harnessing nature's potential for novel biotech solutions, even in challenging times such as the COVID-19 pandemic.

While testing the installation in different weather and spatial conditions in previous projects allowed us to keep other variables, such as light (natural or artificial), technology (water or air pumping system), the density of the cultures, spatial configurations, materials use, and other, the team further applied the collected knowledge in the Microflows project. Overall, the project employed a combination of experimentation, adaptation, and creative design, to demonstrate the remarkable photosynthetic efficiency of the 30-litre medium and emphasize the potential of microalgae and efficient biomass production. The topic of Microflows resonated deeply with the event attendees, as it addressed the topic of potential air purification during a time of heightened global insecurity. With the COVID-19 pandemic affecting communities worldwide and raising concerns about air quality and health, the installation's focus on the potential of microalgae to contribute to cleaner air excited the visitors. After installing Microflows, the cultures were maintained in the interior space and aerated for two months, serving as a valuable plant fertilizer for the indoor plants.

Fig. 10. Microflows, Designblok 2020. (Photo: Tomáš Zumr, 2020)

When evaluating the previous research, the team concluded that the most serious issue was the overall maintenance of the system, the inability to reuse some components (long-term unsustainability of the concept), and the lack of on-site laboratory equipment and technical support. The optical density of the medium was monitored during culturing in the laboratories of the Algatech Centre, and we have consulted the cultivation process and maintenance of these systems, including microalgae nutrition; however, instrumental quantification of the data in these projects was not possible online.

Project 4: Biotopia

The concept of microalgae exploitation has been well-known to the world's professional community. Still, there are only few examples of long-term cultivation outside the laboratory. This is also because the maintenance of these systems is still relatively challenging – all systems require regular maintenance. On the other hand, it must be remembered that this is the culturing of living microorganisms, and the priority is to maintain suitable conditions in all systems. Long-term or permanent installations of PBRs can improve the overall quality of the local environment, based on the photosynthetic efficiency and given or created conditions. These installations can be tailored to serve various purposes. When incorporating PBRs as permanent fixtures, several factors need to be considered, such as system maintenance, as long-term installations require regular maintenance to ensure optimal performance. This includes monitoring and controlling variables like temperature, pH, light exposure, and nutrient supply, as well as periodic cleaning and sterilization to prevent contamination. Secondly, it is the integration with existing building systems, such as heating, ventilation, air conditioning, electrical systems and other, if necessary, to ensure proper functioning and energy efficiency. Lastly while naming a few, it is aesthetics and functionality: the design should complement the building's or space's overall aesthetics while maintaining functionality.

The system called Biotopia (Fig. 11) is a permanent interior installation created for ITB Development (ITB, 2022) and located in the lobby of the Wallenrod Business Centre in Bratislava, Slovakia. Finding a suitable local technical partner capable of maintaining and cultivating the seed culture of microalgae was dictated by the project's location. The fabrication process of the Biotopia system involved a dedicated team of three individuals, all based at UMPRUM Studio Architecture III: Veronika Miškovičová, Daniel Sviták, and Adam Varga, who designed and constructed the installation. Throughout the development process, they received valuable support and consultations from Prof. Imrich Vaško and engaged in regular discussions with the clients from ITB Development. The team collaborated with experts, including microbiologists, engineers, electricians, and technicians. These specialists played a crucial role in supporting the research and development of the project's microalgae cultivation and 3D printing aspects. Their expertise contributed to the successful implementation of the on-site installation. The Biotopia system was commissioned as a permanent interior installation for ITB Development, located in the lobby of the Wallenrod Business Centre in Bratislava, Slovakia.

Fig. 11. Biotopia, Wallenrod Business Centre in Bratislava, Slovakia. (Installation design and construction: Veronika Miškovičová, Daniel Sviták, Adam Varga, mentoring: Imrich Vaško, Igor Lichý, Tomáš Šebo; source: ITB Development, 2022)

Due to the specific requirements of the project's location, the team sought a local technical partner capable of maintaining and cultivating the microalgae seed culture. In this context, knowledge was shared across our research interests and specialists, resulting in a partnership with the University of Ss. Cyril and Methodius, Faculty of Natural Sciences (Department of Biology) in Trnava, Slovakia. The team led by Prof. Juraj Krajčovič consisted of Lenka Hutárová, Dominika Vešelenyiová, and Andrej Jedlička. The team is dedicated to research in the field of microbiology, genetics, and evolutionary biology. The project has combined two approaches, one incorporating algal biotechnologies in architectural and design objects, and the other using the technology of 3D printing with a robotic arm. The project was implemented after more than a year of research and technology testing while searching for the optimal design solution in cooperation with the developer.

After the investigation and test samples, the relief structure was fabricated using the technology of automatic printing from transparent PLA granulate with manually added green pigmentation, which resembled the natural colours of the microalga Chlorella. The printed structure was designed to support the glass vessels with microalgae (Fig. 12). The system was mounted on a suspended wall, with a light and air pumping system located behind. We used the generative algorithm simulating differential growth with the primary input of the geometries of the glass reservoirs, placed on the wall in various coordinates to reach the optimal light mode. This algorithm allowed us to adapt the object's angles to the lobby's space, tangling around the reservoirs with microalgae and the other fabricated curves. The structure was also optimized into smaller pieces for production, transport, and installation efficiency (Pišteková, Tholt, 2022).

While still incorporating algal biotechnologies, the project primarily focused on creating an interior installation within the given space of the lobby. The project aimed to merge applied research into microbiology and 3D printing technology to develop an aesthetically pleasing and functional system. The main priorities were to design an installation that symbolized the photosynthetic efficiency of microalgae and facilitated air purification in an indoor environment. The project's main goals encompassed various aspects, such as technological advancements, aesthetic integration, and potential functional applications within various interiors in the future. Contrasting with previously mentioned projects, the Biotopia project prioritized the integration of algal biotechnologies in the interior and enhanced their visual aspect.

Fig. 12. Biotopia, Wallenrod Business Centre - detail, Bratislava, Slovakia. (Installation design and construction: Veronika Miškovičová, Daniel Sviták, Adam Varga, mentoring: Imrich Vaško, Igor Lichý, Tomáš Šebo; source: ITB Development, 2022)

The main goal was to create a permanent indoor installation showcasing microalgae's potential in a fully controlled environment. The methodology focused on the installation's design, fabrication, and optimization to achieve a visually captivating and functional structure. While the project aimed to highlight the overall photosynthetic efficiency of the microalgae, practical issues related to algae cultivation and maintenance were considered to be less prominent due to the controlled nature of the installation. The methods employed in the Photosynthetic Landscape and Biotopia projects played a pivotal role in achieving their respective goals and priorities. While the previously mentioned projects tackled the practical challenges of algae cultivation in natural environments, Biotopia showcased the integration of algal biotechnologies in a controlled setting. By conducting a comparative analysis between these projects, a deeper understanding of the implications for algae cultivation and maintenance can be gained, further enhancing future research and applications in this field.

Long-term or permanent installations using algal biotechnologies have the potential to enhance interior spaces. When conducting the research, it is also important to search for real-scale applications and demonstrations to prove and test the proposed ideas and their feasibility. While architects and engineers can develop answers to environmental problems – increasing the built-up environment's appearance and functionality by incorporating these systems into architectural design, it is still important to consider the overall functionality and benefits for the society. Even though the Biotopia project has been designed and produced for the private sector, it was important to maintain it usable for the public, while placing it in the entrance lobby, where it is visible from the street level.

These factors, together with the fact that the project was conducted as cross-disciplinary research among the Academy of Arts, Architecture and Design in Prague (UMPRUM) – Studio Architecture III, led and mentored by Prof. Imrich Vaško, in two architectural research projects (Veronika Miškovičová and her research on microalgae, Daniel Sviták and Adam Varga with their research on the robotic arm 3D printing), in collaboration with the Czech Academy of Sciences, Czech Republic, and the University of Ss. Cyril and Methodius in Trnava, Slovakia, contributed to comprehensively exploring the relationship between material and technological research, advanced fabrication techniques, and collaboration with scientific fields.

Project 5: Exchange Instruments

The Exchange Instruments project (Fig. 13) has allowed using the results of two years of discussion and research in semi-closed cultivation systems and their potential applications. The outcome was the production of two spirals made of laboratory glass. Here, the spirals serve as a "photo stage" (Fig. 14) and thus a kind of light-harvesting system for the culture medium – the spiral houses a light bar with LED illumination of sufficient intensity for optimal microalgae growth regardless of the natural light supply. The lower part consists of the main culture vessel (Fig. 15) with a circulation pump and a stainless-steel base with a chamber housing the air pump and electrical wiring. The assembly functions as a complete unit and continuously circulates twenty litres of microalgae culture functioning photosynthetically as a tree: it "inhales" carbon dioxide, "exhales" oxygen, and continuously bioremediates the environment. The tools of exchange are not meant to be a simulation of the natural environment but a reflection on the potential interdisciplinary cooperation.

The project combined various disciplines and crafts to create a functional and aesthetically appealing installation. The employed methodology revolved around fostering collaborations with glassmaking and welding companies, allowing to integrate their expertise into the fabrication process. A collaboration with a glass-making company was established to bring the concept of the one-meter-high glass spiral structure to life. Through continuous discussions with the artisans, the spiral design was given specific dimensions based on the company's technical abilities. The glass spiral had a specific function and served as a light-harvesting system for the culture medium while being edgeless to avoid sedimentation in the crevices. It housed a light bar with LED illumination, providing optimal light intensity for microalgae growth regardless of the natural light supply.

Fig. 13. Exchange Instruments, UM Gallery - installation, Prague, Czech Republic. (Photo: Markéta Slaná, 2022)

Integrating glass-making techniques into the project added a visually captivating element while ensuring the installation's functionality by utilizing laboratory glass, which possesses essential properties for various applications. These properties include high resistance to chemical corrosion, excellent transparency for observing cultures, and the ability to withstand extreme temperature variations, ensuring the integrity and durability of the installation throughout its lifespan. On the other side, working with laboratory glass with such specific geometry was problematic in terms of maintenance and fragility, as the spiral had to resist constant vibrations and motion of liquid pumping in and out of the attached water pump. That, with the overall weight of the liquid, caused several cracks in the glass, which had to be fixed during the exhibition, and later maintained.

Fig. 14. Exchange Instruments, UM Gallery - detail, Prague, Czech Republic. (Photo: Markéta Slaná, 2022)

In addition to the collaboration with the glass-making company, discussions were held with a construction (welding) company to adapt the structure to the needs of the glass spiral and accommodate the necessary technological chambers for the pumping systems and lighting. The methodology involved ongoing dialogue with the construction (welding) team to ensure seamless integration between the glass spiral and the supporting structure. This collaborative approach created a cohesive and functional unit that effectively circulated the microalgae culture and facilitated photosynthesis. The methodology employed in the Exchange Instruments project exemplified the importance of interdisciplinary collaboration and craft integration. The project successfully merged different disciplines by establishing partnerships with glass-making and construction (welding) companies to create a visually captivating and functional installation. The continuous discussions and adaptations throughout the fabrication process ensured a seamless integration of the glass spiral and supporting structure, showcasing the potential of interdisciplinary cooperation in artistic and scientific endeavours.

Fig. 15. Exchange Instruments, UM Gallery - detail, Prague, Czech Republic. (Photo: Markéta Slaná, 2022)

Project 6: Cultivated Environment

The most recent Cultivated Environment project (Fig. 16) has applied the gained knowledge and dialogues with other disciplines from previous projects. It is considered a small laboratory and a thought-invoking element to make us think about the value of water and its infinite possibilities of use, using the example of the cultivation of photosynthetic organisms. The project addresses creation and maintenance of an apparatus that can be operated easily by non-professionals. The support frame is designed as a one-piece stainless-steel construction and visually complements the series of closed systems from the Exchange Instruments project. On the contrary, it offers a solution with simplified technology and intuitive operation in comparison to previous projects.

Ten litres of microalgae culture are continuously lifted by an air pump in the glass container. The installation and deinstallation of the system is simple and can be performed in 10 minutes by dismantling the stainless steel “U” pipe from the rest of the steel structure. At the bottom of the stainless-steel tubular container there is a "technology control box" for the air pump or other necessary parts, such as the light source, tubing, wiring and electronics. The design of the support frame with the integrated technology control box aimed for simplicity and an intuitive setup, allowing an easy installation, maintenance, and operation.

The installation included an airlift system for the microalgae culture. An air pump continuously lifted a ten-litre culture of microalgae, ensuring an efficient flow and exchange of nutrients and gases.

Fig. 16. Cultivated Environment, Maker Faire - detail, Prague, Czech Republic. (Source: Vulca NGO, 2022; photo: Alex Rousslet, 2022)

This setup enables easier testing of other types of microalgae and has the ambition to test various types of PBRs for potential biomass production. The project built on previous dialogues and knowledge acquired from other disciplines and projects. Insights and experiences gained from previous installations and research were leveraged to inform the design and development of Cultivated Environments. Building on the concept of simplicity and accessibility, the Cultivated Environment project drew inspiration from the widely popular and DIY-friendly airlift systems used in microalgae cultivation. These systems offer an inclusive approach, allowing individuals of various backgrounds and expertise to engage with technology. By utilizing essential components such as an air pump and, if necessary, additional extensions for aeration or added artificial light, these units can be easily operated by anyone interested in experimenting with microalgae cultivation. The apparatus provided a platform for experimentation and innovation in photobioreactor systems. By employing these methods, the Cultivated Environments project successfully integrated microalgae biotechnologies into architecture, emphasizing accessibility, user-friendliness, and the potential for future research and application.

DISCUSSION AND CONCLUSION

The practical work described in this article focuses primarily on technical, scientific and design aspects of microalgae biotechnology, while taking into consideration the educational aspect of the artefacts. Integrating biotechnological artefacts and systems, particularly research on microalgae, into future application scenarios requires an interdisciplinary approach that combines academic and applied research. This process is vital to fostering multidisciplinary collaboration between researchers from various fields, such as biotechnology, microbiology, architecture and design, engineering, sociology and environmental sciences. By exchanging information and approaching the topic from different points of view, researchers can develop innovative ideas and address potential challenges from multiple perspectives via collaboration.

The scalability of the projects is an important consideration; however, it is contingent upon the specific task and site for which the project is designed. For example, the Photosynthetic Landscape project was initially conceived as a modular and scalable system comprising multiple loops. Similarly, Biotopia demonstrates a continuously operated photobioreactor (PBR) system, with its technical aspect capable of scaling up. In contrast, the design aspect is subject to individual preference, allowing for variations in the size and geometry of the glass reservoirs and the "support structure," which can be 3D printed but is not mandatory. The authors recognized the significance of developing these projects in tandem to gain a comprehensive understanding of maintaining optimal conditions for living organisms while creating solutions that could be applicable outside of laboratory settings.

Similar to the Biotopia project, the Microflows project offers a range of design interpretations, providing the flexibility to scale up or down in terms of the total cultivated biomass. The design concept of Microflows, inspired by a fictional forest, utilizes PVC pipes suspended from a ceiling mesh. The installation consists of three main reservoirs, one containing the mother culture and the other circulating within the pipe loops. This adaptable design allows for variations in the size and number of reservoirs, enabling the project to accommodate different scales of cultivation. By incorporating this scalability, Microflows demonstrates the potential to adjust and adapt to various spatial contexts and desired biomass production levels while still maintaining its conceptual and aesthetic integrity.

The Exchange Instruments project is also designed to incorporate one or multiple units within the system. With its unique geometry, the spiral photo stage can absorb a significant amount of light. The main reservoirs connected to the spirals offer flexibility in size and quantity. It can be a single large vessel or multiple individual ones. This project draws inspiration from industrial tubular photobioreactors that typically operate on large quantities of biomass. However, incorporating glass elements assumes a dual role as both a design object and a light object. The Cultivated Environment project embraced this user-friendly philosophy to make the technology accessible to a broader audience.

By simplifying the design and operation of the system, the project emphasizes the democratization of microalgae cultivation. It encourages individuals, regardless of their technical proficiency, to explore and experiment with the technology, fostering a culture of curiosity and innovation. Therefore, the scalability of this project could be improved in terms of the total volume of cultivated biomass. However, it is possible to scale up in terms of knowledge distribution and public education on this topic. This project demonstrates that even with minimal equipment and resources, individuals can engage with microalgae cultivation and contribute to exploring its potential applications. By integrating the concept of simplicity and the DIY ethos, the Cultivated Environment project empowers individuals to become active participants in microalgae biotechnologies, further expanding the possibilities and impact of this emerging discipline.

Conducting a comprehensive literature review in all the topics is essential for using the microalgae research in future applications. This analysis will help to identify knowledge gaps, explore possible methods for further investigation, and develop novel approaches toward specific issues. In addition, investing in developing new biotechnological techniques for optimizing microalgae cultivation, and processing is crucial. For instance, researchers could focus on improving growth conditions, selecting high-yield strains, exploring new designs and materials, and employing engineering methods to enhance specific properties of microalgae.

The effects of climate transformation are not purely based on ecological factors. More than other fields, architecture is characterized by its ability to reshape the local and global environment and integrate scientific and technological knowledge into the surroundings in which we live. In this way, it is possible to transform the environment into a sustainability tool and see these implementations as a positive direction in improving the climate. Continuous education of the general public and dissemination of scientific and technological knowledge is vital for the various groups of our society, including the applied and private spheres. Through the example of the creation of individual small-scale biotechnological artefacts, functional prototypes, and site-specific installations, it is possible to gradually deepen this knowledge while testing new methods, in this case, of cultivating microalgae within different geometric or technological systems whose primary benefit is the active absorption of carbon dioxide from the air and the production of nutritionally rich biomass.

Although these systems are being developed for immediate application in the professional sphere and require further research, individual projects provide partial knowledge on the subject that can be a pathway to their implementation and cutting-edge research. A key point and a necessary aspect is the interdisciplinary approach and the intersection of various sectors. These collaborations are most effective when they take place locally, with opportunities for networking, joint research, and meetings. Still, cross-border cooperation and knowledge exchange on the problems being addressed is also necessary. The last essential aspect is a continuous and critical debate. By doing so, it is possible to connect – horizontally and vertically – various groups of our society, in the professional and other than professional spheres and, ultimately, in practical application.

Acknowledgements

This project was funded by the European Structural and Investment Funds (NERD grant programme, UMPRUM, 2022). We extend our gratitude to Prof. Imrich Vaško for his guidance and assistance in architectural research and prototyping, and to Klára Brůhová for her mentorship in the architectural theory.

References

Acién, F. G., Molina, E., Reis, A., Torzillo, G., Zittelli, G., Sepúlveda, J., Masojídek, J. (2017) 'Photobioreactors for the production of microalgae'. In: Gonzalez-Fernandez, C., Muñoz, R. (eds) 'Microalgae-based Biofuels and Bioproducts: From Feedstock Cultivation to End-products', Woodland Publishing, Cambridge, UK, pp. 1–44.

Araújo, R., Vázquez Calderón, F., Sánchez López. J., Azevedo, I. C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J. (2021) 'Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy'. Frontiers in Marine Science, Vol. 7. https://www.doi.org/10.3389/fmars.2020.626389

Arup (2013) 'Worldwide first façade system to cultivate micro-algae to generate heat and biomass as renewable energy sources', SolarLeaf, Hamburg, Germany. [online] Available at: https://www.arup.com/projects/solar-leaf

Christenson, L., Sims, R. (2011) 'Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts'. Biotechnology Advances, 29(6), pp. 686-702. https://www.doi.org/10.1016/j.biotechadv.2011.05.015

Davis, H., Turpin, E. (2014): 'Art in the Anthropocene: Encounters Among Aesthetics, Politics, Environments and Epistemologies', Open Humanities Press, London, UK.

European Environmental Agency (2019) 'Soil, Land and the Climate Change'. [online] Available at: https://www.eea.europa.eu/signals/signals-2019-content-list/articles/soil-land-and-climate-change [30 Sep 2019, Modified: 11 May 2021]

Eurostat Statistics Explained (2023) 'Quarterly greenhouse gas emissions in the EU'. [online] Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU [Modified: Feb 2023]

Ezbahn, M. (2019) 'Catalythic Polycultures in Aquaculture Landscapes: Fish Farms and the Public Realm', pp. 26–31. Routledge, Abington, UK. [online] Available at: http://kongkic2.sg-host.com/wp-content/uploads/2020/08/1-TChung-Floating-Fields-Catalytic-Polycultures-Aquaculture-Landscapes.pdf

Fabris, M., Abbriano Raffaela, M., Pernice, M., Sutherland, D. L., Commault, A. S., Hall, C. H. C., Labeeuw, L., McCauley, J. I., Kuzhiuparambil, U., Ray, P., Kahlke, T., Ralph, P. J. (2020) 'Emerging Technologies in Algal Biotechnology: Toward the Establishment of a Sustainable, Algae-Based Bioeconomy', Frontiers in Plant Science, Vol. 11. https://doi.org/10.3389/fpls.2020.00279

Haraway, D. (2016) 'Staying with the Trouble: Making Kin in the Chthulucene', Duke University Press, Durham, USA. https://doi.org/10.1215/9780822373780

ITB (2022) 'Zelený Wallenrod je odteraz ešte zelenší' (Green Wallenrod is now even greener). [online] Available at: https://www.itb.sk/zi-s-itb/zeleny-wallenrod-je-odteraz-este-zelensi (in Slovak)

Karyono, T. (2015) 'Architecture and Technology: The impact of modern technology on global warming', International Conference on Technology and Local wisdom, University of Sains Al Quran Wonosobo, Indonesia. [online] Available at: https://www.researchgate.net/publication/280711716_Architecture_and_Technology_The_impact_of_modern_technology_on_global_warming

Koller, M. (2015) 'Design of Closed Photobioreactors for Algal Cultivation'. In: Prokop, A., Bajpai, R., Zappi, M. (eds.), 'Algal Biorefineries', Springer, Cham, Switzerland, pp. 133-186. https://doi.org/10.1007/978-3-319-20200-6_4

Leong, Y. K., Chang, J. S., Lee, D. J. (2023) 'Chapter 3 - Types of photobioreactors'. In: Sirohi, R., Pandey, A., Sim, S., Chang, J. S., Lee, D. J., 'Photobioreactors: Design and Applications', Current Developments in Biotechnology and Bioengineering; Photobioreactors : Design and Applications, pp. 33–58. https://doi.org/10.1016/B978-0-323-99911-3.00007-5

Loke Show, P. (2022) 'Global market and economic analysis of microalgae technology: Status and perspectives', Bioresource Technology, Vol. 357. https://doi.org/10.1016/j.biortech.2022.127329

Lowenfels, J., Lewis, W. (2010) 'Teaming with Microbes: The Organic Gardener's Guide to the Soil Food Web', Timber Press, Portland, USA, p. 13.

Narala, R. R., Garg, S., Sharma, K. K., Thomas-Hall, S. R., Deme, M., Li Y., Schenk, P. M. (2016) 'Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System', Frontiers in Energy Research, Vol. 4. https://www.doi.org/10.3389/fenrg.2016.00029

Peruccio, P. P., Vrenna, M. (2019) 'Design and microalgae: Sustainable systems for cities'. AGATHÓN – International Journal of Architecture, Art and Design, 6, pp. 218-227. https://www.doi.org/10.19229/2464-9309/6212019

Pišteková, D., Tholt, T. (2022) 'Biotopia už nie je len utópia' (Biotopia is no longer just a utopia), ARCH, (27)3, p. 96. [online] Available at: https://sebolichy.sk/wp-content/uploads/2022/10/ARCH-03.22-BIOTOPIA.pdf (in Slovak)

Raupach, M., Davis, S., Peters, G., Andrew, R. M., Canadell, J .G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D. P., Le Quéré, C. (2014) 'Sharing a quota on cumulative carbon emissions', Nature Climate Change, 4, pp. 873–879. https://doi.org/10.1038/nclimate2384

Santos, L., Mendes, A., Mendes, J. (2020) 'Algae in building façades - A review on the potential of microalgae incorporation in building envelopes', Renewable and Sustainable Energy Reviews, 120. https://www.doi./10.1016/j.rser.2019.109671

Singh, U. B., Ahluwalia, A. (2013) 'Microalgae: A promising tool for carbon sequestration', Mitigation and Adaptation Strategies for Global Change, 18, pp. 73-95. https://doi.org/10.1007/s11027-012-9393-3

Tsing, A. L. (2015) 'The mushroom at the end of the world', Princeton University Press, Princeton, USA.

Wijffels, R. H., Barbosa, M. J. (2010) 'An outlook on microalgal biofuels', Science, Vol. 329(5993), pp. 796-799. https://www.doi.org/10.1126/science.1189003