ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Bioregenerative algal architectures

Ramandeep Shergill*

Department of Bio-Integrated Design, Faculty of the Built Environment, The Bartlett School of Architecture, University College London, London, United Kingdom

(This article belongs to the *Special Issue: Regenerative Architecture*)

Abstract

Contemporary biospheres will be needed in terms of life support in the face of climatic consequences of the Anthropocene and to sustain future space travel. For life to flourish on Earth and beyond, key elements are required — including carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorous — which need to regenerate through physiochemical alliances and symbioses with other life forms. Bioregenerative systems are defined as artificial ecosystems, which are made up of intra-relationalities with various species including higher plants, microorganisms, and animals. In this paper, bioregenerative architectural habitats are considered a solution for a planet that faces substantial ecological damage and for the likelihood of multiplanetary inhabitation in future. Mutually beneficial systems incorporating working with microalgae in conjunction with bioreactor technologies could constitute a means of survival on a damaged planet or to help start multiplanetary colonies. This paper illustrates the potential of a non-anthropocentric, bioregenerative life support strategy working with various microalgae species. Past- and present-related bioregenerative systems are reviewed and future applications of microalgae enhancing a *sympoietic* alignment (collectively producing systems) of the human and nonhuman with microorganisms are considered. Future alliances with microalgae, *Chlorella vulgaris,* are proposed to work within bioregenerative systems on Earth and in space. This paper clarifies how the combination of technology, speculative architectural design and microalgae can enhance carbon dioxide mitigation, furthering gaseous exchange for life support, enabling human and nonhuman species to flourish in harsher environments on Earth and beyond low Earth orbit.

Keywords: Microalgae; Ecological impact; Photobioreactor; Carbon dioxide mitigation; Sympoiesis; Biological *in situ* resource utilization

1. Introduction

The human body is intrinsically connected to the biosphere it is surrounded by (Margulis, 2008; Haraway, 2016). On Earth, the biosphere is made up of intra-relationalities and relies on the connectivity of *sympoietic* systems. Natural systems on Earth consist of crucial relationships with plants, animals, and gaseous exchanges, which actively co-exist in planet Earth's overarching biosphere. Without the inherent connected make-up of the ecological system, the human and nonhuman would find it difficult to function. Gaseous exchange — in terms of carbon dioxide and oxygen between plant and animal species — is conducive to the flow of life. Respiration and photosynthesis are essential

***Corresponding author:**
Ramandeep Shergill
(ramandeep.shergill.19@ucl.ac.uk)

Citation: Shergill, R. (2023). Bioregenerative algal architectures. *Journal of Chinese Architecture and Urbanism*, 5(3):179.
https://doi.org/10.36922/jcau.179

Received: March 14, 2023

Accepted: August 16, 2023

for life systems to exist (Nelson, 2011). Radical imbalances within ecological systems force the Earth's biosphere to fail (Schramski *et al.* 2015; Bostrom & Ćirković, 2020). As we approach anthropogenic scenarios due to these radical changes, the human and nonhuman will need to adapt to each scenario it is placed in (Figure 1).

A possible solution to the anthropogenic changes in Earth's ecological environment is the construction of contemporary biogenic architectures which can benefit Earth's damaged atmosphere. Mini biospheres embedded into buildings and urban environments can enhance breathability when there is a lack of air. The human species has been able to adapt to highly extreme environments and conditions (Fong, 2013). However, when there is a point of no return (Bostrom, 2019), novel interventions through design, engineering and architecture must be innovated. Radical changes in temperature and lack of oxygen, nitrogen and other gases will require a contemporary miniature "spaceship earth" mindset. In the very near future, it will be pertinent to conceptualize novel regenerative architectures within and surrounding urban environments. These architectures can respond to the potential impact of future dystopian scenarios arising from climate change. Once realized, different types of bioregenerative architecture will need to be effectively managed through science and technology.

Philosopher Peter Sloterdijik asserts, "The construction of shells for life creates a series of uterus repetitions in outdoor milieus" (Sloterdijik, 2009). In this paper a continuum is suggested between the human body and an extended "microbiome" that is supported via a bioregenerative apparatus. The building and its bioregenerative parts can work in different forms of *sympoiesis*, growing together for a mutualistic furtherance of life, providing new ways for respiration through photobioreactors embedded into its structure. The anatomy of a building can be compared to the human *holobiont.* Disparate parts work in unison *becoming* a unique ecological unit. This analogy of the building as a body is comprised of an assemblage of species, containing a host of *bionts* incorporated as unique engineered architectures within. Bioregenerative photobioreactor systems work and evolve in a continuum of complex integrations within the building's interior and exterior walls.

Figure 1. Speculative design of body in extreme environment, the system can be furthered as a living system with bio-integrated design. Source: Creative Direction and photography, Ram Shergill, Robotic Sea Urchin by Jack Irving, Art direction by Daen Palma Huse

This paper first defines the field of bioastronautics in relation to bioregenerative algal architectures; second it discusses current bioregenerative systems; third it evaluates what species of microalgae can be worked with in bioregenerative systems. In this paper, I suggest that bioregenerative algal systems are defined as artificial ecosystems which comprise of sympoietic relationships with microalgae through architecturally designed photobioreactor systems. Bioregenerative photobioreactor (PBR) microalgal systems consist of microalgae and through a process of photosynthetic gaseous exchange they capture carbon dioxide to produce oxygen. Furthermore, these engineered devices can purify water and, in the long term, can create food from biomass. Once processed, harvested biomass can be used to create biofuel to produce energy.

Feminist and postmodern theorist Donna Haraway highlights that "*Sympoiesis* is a simple word; it means "making-with." Nothing makes itself; nothing is really autopoietic or self-organizing" (Haraway, 2016). Haraway, following Margulis (2008) and Gilbert *et al.* (2012), asserts that all living organisms are inter-relational and harmoniously coexist by assimilating and linking with "other" cells, becoming ecological assemblages. Equally, I assert that the future is reliant on a *critical posthuman practice,* where the human and nonhuman conjoin for mutually beneficial scenarios. In terms of my concept, the adjective "critical" has two relative definitions: first, re-negotiating anthropocentric thinking critically challenges the notion of the posthuman; second, it describes a condition in which a "critical practice" is developed through ecologically aligned praxis pertaining to human and nonhuman survival. Fundamentally, a future is speculated in which life cycles may have their foundations based on physiochemical alliances with nonhuman organisms.

The significance of endosymbiotic theory was proven by Lynn Margulis in 1967 and incorporated into the fabric of evolutionary thinking (Martin, 2017). Research in terms of symbioses and oxygenation of Earth's atmosphere is being continuously advanced (Lenton *et al.*, 2016; Yao *et al.*, 2019). While there are various questions arising from which type of evolutionary theory is correct, this paper's main objective is primarily to discuss the benefits of bioregenerative algal architectures and not to authenticate any type of evolutionary process or theory. Therefore, it is important to consider that bioregenerative algal architectures rely on an integrated altruistic alliance with microalgae species. Posthuman theorizer Rosi Braidotti affirms that the body is not a singular species but is composed of a plethora of "other bodies" and becomes a "transversal force that cuts across and reconnects previously segregated species, categories and domains" (Braidotti, 2013). Bioregenerative systems in harsh environments, whether on Earth or in space, require new alliances with segregated and multispecies entities. It is fundamental to look at space scenarios reflexively to see how innovated systems can benefit a damaged Earth.

2. Earth and space

To produce bioregenerative systems for future scenarios, a multidisciplinary set of methods is required, incorporating a mix of science, architectural design, creative practice, and technology. Bioastronautics is the study of the biological, astronautical body in space flight scenarios (Young & Sutton, 2021), and investigates biological, medical, scientific, technological, and behavioral conditions of humans and other organisms in such conditions. Earth, space and multiplanetary atmospheres become inextricably linked — specifically when responding to environments the human and nonhuman body are not accustomed to or prepared for (Dominoni, 2020). Comparing one extreme environment to another can benefit each situation the body is placed in. An example of a worst-case scenario would be the Martian landscape, where there is a lack of atmosphere, high amounts of CO_2 and very low temperatures, amongst many other challenges in space (Mapstone *et al*, 2022; Verseux *et al.* 2016; Fahrion *et al.* 2021). Visualizing extreme environments and creating propositional responses to indeterminate situations through speculative design can be used as a method to see how design can be incorporated further with living systems (Figure 1). Biotechnology experiments carried out in space on the International Space Station enable a visualization and provide evidence of how microalgae in bioreactor systems react to harsher environments (Detrell *et al.* 2020b). Bioregenerative experiments are fundamental for assessing how life support systems can be adapted on Mars. They will be pertinent both for an unknown future on Earth and for the potential inhabitation of multiplanetary surfaces (Verseux *et al.*, 2022; Häder, 2020).

On Earth, or in space, the medical, biological, and behavioral aspects in the administration of human and nonhumans in a space flight environment are required for future scenarios. One of the objectives of bioastronautics is to improve possible futurist habitable systems beyond low Earth orbit. In space, there are many factors to consider in terms of successful plant growth, such as *gravitropism* and the workings of Closed Ecological Life Support Systems (CELSS). The CELSS is a system that uses physiochemical methods through the application of miniature enclosed ecosystems (Olson *et al.*, 1988). Algal space research has been considered fashionable since the 1960s (Hendrickx *et al.*, 2006). The model organism *Chlorella vulgaris*, widely used in research, has been one of the most responsive organisms for experiments in life support systems (Niederwieser, 2018). Extra Vehicular Engineer, Dr. Emily Matula, who is based at the NASA Johnson Space Center, contends that closed systems can be advanced on exponentially, stating that they have the potential to produce substantially more oxygen than pre-existing closed (smaller) systems export. Furthering economies of scale, a larger system incorporated into thermal loops of space craft have the potential to create large photobioreactor systems which have advantages in future scenarios.

Matula & Nabity (2019) hypothesizes the benefits in producing a large-scale ECLS (Environmental Control and Life Support) system;

> Algal photobioreactors have been researched as potential solutions to air revitalization in a spacecraft cabin environment by absorbing CO_2 and producing O_2 through photosynthesis. This photosynthesis and consumption of produced biomass, theoretically provides a closed-loop solution for long-duration spaceflight. Addressing multiple spaceflight requirements simultaneously with algae has the potential to reduce launch mass, power, and volume of future Environmental Control and Life Support (ECLSS) systems (Matula & Nabity, 2019).

Matula suggests that if an incorporated system of inoculating algal cultures were placed into water-based cooling loops[1] on a large scale in the International Space Station, the algae would "thrive" through a large photobioreactor system in the cooling loops of the craft. While this can be advantageous in many ways, it is important to realize that systems can have difficulties, such as biofilm formation and blockages to cooling systems.

---

[1] The International Space Station's cooling loops through the Active Thermal Control Systems (ATCS), which are the thermal control systems, allow fluids to pass through the system, using liquid ammonia to keep the solar panels at a controlled temperature. Through photovoltaic systems from the solar panels, the system proves to be successful, which is also used for electricity generation.

This, however, can be overcome with system overrides as well as manual and autonomous technologies, which enable a smooth flow of algal broth within a system.

Incorporating photosynthesis in such a system would explicate air revitalization as well as thermal control into a common system (Matula & Nabity, 2019). Matula goes on to suggest that more research is needed in terms of algal cultures responding to thermal and gravitational conditions in low Earth orbit relating to oxygenic production. The analysis, failures, and successes of the previous experiments with microalgae are used as aids to assess and innovate bioregenerative life support in photobioreactor systems, allowing Matula to evaluate feasibility factors of photobioreactor systems being used for future planetary inhabitation (Matula & Nabity, 2019). On Earth, finding solutions to carbon dioxide concentration, and for areas requiring air revitalization in dystopian environments, photobioreactor research is crucial, as it could potentially prove to be a mitigation method for planetary damage. Tobias Niederwieser, the Research Associate at BioServe Space technologies USA, asserts:

> Through new innovative designs, biology and engineering can exist in symbiosis that benefits both sides. In addition, while this technology development is tailored for spaceflight life support systems that might 1 day allow us to travel to and live on Mars and beyond, it might also help us to make life on Earth more sustainable by reducing the carbon dioxide concentration (Niederwieser, 2018).

Niederwieser's concluding statement for his doctoral thesis is significant for the future implications of life on Earth and for future life beyond low Earth orbit. Future advanced life support systems would be necessary for multiplanetary and interstellar travel (Volponi & Lasseur, 2020). Similarly, Zheng *et al.* (2008) assert that Bioregenerative Life Support Systems (BLSS) would radically improve living conditions in terms of working BLSS being placed on space stations, enabling potential inhabitation on the Moon and Mars, also furthering the uses in transport vehicles relating to Extra Vehicular Activity (EVA) on the lunar and Martian surfaces (Dempster *et al.*, 2004). It is crucial to reflect this back to Earth, as conditions on Earth are imminently changing and environments where you will not be able to breathe are becoming inevitably uninhabitable due to the harsh and radical changes in the environment. It is in this context that algal photobioreactor research can be seen as existentially fundamental.

3. Environmental immunology

The demise of the planet is predicted by many thinkers, scientists, and writers (Bostrom, 2019; Lewis & Maslin, 2018). However, detailed and rigorously researched the problems of the planet are, practical solutions relating to the source of the problems are rarely addressed. There needs to be an affirmative, radical, and catalytic response to the results of the huge amount of research that has been undertaken. Moreover, one might consider in this decade of the 2020s that there is an urgent need for a novel form of architecture, responding to the effects of disease, pollution, and anthropogenic atmospheres. A critical posthuman architectural solution will be necessary for human and nonhuman survival.

In the 1960s, design group Archigram's work was created at a time when architects were fascinated with the futurist aesthetics of the Moon Landing and the notion of astronauts in space. Archigram took these inspirations and merged them with their desire to make cities mobile. They looked at standardized minimum spaces, creating new and "futurist aesthetics," enabling mobility through design, and juxtaposed it with large-scale modernist architecture. The work they produced was experimental, neo-futurist and took inspiration from technological advances, imagining speculative worlds and scenarios through their collage design and pamphlets. The group experimented with consumerist imagery, modular machinery, mobility, and neo-futurist space capsules.

Archigram conceptualized modular systems for potential ways of living and was followed by the architectures emerging from the *Existenzminimum* concept (see The Capsule Hotel by Kisho Kurokawa in Tokyo, completed 1972). Archigram and their futuristic visions, designs, imaginings, and aesthetics set precedents for what could be imagined and achievable in terms of designing for Anthropocene and "bare life" type scenarios.

4. The Biospherians

There have been many experiments carried out over long durations of time related to bioregenerative systems and considered as failures. Biosphere 2 (1991) was a large-scale vivarium which covered an area of 3.14 acres of the American land, designed as a futurist pneumatic architecture. The reason for calling the project Biosphere 2 was that planet Earth itself is perceived as Biosphere 1. The biospheric architecture housed a "complete ecosystem" and set out to test the possibilities of how humankind could potentially survive for long durations in outer space. The biosphere was made up of seven types of biome areas, including a rainforest, ocean, coral reef, mangrove, wetlands, fog desert, and many other individual experimental habitats. The original crew had been inspired by the books *Silent Spring* (1962) by Rachel Carson and *Mount Analogue* (1952) by Rene Daumal, and *Operating*

Manual for Spaceship Earth (1967) by Buckminster Fuller, as well as *The Last Whole Earth Catalogue* (1968). The crew was also inspired by William S. Burroughs who thought that the countdown to ecological disaster had begun.

Whilst this high-budget enterprise was seen as a failure, it could be argued that the experiment did not altogether fail, for over a period of 2 years the crew of eight people survived in an enclosed ecosystem and successfully grew vegetables, fruits, and a host of other crops (Zimmer, 2019). Most of the data and records of the experiment mysteriously vanished, and the results from several of the experiments have never been published. This was due to takeovers by different companies who had commercial interests. There were many complex reasons proposed for Biosphere 2's failure, none of which have, to this date, been scientifically proven (Hüpkes & Dürbec, 2022). The fact the construction was made chiefly of concrete and was the project's main downfall, as the concrete contained calcium hydroxide. The carbon dioxide was not reacting with the soil within the biosphere and plants could not produce enough oxygen, the carbon dioxide was reacting with calcium hydroxide in the concrete, forming calcium carbonate and water (Cohen & Tilman, 1996; Marino and Odum, 1999). To move forward with potential bioregenerative systems, it must be realized that working with any living organism has its complexities in which mitigation of potential hazards must be taken into consideration.

5. Current bioregenerative systems

To understand what is needed on a damaged Earth, it is pertinent to look at bioregenerative systems that have been conceptualized for space. This gives us unique insights and allows us to consider and imagine how these technologies could be applied to Earth. In space, humans require the essentials in terms of "requirements of the body." Specifically, for survival, the body requires (per day) "1 kg of oxygen, 1 kg of food and 3 kg of water" (Anderson *et al.*, 2018). This is documented in the in-depth NASA study of The Baseline Life Support Values and Assumptions Document (BVAD). To travel and live on another planetary body, robust regenerative environments are needed which mirror biogeochemical cycles on Earth (Young & Sutton, 2021). It is feasible that for long-haul space travel or for successful inhabitation in harsher environments, human essentials (food, packaging, and waste management) required for existence are not sustainable unless regenerative systems are put into place. We will now look at some related experiments and projects that can be seen as foundational for bioregenerative algal futures.

Rack-like unit for consistent on-orbit leafy crops availability was an analogous experiment based on Earth and used higher plants in extreme environments (Antarctica). The project was carried out on EDEN ISS, which was a ground demonstration of plant cultivation technologies for food production in space. The project encompassed unique ideas and methodologies in fertigation, which researched oxygen-producing systems for Earth and for interplanetary travel, experimenting with gravity as well as autonomous cultivation techniques.

Another notable experiment, Euglena and Combined Regenerative Organic-Food Production in Space (*Eu: CROPIS*), was a mini satellite from the German Aerospace Centre by Deutschen Zentrum für Luft- und Raumfahrt (DLR) program. Its purpose was to study plant life and food production for long manned space flights (Häder, 2020). The experiment worked with the photosynthetic microalga *Euglena gracilis,* which is considered to be an optimum organism for working with gravity and liquid for photosynthetic growth (Häder, 2020). The species uses light (photoaxis) and gravity (gravitaxis) to maneuver in its environment (Häder & Hemmersbach, 2017; Häder *et al.*, 2017). The organism was put on a rotating satellite, which mimics the axial rotation of the gravity levels on the Moon and Mars. Both experiments (one to replicate lunar atmosphere and one replicating a Martian atmosphere) lasted for 6 months (Schulze *et al.*, 2016). The objective was to produce biomass out of urine to fertilize crops, indicating a possible bioregenerative system. Due to software upgrade issues on the satellite; this experiment could not fulfill its objectives. The section of the vessel, which was to propagate six tomato seeds, including "two greenhouses hosting a symbiotic community of bacteria, single-celled microalgae *(Euglena)* and synthetic urine as a fertilizer" (Shulze *et al.*, 2016), remained dormant. Biologist Jens Hauslage, who was the principal investigator of the experiment and is based at the Institute of Aerospace Medicine, asserts that "in principle the experiment works, and it is functional. Through our work on *Eu: Cropis* we have developed a long-term test bed for biological research in space" (Hauslage, 2018). The importance of this experiment portrays that a bioregenerative system could be feasible to house a system holding bacteria, rejuvenating human liquid waste via microalgae leading to growth of higher plants (tomatoes) on a satellite. In principle, if it were not for the software upgrade issue, this experiment could indicate that future possibilities through life regeneration systems are possible in harsh gravitational and environmental conditions. *E. gracilis* produces oxygen and biomass to protect the whole system against ammonia concentrations (Hauslage, 2018). Artificial light (LED) is used in combination with a pressure tank to mimic the atmosphere on Earth, a type of "regolith" is applied through inoculation of soil onto lava rock, allowing various microbial organisms to *bioleach* into porous rock, creating a new habitat for "cosmic tomatoes" to grow symbiotically with urine. In *Eu: CROPIS*, *E. gracilis* is part of a system, as it provides the Combined Regenerative Organic-food Production (C.R.O.P.®) filter with oxygen allowing urine to convert to nitrate, aiding tomatoes in the experiment to gain sufficient oxygen to photosynthesize. Specifically, *E. gracilis* acts as an aid to oxygen production where it is part of a larger experiment, for an investigation into hybrid combined biological life support systems.

Urine processing and water recycling systems are an integral part of any BLSS, as systems should incorporate circular closed loop or partially closed loop systems to produce food, water, and oxygen from what is considered as human and nonhuman "waste" (Verbeelen *et al.*, 2021). More research is needed for furthering methods pertaining to the nitrification of urine via ureolysis. Bioregenerative systems for multiplanetary surfaces would benefit from research incorporating "closed loop" human and nonhuman waste management systems combined with finding innovative ways of biological in-situ resource utilization BISRU.

5.1. Micro Ecological Life Support System Alternative program (MELiSSA)

Photobioreactor systems are placed within the European Space Agency's MELiSSA to create a circular regenerative system. The system replicates a mountain lake ecosystem (Volponi & Lasseur, 2020; Häder, 2020) and creates a circular bioregenerative system for manned space flights — recycling everything to form a mini ecosystem. First, a liquefying stage uses bacteria to rejuvenate human waste into ammonium, carbon dioxide, fatty acids, and minerals (Volponi & Lasseur, 2020; Häder, 2020). The degradation is processed through proteolysis, saccharolysis, and cellulolysis. The second stage is the "photoheterotrophic" phase and uses bacteria *Rhodospirillum rubrum,* discarding and destroying undesired products of the liquefying stage such as fatty acids and other unwanted degraded products.

In the third phase, bacteria are used for nitrification — combining urine and "good outputs" from the first and second stages. The chemolithoautotroph *Nitrosomonas europaea* is used to oxidize ammonium NH_4^+ into nitrite ions NO_2^-. Furthermore, bacteria *Nitrobacter winogradskyi* is used to oxidize nitrite into nitrate NO_3^-, creating a form of nitrate, which is used by higher plants and microalgae (Hendrickx *et al.* 2006).

In the MELiSSA loop (Figures 2 and 3), forms of bacteria work together in symbiogenesis. Nitrogen fixing is established, enabling microalgae and higher plants to grow. The nitrification stage of MELiSSA requires oxygen to be a necessary factor in the workings of the process. The photoautotrophic phase splits into two parts for the next stage — first the "algae stage" and then a "higher plants" stage. A photobioreactor is used to house spirulina (Hendrickx *et al.*, 2006), which is also known as *Limnospira indica* (Poughon *et al.*, 2020). This can be used as a source of food protein for the crew/inhabitants. Through the photobioreactor, spirulina is formed through photosynthesis and turns into an edible mass — it produces oxygen as well as a nonedible biomass (which would need to be processed before it is eaten) and is then furthered

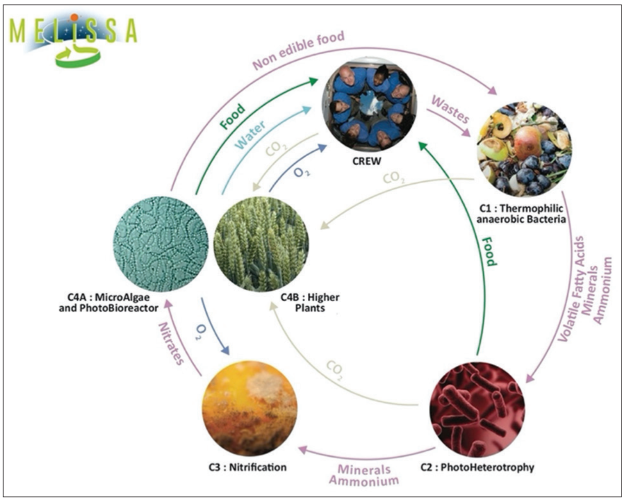

Figure 2. A schematic representation of the Micro Ecological Life Support System Alternative program (MELiSSA) loop, with the five compartments and their relations highlighted. Source: Courtesy of the MELiSSA Foundation

Figure 3. Micro Ecological Life Support System Alternative program (MELiSSA) proposes regenerative life support technologies to produce food, recovery of water, and atmosphere regeneration, together with waste reclamation. Source: MELiSSA Foundation

through the cyclical loop, moving to stage one and being processed (Figure 3). MELiSSA becomes a closed loop bioregenerative system, which could regenerate life in remote conditions. The MELiSSA core goals are the "production of food, recovery of water and regeneration of the atmosphere, with a concomitant use of wastes, that is, CO_2 and organic wastes, using light as a source of energy" (MELiSSA Foundation, 2020). MELiSSA is part of the European Project of Circular Life Support Systems, which is continuously researching into current and future ways of regenerative life support systems for long-term space missions.

5.2. MarsOASIS

MarsOasis is a concept originating from the University of Colorado, Boulder, researching ways of utilizing *in situ* resources for crop production in the Martian atmosphere (Darnell *et al.,* 2015). The objective is to plant crops in preparation for human consumption on the Martian surface. Sunlight and ultraviolet rays are used in a greenhouse-type architecture. In a crop production experiment, Outredgeous lettuce grew autonomously. The motivation came from NASA's VEGGIE food production system, which is a way to provide fresh food in an enclosed system to astronauts on the International Space Station. A prototype lunar greenhouse was made by the University of Arizona, with an architecture that has collapsible and expandable bellows. The technology inside maintains humidity, power for LED lighting, and root mats which provide nutrients to the plants (Darnell *et al.*, 2015) The system becomes a space greenhouse allowing for life to thrive (Furfaro *et al.*, 2016).

Any project aiming to allow for human life to thrive on the Martian surface is ambitious, as the challenges of harsh environments include (and are not limited to) reduced gravity, intermittent inhospitable surface temperatures, low atmospheric pressure, absence of a magnetic field, radiation, and wind-induced dust storms. However, Mars and several exoplanets do have some positive conditions that can benefit the harvesting and growing of crops. The MarsOASIS team visualized a system using *in situ* CO_2 and Martian sunlight. Simulation was provided by AcroOptics, allowing the team to simulate Martian sunlight for their experiments. In any space environment, there are many obstacles that must be overcome. Unfortunately, the PBR$^{@}$ LSR algae-based photobioreactor experiment on the International Space Station (2019) was functional for only 2 weeks. The premise of the experiment was to assess the feasibility of axenic cultivation of *C. vulgaris* for long periods of time (over 180 days) under microgravity conditions in space through a hybridized life support system (Helisch *et al.,* 2020). The power source to the engineered PBR@LSR failed after 15 days (Detrell *et al.*, 2020a). Resilient design and contingency planning are fundamental for working with complex bio-integrated systems. The MarsOASIS system becomes a precursor for Earth, as it has benefits in understanding what is required in terms of contingency planning, designing, and how researching Mars as a twin allows us to see how Earth architectures can benefit from resilient bioregenerative structures. MarsOasis is being further developed with various projects situated in the Bioastronautics Department at The University of Colorado, Boulder, USA.

6. Back to Earth

Leading on from Archigram's futuristic premonition of the 1960s, there have been many projects that take into consideration algal design in terms of architecture. While there are concepts in adopting algae façades (Elrayies, 2018; Talaei *et al.*, 2020; Warren *et al.*, 2023), to date there has not been an implicit type of bioregenerative architecture that has been conceptualized. Previously, living façades have been at the cutting edge of urban architectures (Armstrong, 2016). Algae building technology (ABT) was used in the BIQ house in Hamburg (2013) and led by a team of engineers, architects from ARUP, and the Strategic Science Consulate of Germany for an International Building Exhibition. The building consisted of 200 m^2 PBRs (Wilkinson, 2018). A bioreactor façade was built, with the maximum temperature in the algal broth controlled at up to 40°C (Wilkinson *et al.,* 2017). Building algal-based façades for architectural applications has become increasingly "in vogue" and was perceived to be similar to the way, in which biophilic green buildings were previously imagined.

The key difference is that algal façades do not encompass closed loop systems incorporating life support, food, waste, water, biofuel, and energy, which are portrayed in a true bioregenerative system, such as the MELiSSA closed loop system. Bioregenerative algal architecture would encompass metabolic cycles, improving oxygenation of an environment whilst addressing nitrogen, phosphorous, and carbon dioxide regeneration. When humans or animals produce urine, the urine should not be considered a waste product as it contains essential nitrogen and phosphorus supplies, which could be used for fertilization in plants, as nitrogen is formed in ammonia (Hogle *et al.*, 2023). A unique autonomous system has been developed by the Living Architecture project, which is a modular selectively programmable bioreactor system wall and operates through the application of microbial fuel cells (Figures 4-6).

Wastewater and air are used to generate oxygen and proteins creating a micro-agriculture, using methods of

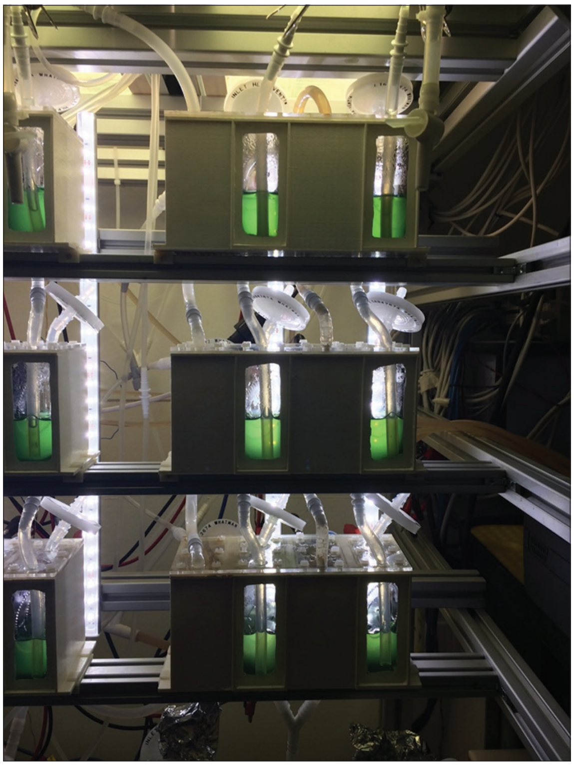

Figure 4. Living Architecture "wall" series of bioreactor. Source: Photograph courtesy of the Living Architecture project, 2019

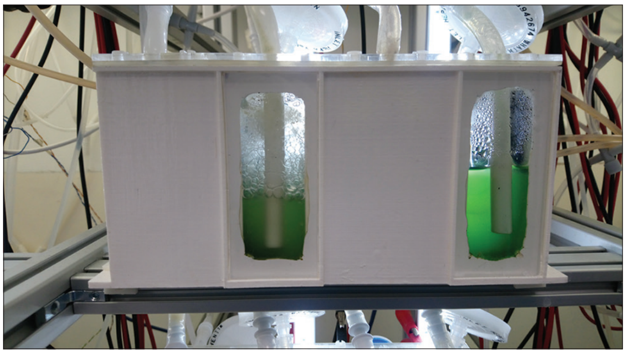

Figure 5. "Wall detail" in the Living Architecture bioreactor installation. Source: Photograph courtesy of the Living Architecture project, 2019

bioremediation, biophotovoltaics, and bioregenerative implementation in the design. Biophotovoltaics incorporate clean power generation and uses self-renewing organism-mediated photosynthesis to capture solar power for generating electric currents (Zhu *et al.*, 2023).

Wastewater and organic waste are passed through a series of three bioreactors to produce clean water, electricity, biomass, and phosphate as well as other by-products. The concept of the project was to find a way to create pertinent resources from household waste utilizing the work of microbes. The living architecture system has the potential of being integrated into the walls of high-rise buildings and architectures in which biological processes use waste urine to provide multiple functions for a building. Modular bioreactor units are used (microbial fuel cells, synthetic microbial consortia, and photobioreactor) which integrate into one hybrid system (Hogle *et al.*, 2023). Prototypes created are stackable horizontally and vertically — this has positive implications when constructing buildings as the algal bioreactors can be embedded into walls. Outputs include polished water, fertilizer, and recoverable biomass (Hogle *et al.*, 2023). Algae are embedded and provide oxygen through a system of biophotovoltaics, thereby creating a microbial fuel cell. The living architecture system prototype speculates a partially closed loop system, which has the potential of producing oxygen and biomass, and regenerating liquids and waste, and becomes a multifunctional architecture in the elucidation of a mini ecosystem (Figure 6).

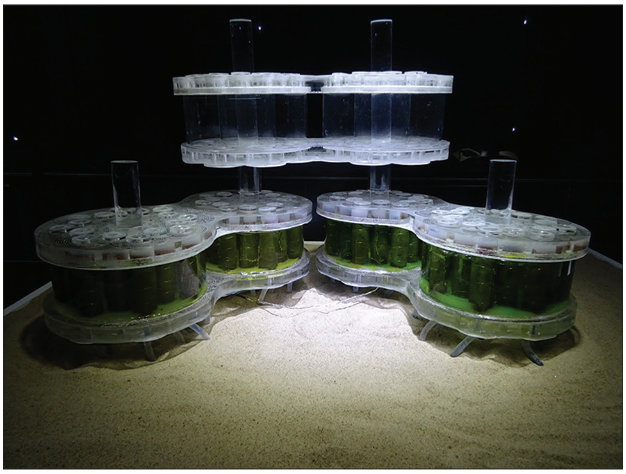

Figure 6. Complex combined "brick" structure with rod-based assembly system that co-houses photosynthetic and anaerobic populations of microbes. The photo shows the prototype by Simone Ferracina for the Living Architecture project. Source: Photography courtesy of the Living Architecture project, 2017

Systems such as Living Architecture are pertinent for counteracting future instability and for survival. Bioregenerative algal architectures would specifically consider contemporary dynamic cities, where the building adapts to the environment and becomes an extension in which the human works *sympoietically* with the nonhuman (microalgae) for the furtherance of life. Architecture designed through artistic and speculative means allows for the visualization of habitats, which can exist in extreme environments.

7. Speculative bioregenerative algal design

Working with architectural PBR systems and designing physiochemically with life has its obstacles. However, if a unique bioregenerative algal architecture was innovated with a resilient species in mind, or a multiple species that could be *worked with* in harsher environments — such as extremophiles or diatoms — the advantages of such a system would be numerous. The need to revitalize the air that we breathe is intensifying. Having unique systems embedded into architectures would benefit air revitalization and much more.

A bioregenerative mask system was created and displayed at The Museum of Contemporary Art (MOCA) (Figures 7 and 8; Shergill, 2022). The mask system is an iteration in speculative design, projecting how contemporary bioreactor systems can work together as a modular set of devices. The Bioregenerative Mask System works cohesively as an intra-connected contemporary gaseous exchange system for potential use on multiplanetary surfaces. The system incorporates addressing issues, such as not being able to breathe pure clean air efficiently, carbon dioxide management, conducive gaseous exchange, and protection against pathogens. The elucidation of the mask system is the starting point in the birth of a "Critical Posthuman Practice" (Shergill, 2022) — this praxeology was clarified at The Museum of Contemporary Art, London in 2022.

Figure 7. *Bioregenerative Algal Mask System*. The photo shows the mask created by Ram Shergill. Source: Photo by Ram Shergill, The Museum of Contemporary Art (MOCA), 2022

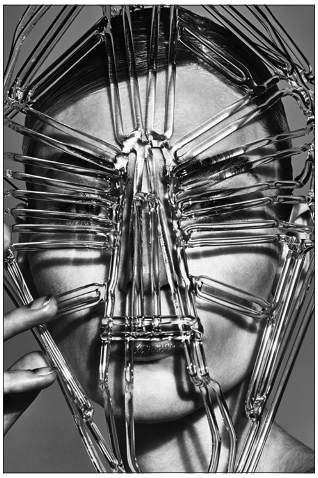

Figure 8. *The Birth of a Critical Posthuman Practice*, Borosilicate Glass Mask. Source: Ram Shergill, MOCA Gallery, 2022

The critical posthuman can be defined as a *being* of multiple becomings, transformations, and intra-connections with the nonhuman — applying forms of *sympoietic* hybridization. Whilst the notion of the critical posthuman has risen from a critical theory perspective, I have embedded this theory and conceptualized a new form of *critical posthuman practice*, which is critically and ecologically aligned. In terms of my concept, the adjective "critical" has two relative definitions: first, it re-negotiates anthropocentric thinking and critically challenges the notion of the posthuman; second, it describes a condition in which a "critical practice" is developed through a type of ecotechnology to further human and nonhuman survival. Ecotechnology is defined as a branch of science that works with natural resources to cause minimum ecological disruption. Therefore, my definition of a *critical posthuman practice* is a twofold combination of ecologically focused design practice and theoretical underpinning, diffractively intertwined for the furtherance of life. Creative photobioreactor design allows for working with a variety of species, and therefore advantageous for many applications — whether on Earth, in space or for multiplanetary surfaces.

8. Species

Whilst species from the genus *Chlorella* are considered a model species for space applications (Niederwieser *et al.*, 2018), it is important to contemplate that there are many species that can be beneficial in bioregenerative architectures. There is not just one "ideal species" that benefits all locations — be it on Earth, the surface of Mars or the Moon. Each site will need a plethora of species which can aid the specific site — for example, the extremophile *chroococidiopsidales* can be stored desiccated for long durations. The species *Anabaena* and *Nostoc* with their harvest index may be good for bioleaching in industrial applications (Helisch *et al.*, 2018). In prior space-related research, microalgae *C. vulgaris* has shown great potential (Niederwieser *et al.*, 2018), and *Anabaena cylindrica* also has potential growth capabilities on Martian rocks (Mapstone *et al.*, 2022). Research, laboratory testing and *in situ* applications have shown that these species are optimum for various applications. Each species will need to be nurtured, and aligned with — in terms of nutrients, conditions and solar irradiation required for the species to survive.

It is important to be aware of the difference between microalgae and cyanobacteria in terms of what species could be beneficial for bioregenerative futures. Cyanobacteria were previously known as blue-green algae as large density in water would make the color of the water bluish or brownish green. However, cyanobacteria are technically bacteria. Microalgae are, in general, unicellular eukaryotic or prokaryotic plant-like organisms that possess a nucleus, chloroplasts and mitochondria, and can photosynthesize. Examples of microalgae are *Chlamydomonas* and *Chlorella*. Examples of cyanobacteria are Anabaena and Nostoc, which can fix nitrogen from the atmosphere into ammonia. In research for extreme environmental applications, there has been generic favorite species for space-related possibilities. However, more research is needed into which species will benefit each condition. A potential way to work with cyanobacteria in terms of nitrogen fixing on the surface of planets could be the use of novel photosynthetic biomineralized living tissues (Figure 9). This way living tissue can potentially photosynthesize by being embedded with cyanobacteria to produce oxygen, and at the same time fix atmospheric nitrogen. BioServe space technologies, DLR, MIT, and Saarland University are working in collaboration with NASA on a Space Biofilms project, and its primary objective is to characterize fungal and bacterial biofilm in space in a controlled way.

NASA and their team aim at assessing mechanisms that aid biofilm formation in space. Working with photosynthetic tissues, hydrogels and biofilms could alleviate relying on suspension-based microalgae in liquid forms. Supplying water to multiplanetary surfaces will be a gargantuan task as microgravity and mass transport of water must be considered. This transfer of liquids and water may prove to be unnecessary as systems could be developed to produce water on multiplanetary surfaces (Zubrin, 2023). To sustain life on a planet such as Mars from the outset, *in situ* resource utilization is required (Pazar, 2020). Working with immobilized photosynthetic biomaterials in regenerative structures could have many advantages for multiplanetary built environments. However, it is important to consider the use of correct bioregenerative PBR systems for each specific location and application. Liquid suspension can be used for creating oxygen through hybridized PBR systems efficiently, whereas biocomposites may be beneficial to be used on architectures and be an asset for building materials.

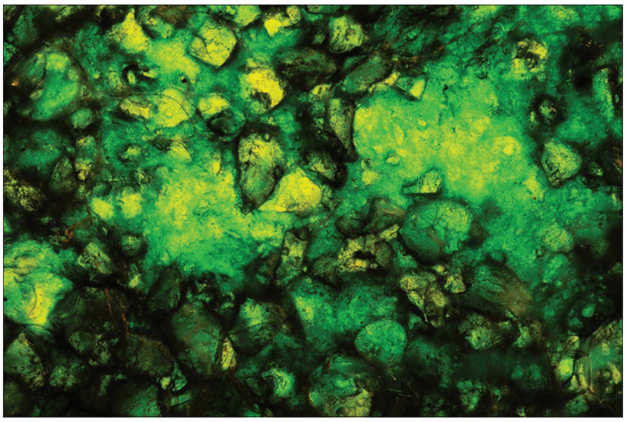

Figure 9. *Tectonic Conferviance*. Emergent texture of photosynthetic biomineralized living tissue formed by the growth of filamentous cynobacteria biofilm (*Oscillatoria animalis*) in hydrogel scaffold. This project was led by Prantar Tamuli, together with Brenda Parker, Anete Salmane, and Marcos Cruz. Source: Image by Ram Shergill (UCL)

The microalgae *C. vulgaris* is considered a resilient species and is an all-round resilient species for bioregenerative applications (Matula & Nabity, 2019; Detrell, 2021; Niederwieser *et al*., 2018; Fahrion *et al*., 2021). The portfolio of species is vast and there are many species of microalgae that require further research. In future research, it will be important to experiment with many species to understand the applications that each species can be of special benefit for, specifically which species would benefit in bioregenerative immobilized biocomposite building materials (Caldwell *et al*., 2021). Therefore, it is feasible that not only one species will benefit bioregenerative algal architecture, but that multiple species will be able to be used for differing applications in space or on Earth. It is not practical to rely on one species.

9. Microalgae: Promising organisms

Photoautotrophic growth with microalgae presents us with the following formula in which *C. vulgaris* conducts photosynthesis.

$$6\ CO_2 + 12\ H_2O + \Delta H_{hv} \rightarrow C_6H_{12}\ O_6 + 6\ H_2O + 6\ O_2$$

(Where $\Delta H h\nu = 2870\ kJ\ mol^{-1}$ glucose)

Photosynthesis of microalgae and cyanobacteria produces $O_{2,}$ as well as, in some cases, edible biomass from CO_2 and H_2O in Biomass Production Chamber (Helisch *et al*., 2018). The addition of microalgae and higher plants into a habitat enables breathability and allows humans to be enclosed for long periods. A resilient species of microalgae in a photobioreactor system can allow for breathability for the human in varying atmospheres. Evidence suggests that microalgae have a high harvest index (Hi>95%) with high light utilization (>10%) and do not require as much water as higher plants (Helisch *et al*., 2018). In photobioreactor systems, microalgae are cultivated in liquid medium (water enriched with the necessary nutrients), enabling long cultivation periods.

Photosynthetic organisms are ideal for absorbing human exhalations of CO_2 in an enclosed environment, as oxygen is produced from photosynthetic activity (Häder, 2020). The exchange rates of CO_2 and O_2 between the human and species are dependent on many factors; these factors can depend on size and body type of the human and how much CO_2 and O_2 the human body produces in an enclosed environment. It would be important to measure CO_2 exhalations from a species, because excessive production of CO2 by the species could be detrimental to a human in an enclosed environment. Any systems created would need to be rigorously managed. Many experiments have been carried out with the *C. vulgaris* strain (SAG 211-12) and research indicates that this strain is a promising candidate and can benefit from long-term cultivation (>180 days). Microalgae can be ideal companions to support humans for long durations if the correct systems and architectures are in place, as they possess the ability to recycle human waste, remove CO_2 and become a provider of O_2 through photosynthetic activity. Even though green algae have the potential to provide life support, it can also lead to certain digestive problems as side effects; however, forms and relational species including cyanobacteria could be digested without huge impact to humans (Escobar & Nabity, 2017). The chosen companion microalgae/cynobacteria species is crucial to the success of a BLSS — for example, MELiSSA has proven that cyanobacteria and microalgae have benefits in bioregenerative systems. This is because certain species, like spirulina, are multi-functional. Various iterations in cyanobacteria biofilms have been created at University College London's bio-integrated laboratory (Figure 9). Emergent photosynthetic living tissue in hydrogel scaffolds could take up CO_2 emissions and be a promising building material.

It is important to assess which species could prosper best in each location, as each species functioning within a designed system will have benefits for each environment it is placed in. On harsher parts of planetary surfaces, temperatures can reach extremely low levels. In these harsher environments, diatoms could be possible candidates to align with sympoietically. Diatoms have the ability to inhabit a great range of hostile environments on Earth. They can be found in polar regions, hot springs and geysers, hypersaline and hyperalkaline lakes and pools. Certain species (*Chaetoceras fragilis* and *Fragilaria sublinearis*) function in extreme low temperatures (Sterrenburg & Hoover, 2011). Diatom frustules can protect the organism through a type of exoskeleton (Figure 10). Having this extra layer of protection can enable the species to be resilient and adaptable to harsh and extreme conditions. The frustule can provide the necessary protection against adhesion, gliding, drying out and forming biofilms and colonies (De Tommasi *et al.*, 2017). In terms of new alignments with species, various species of microalgae can thrive in harsher climatic conditions — such as *Galdieria sulphuraria* and Prochlorococcus *(Hume et al., 2015)* — as well as in space, and these species can photosynthesize in lower/higher light conditions. Recent experiments such as ATMOS (an experiment that studies a species in a 96% N_2 and 4% CO_2 gas mixture with 100 hPa pressure) have shown that cyanobacteria *Anabaena* sp. is suitable for a cyanobacterium-based life support system (Verseux *et al.*, 2021).

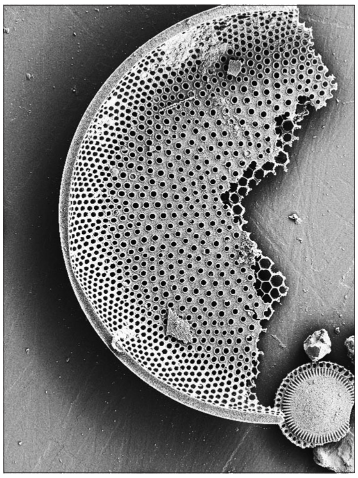

Figure 10. Diatom frustule of *Coscinodiscus*. Source: SEM image by Ram Shergill, Natural History Museum, 2022

The resilient single-cell organism *C. vulgaris* is a eukaryotic green algae species that has an average diameter of 6μm (Vander Wiel *et al.*, 2017). The species can adapt to a range of climatic conditions and pH temperatures; it is resilient to contamination (Lakaniemi *et al.*, 2012) and is competent when facing shear stress. The species was first discovered by the Dutch researcher Martinus Willem Beijerinck in 1890. Etymologically, the name comes from the Greek word "Chloros", with the Latin term "ella" elaborating on the organism's microscopic size (Safi *et al.*, 2014). In the growth of the cell as it reaches maturity, a chitosan or chitin type layer compound of glucosamine is formed (Weber *et al.*, 2022). Once maturity is reached, environmental conditions can change this rigidity, depending on where the species is placed (Němcová & Kalina, 2000). *C. vulgaris* reproduces asexually and at a fast continuous pace; in optimal conditions, it multiplies manifold through *autosporulation* forming daughter cells within its cytoplasm (Yamamoto *et al.*, 2005). These protoplasts divide into groups of 2, 4, and 8 until the mother cell is broken, thus leaving the *autosporangium*. Once this process occurs within 24 h, the daughter cells are set free. *Chlorella* can be seen as a multifunctional species that can be used on Earth for food production, vitamins, minerals, biofuel, bioremediation, wastewater treatment, human health, bioethanol and more. The benefits of working with *Chlorella* become manifold whether the organism is placed in liquid in a photobioreactor, or robotically extruded with hydrogels (Malik *et al.*, 2020).

Fundamentally, a species that can adapt to harsher climates will benefit bioregenerative systems. Algae has been used in many studies and show positive signs of being the optimum organisms to produce oxygen. On Earth, algae produce 50%–80%[2] of the world's oxygen through capturing carbon and creating oxygen by photosynthesis (Pennisi, 2017). Studying the organism in extreme bare-life conditions, allows us to gain insights into how microalgae revitalize air through PBR devices in differing environments. Oxygenic production and CO_2 sequestration needs to be evaluated. It is important to consider that oxygen is not the only primary gas that humans require, as a heady mix of nitrogen, oxygen, and trace gases allow the human and nonhuman to thrive in varying environments.

10. Conclusion

Bioregenerative systems are being implemented and speculated primarily for space applications and multiplanetary surfaces. A large number of possibilities are being considered, such as incorporating and hybridizing bioregenerative cyanobacteria systems with bioleaching on Mars (Verseux *et al.*, 2016), creating new breathability scenarios, extravehicular activities, and much more. While it is good to think of novel ways of interaction with multiple species and habitats on multiplanetary surfaces, it is especially necessary to visualize how bioregenerative algal architectures will enable adaptation to harsher environments. On Earth, there are many current and speculative projects incorporating algal walls and structures into the façades of buildings. However, it is important to consider that bioregenerative algal architecture encompasses structures that are multifunctional and "closed loop" or "partially closed loop systems".

When constructing a bioregenerative algal architecture, the algal species "aligned with" must be managed with care to ensure provision of nutrients. Exchange of resources and many factors need to be considered, as when "designing with life" things can go drastically wrong — such as lack of light, dust storms, power failures, and more. Mitigation measures and "contingency" plans are required in the case of an operational bioregenerative system failure.

Lack of breathability, power, recycling of liquids, urine processing, food, and lack of oxygen will facilitate the needs of projects, such as living architecture on earth (Hogle *et al.*, 2023) or MELiSSA in space. Newer hybrid technologies that mirror the bioregenerative life support systems in space are being speculated for use on Earth. The addition of Sabatier, Bosch and biohybrid engineered architectures embedded into the structures of the built environment on Earth can benefit the future of bioregenerative algal architecture. These types of systems could enable failure-proof methods in living in harsher anthropogenic environments or on multiplanetary surfaces. It is important to acknowledge that bioregenerative algal systems are complex and continuously evolving. Working with living organisms such as microalgae in environmentally fragile atmospheres on Earth, or for surviving in multiplanetary alien atmospheres, will require high levels of maintenance of bioregenerative systems. For efficient bioregenerative systems, it will be fundamental to carry out further research into failure-safe systems, which are hybridized and fully autonomous. In the future, bioregenerative algal architectures will enable physiochemical human and nonhuman "closed loop" life support systems — supporting the necessities of life and existence on multiplanetary surfaces.

Acknowledgments

Thank you to Professor Marcos Cruz (UCL), Dr. Brenda Parker (UCL), and Professor Saul Purton (UCL) for their academic guidance and support in the writing of this paper. Special thanks to Mark Garcia from the Bartlett School of Architecture (UCL).

Funding

None.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

---

[2] The National Ocean Service, U.S. Department of Commerce, state that 50 – 80% of the world's oxygen is produced by drifting plants, algae, plankton, and photosynthetic bacteria such as *Prochlorococcus* which produces 20% of the oxygen in the biosphere. Anthropocentric issues such as hypoxia create dead zones, where life in the oceans cannot thrive, including eradication of algae and any life systems; this is called *hypoxia* – dead zones.

References

Anderson, M.S., Ewert, M.K. & Keener, J.F. (2018). Life support baseline values and assumptions document (No. NASA/TP-2015-218570/REV1).

Armstrong, R. A., editor. (2016). *Star Ark: A Living, Self-sustaining Spaceship*. Germany: Springer.

Bostrom, N. (2019). The vulnerable world hypothesis. *Global Policy*, 10(4):455-476.

https://doi.org/10.1111/1758-5899.12718

Bostrom, N., & Ćirković, M. M., editors. (2020). *Global Catastrophic Risks.* Oxford: Oxford University Press.

Braidotti, R. (2013). Posthuman relational subjectivity and the politics of affirmation. In: *Relational Architectural Ecologies*. Milton Park: Routledge, p. 21-39.

Caldwell, G. S., In-na, P., Hart, R., Sharp, E., Stefanova, A., Pickersgill, M., *et al*. (2021). Immobilising microalgae and *Cyanobacteria* as biocomposites: New opportunities to intensify algae biotechnology and bioprocessing. *Energies*, 14(9):2566.

https://doi.org/10.3390/en14092566

Cohen, J. E., & Tilman, D. (1996). Biosphere 2 and biodiversity: The lessons so far. *Science*, 274(5290):1150-1151.

https://doi.org/10.1126/science.274.5290.1150

Darnell, A., Azad, A., Borlaug, B., Case, D., Chamberlain, C., Fortier, K., *et al.* (2015). MarsOASIS: A Predeployable Miniature Martian Greenhouse for Crop Production Research. In: *45th International Conference on Environmental Systems.*

De Tommasi, E., Gielis, J., & Rogato, A. (2017). Diatom frustule morphogenesis and function: A multidisciplinary survey. *Marine Genomics*, 35:1-18.

https://doi.org/10.1016/j.margen.2017.07.001

Dempster, W. F., & Allen, J. P. (2008). Integration of lessons from recent research for "Earth to Mars" life support systems. *Advances in Space Research*, 41(5):675-683.

https://doi.org/10.1016/j.asr.2007.02.075

Detrell, G. (2021). *Chlorella vulgaris* photobioreactor for oxygen and food production on a moon base-potential and challenges. *Frontiers in Astronomy and Space Sciences*, 8:124.

https://doi.org/10.3389/fspas.2021.700579

Detrell, G., Helisch, H., Keppler, J., Martin, J., Henn, N., Fasoulas, S., *et al.* (2020a). PBR@ LSR: The Algae-based Photobioreactor Experiment at the ISS-operations and Results. In: *2020 International Conference on Environmental Systems.*

Detrell, G., Keppler, J., Helisch, H., Martin, J., Henn, N., Ewald, R., *et al.* (2020b). PBR@ LSR: The Algae-based Photobioreactor Experiment at the ISS-operations and Results. In: *2020 International Conference on Environmental Systems.*

Dominoni, A. (2020). *Design of Supporting Systems for Life in Outer Space: A Design Perspective on Space Missions Near Earth and Beyond*. Germany: Springer Nature.

Elrayies, G. M. (2018). Microalgae: Prospects for greener future buildings. *Renewable and Sustainable Energy Reviews*, 81:1175-1191.

https://doi.org/10.1016/j.rser.2017.08.032

Escobar, C., & Nabity, J. (2017). Past, Present, and Future of Closed Human Life Support Ecosystems-a Review. In: *47th International Conference on Environmental Systems.*

Fahrion, J., Mastroleo, F., Dussap, C. G., & Leys, N. (2021). Use of photobioreactors in regenerative life support systems for human space exploration. *Frontiers in Microbiology*, 12:699525.

https://doi.org/10.3389/fmicb.2021.699525

Fong, K. (2013). *Extremes: Life, Death and the Limits of the Human Body*. France: Hachette UK.

Furfaro, R., Sadler, P., & Giacomelli, G. A. (2016). Mars-lunar Greenhouse (M-LGH) Prototype for Bioregenerative Life Support Systems in Future Planetary Outposts. In: *Proceedings of the International Astronautical Congress, IAC.* France: International Astronautical Federation, IAF.

Gilbert, S. F., Sapp, J., & Tauber, A. I. (2012). A symbiotic view of life: We have never been individuals. *The Quarterly Review of Biology*, 87(4):325-341.

https://doi.org/10.1086/668166

Häder, D. P. (2020). On the way to mars-flagellated algae in bioregenerative life support systems under microgravity conditions. *Frontiers in Plant Science*, 10:1621.

https://doi.org/10.3389/fpls.2019.01621

Häder, D. P., & Hemmersbach, R. (2017). Gravitaxis in *Euglena*. In: *Euglena*: *Biochemistry, Cell and Molecular Biology*. Cham: Springer, p. 237-266.

https://doi.org/10.1007/978-3-319-54910-1_11

Häder, D. P., Braun, M., Grimm, D., & Hemmersbach, R. (2017). Gravireceptors in eukaryotes-a comparison of case studies on the cellular level. *NPJ Microgravity*, 3(1):13.

https://doi.org/10.1038/s41526-017-0018-8.

Haraway, D. (2016). *Staying with the Trouble*. Durham: Duke University Press, p. 97.

Hauslage, J., Strauch, S. M., Eßmann, O., Haag, F. W. M., Richter, P., Krüger, J., *et al.* (2018). Eu: CROPIS-"*Euglena gracilis*: Combined regenerative organic-food production in space"-a space experiment testing biological life support systems under lunar and Martian gravity. *Microgravity Science and Technology*, 30:933-942.

https://doi.org/10.1007/s12217-018-9654-1

Helisch, H., Belz, S., Keppler, J., Detrell, G., Henn, N., Fasoulas, S., *et al.* (2018). Non-axenic Microalgae Cultivation in Space-challenges for the Membrane µgPBR of the ISS Experiment PBR@ LSR. In: *48th International Conference on Environmental Systems*.

Helisch, H., Keppler, J., Detrell, G., Belz, S., Ewald, R., Fasoulas, S., *et al.* (2020). High density long-term cultivation of *Chlorella vulgaris* SAG 211-12 in a novel microgravity-capable membrane raceway photobioreactor for future bioregenerative life support in SPACE. *Life Sciences in Space Research*, 24:91-107.

https://doi.org/10.1016/j.lssr.2019.08.001

Hendrickx, L., De Wever, H., Hermans, V., Mastroleo, F., Morin, N., Wilmotte, A., *et al.* (2006). Microbial ecology of the closed artificial ecosystem MELiSSA (Micro-ecological Life Support System Alternative): Reinventing and compartmentalizing the Earth's food and oxygen regeneration system for long-haul space exploration missions. *Research in Microbiology*, 157:77-86.

https://doi.org/10.1016/j.resmic.2005.06.014

Hogle, M., Imhof, B., Hoheneder, W., Armstrong, R., Ieropoulos, I., Wallis, L., *et al.* (2023). Living architecture: Metabolic applications for next-generation, selectively programmable bioreactors. In: *Urban and Regional Agriculture*. Cambridge: Academic Press, pp. 595-614.

Hume, B. C. C., D'Angelo, C., Smith, E. G., Stevens, J. R., Burt, J., & Wiedenmann, J. (2015). *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian/Arabian Gulf. *Scientific Reports*, 5(1):8562.

https://doi.org/10.1038/srep08562

Hüpkes, P., & Dürbeck, G. (2022). The technical non-reproducibility of the Earth system: Scale, Biosphere 2, and T.C. Boyle's terranauts. *The Anthropocene Review*, 9(2):161-174.

https://doi.org/10.1177/20530196211048935

Lakaniemi, A. M., Hulatt, C. J., Wakeman, K. D., Thomas, D. N., & Puhakka, J. A. (2012). Eukaryotic and prokaryotic microbial communities during microalgal biomass production. *Bioresource Technology*, 124:387-393.

https://doi.org/10.1016/j.biortech.2012.08.048

Lenton, T. M., Dahl, T. W., Daines, S. J., Mills, B. J. W., Ozaki, K., Saltzman, M. R., *et al.* (2016). Earliest land plants created modern levels of atmospheric oxygen. *Proceedings of the National Academy of Sciences of the United States of America*, 113(35):9704-9709.

https://doi.org/10.1073/pnas.1604787113

Lewis, S. L., & Maslin, M. A. (2018). *Human Planet: How we Created the Anthropocene*. United Kingdom: Yale University Press.

Malik, S., Hagopian, J., Mohite, S., Lintong, C., Stoffels, L., Giannakopoulos, S., *et al.* (2020). Robotic extrusion of algae-laden hydrogels for large-scale applications. *Global Challenges*, 4(1):1900064.

https://doi.org/10.1002/gch2.201900064

Mapstone, L. J., Leite, M. N., Purton, S., Crawford, I. A., & Dartnell, L. (2022). *Cyanobacteria* and microalgae in supporting human habitation on Mars. *Biotechnology Advances*, 59:107946.

https://doi.org/10.1016/j.biotechadv.2022.107946

Margulis, L. (2008). *Symbiotic Planet: A New Look at Evolution*. United States: Basic Books.

Marino, B. & Odum, H. (1999). Biosphere 2. Introduction and research progress. *Ecological Engineering*. 13(1-4): 3–14.

Martin, W. F. (2017). Physiology, anaerobes, and the origin of mitosing cells 50 years on. *Journal of Theoretical Biology*, 434:2-10.

https://doi.org/10.1016/j.jtbi.2017.01.004

Matula, E. E., & Nabity, J. A. (2019). Failure modes, causes, and effects of algal photobioreactors used to control a spacecraft environment. *Life Sciences in Space Research* (*Amst*), 20:35-52.

https://doi.org/10.1016/j.lssr.2018.12.001

MELiSSA Foundation. (2020). Available from: https://www.melissafoundation.org/page/melissa-pilot-plant [Last accessed on 2023 Jul 20].

Nelson, N. (2011). Photosystems and global effects of oxygenic photosynthesis. *Biochimica et Biophysica Acta*, 1807(8):856-863.

https://doi.org/10.1016/j.bbabio.2010.10.011

Němcová, Y., & Kalina, T. (2000). Cell wall development, microfibril and pyrenoid structure in type strains of *Chlorella vulgaris*, *C. kessleri*, *C. sorokiniana* compared with *C. luteoviridis* (*Trebouxiophyceae*, *Chlorophyta*). *Archiv für Hydrobiologie Supplement Volumes*, 100:95-106.

https://doi.org/10.1127/algol_stud/100/2000/95

Niederwieser, T. (2018). *Analysis of Factors Affecting the Implementation of an Algal Photobioreactor into a Spacecraft Life Support System*. Ann Arbor, Michigan: ProQuest Dissertations Publishing.

Niederwieser, T., Kociolek, P., & Klaus, D. (2018). A review of algal research in space. *Acta Astronautica*, 146:359-367.

https://doi.org/10.1016/j.actaastro.2018.03.026

Olson, R. L., Oleson, M. W., & Slavin, T. J. (1988). CELSS for advanced manned mission. *HortScience*, 23(2):275-286.

https://doi.org/10.21273/hortsci.23.2.275

Pazar, C. C. (2020). Resource utilization on mars. *Journal of Geophysical Research*, 124:12.

Pennisi, E. (2017). Making waves. *Science*, 355:1006-1009.

https://doi.org/10.1126/science.355.6329.1006

Poughon, L., Laroche, C., Creuly, C., Dussap, C. G., Paille, C., Lasseur, C., *et al.* (2020). *Limnospira indica* PCC8005 growth in photobioreactor: Model and simulation of the ISS and ground experiments. *Life Sciences in Space Research* (*Amst*), 25:53-65.

https://doi.org/10.1016/j.lssr.2020.03.002

Safi, C., Zebib, B., Merah, O., Pontalier, P. Y., & Vaca-Garcia, C. (2014). Morphology, composition, production, processing and applications of *Chlorella vulgaris*: A review. *Renewable and Sustainable Energy Reviews*, 35:265-278.

https://doi.org/10.1016/j.rser.2014.04.007

Schramski, J. R., Gattie, D. K., & Brown, J. H. (2015). Human domination of the biosphere: Rapid discharge of the earth-space battery foretells the future of humankind. *Proceedings of the National Academy of Sciences United States of America*, 112(31):9511-9517.

https://doi.org/10.1073/pnas.1508353112

Schulze, D., Philpot, C., Morfill, G., Klein, B., & Beck, T. (2016). Food Production in Space-operating a Greenhouse in Low Earth Orbit. In: *14th International Conference on Space Operations*, p. 2533.

https://doi.org/10.2514/6.2016-2533

Shergill, R. (2022). *The Birth of a Critical Posthuman Practice*. London: The Museum of Contemporary Art (MOCA).

Sloterdijk, P. (2009). *Talking to Myself about the Poetics of Space*. Cambridge, MA: Harvard Design Magazine. Available from: https://www.harvarddesignmagazine.org/issues/30/talking-to-myself-about-the-poetics-of-space [Last accessed on 2023 Mar 09].

Sterrenburg, F. A. S., & Hoover, R. B. (2011). Extremophile Diatoms: Implications to the Drake Equation. In: *SPIE Conference OP409: Instruments, Methods, and Mission for Astrobiology XIV* (No. M11-0447).

Talaei, M., Mahdavinejad, M., & Azari, R. (2020). Thermal and energy performance of algae bioreactive façades: A review. *Journal of Building Engineering*, 28:101011.

https://doi.org/10.1016/j.jobe.2019.101011

Vander Wiel, J. B., Mikulicz, J. D., Boysen, M. R., Hashemi, N., Kalgren, P., Nauman, L. M., *et al.* (2017). Characterization of *Chlorella vulgaris* and *Chlorella protothecoides* using multi-pixel photon counters in a 3D focusing optofluidic system. *RSC Advances*, 7(8):4402-4408.

https://doi.org/10.1039/C6RA25837A

Verbeelen, T., Leys, N., Ganigué, R., & Mastroleo, F. (2021). Development of nitrogen recycling strategies for bioregenerative life support systems in space. *Frontiers in Microbiology*, 12:700810.

https://doi.org/10.3389/fmicb.2021.700810

Verseux, C., Baqué, M., Lehto, K., de Vera, J. P. P., Rothschild, L. J., & Billi, D. (2016). Sustainable life support on Mars-the potential roles of *Cyanobacteria*. *International Journal of Astrobiology*, 15(1):65-92.

https://doi.org/10.1017/S147355041500021X

Verseux, C., Heinicke, C., Ramalho, T. P., Determann, J., Duckhorn, M., Smagin, M., *et al.* (2021). A low-pressure, N_2/CO_2 atmosphere is suitable for *Cyanobacterium*-based life-support systems on Mars. *Frontiers in Microbiology*, 12:611798.

https://doi.org/10.3389/fmicb.2021.611798

Verseux, C., Poulet, L., & de Vera, J. P. (2022). Bioregenerative life-support systems for crewed missions to the Moon and Mars. *Frontiers in Astronomy and Space Sciences*, 9:977364.

https://doi.org/10.3389/fspas.2022.977364

Volponi, M., & Lasseur, C. (2020). Considerations on life support systems for interstellar travel: A regenerative story. *Acta Futura*, 12:133-149.

https://doi.org/10.5281/zenodo.3747356

Warren, K., Milovanovic, J., & Kim, K. H. (2023). Effect of a microalgae facade on design behaviors: A pilot study with architecture students. *Buildings*, 13(3):611.

https://doi.org/10.3390/buildings13030611

Weber, S., Grande, P. M., Blank, L. M., & Klose, H. (2022). Insights into cell wall disintegration of *Chlorella vulgaris*. *PLoS One*, 17(1):e0262500.

https://doi.org/10.1371/journal.pone.0262500

Wilkinson, S. J. (2018). Algae building technology: Is it the next sustainable technology? *Building Economist*, 2018:31-35.

Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L. N., & Kuzava, G. S. (2017). Exploring the feasibility of algae building technology in NSW. *Procedia Engineering*, 180:1121-1130.

https://doi.org/10.1016/j.proeng.2017.04.272

Yamamoto, M., Kurihara, I., & Kawano, S. (2005). Late type of daughter cell wall synthesis in one of the *Chlorellaceae*, *Parachlorella kessleri* (*Chlorophyta*, *Trebouxiophyceae*). *Planta*, 221:766-775.

https://doi.org/10.1007/s00425-005-1486-8

Yao, S., Lyu, S., An, Y., Lu, J., Gjermansen, C., & Schramm, A. (2019). Microalgae-bacteria symbiosis in microalgal growth and biofuel production: A review. *Journal of Applied Microbiology*, 126(2):359-368.

https://doi.org/10.1111/jam.14095

Young, L. R., & Sutton, J. P., editors. (2021). *Handbook of Bioastronautics*. Germany: Springer, pp. 3-19.

Zheng, Y., Ouyang, Z., Li, C., Liu, J., & Zou, Y. (2008). China's lunar exploration program: Present and future. *Planetary and Space Science*, 56(7):881-886.

https://doi.org/10.1016/j.pss.2008.01.002

Zhu, H., Wang, H., Zhang, Y., & Li, Y. (2023). Biophotovoltaics: Recent advances and perspectives. *Biotechnology Advances*, 64:108101.

https://doi.org/10.1016/j.biotechadv.2023.108101

Zimmer, C. (2019). *The Lost History of One of the World's Strangest Science Experiments*. New York: The New York Times. Available from: https://www.nytimes.com/2019/03/29/sunday-review/biosphere-2-climate-change.html [Last accessed on 2023 Mar 08].

Zubrin, R. (2023). Local resource creation on Mars. In: *Handbook of Space Resources*. Cham: Springer International Publishing, pp. 669-687.