ENGINEERING A LIVING BUILDING REALM: DEVELOPMENT OF PROTECTIVE COATINGS FOR PHOTOSYNTHETIC CERAMIC BIOCOMPOSITE MATERIALS

Assia STEFANOVA*, Ben BRIDGENS, Rachel ARMSTRONG, Pichaya IN-NA, Gary S. CALDWELL

Newcastle University

School of Architecture, Planning & Landscape, Hub for Biotechnology in the Built Environment, Newcastle upon Tyne, NE1 7RU, United Kingdom; a.stefanova@newcastle.ac.uk

Photosynthetic microorganisms are responsible for the habitable atmosphere that sustains the plethora of life on the planet. In a time when humanity is encountering one of its greatest challenges in the form of a global environmental crisis we look for solutions present within nature. Within bio-design we seek to incorporate living metabolic functions within buildings that enable microorganisms to adapt to a wide range of environments and feed on products we wish to transform. Owing to the responsive nature of living organisms we can foster a dialogue between our species and microorganisms by engineering environments that can help those organisms to flourish. The studies outlined in this paper explore the potential of sustaining photosynthetic microorganisms in minimal moisture environments through the use of laboratory design practice. Thus, enabling their integration within interior settings for the purpose of sequestering carbon dioxide and generation of oxygen. In this paper we assess the limitations and performance of such living materials that would help inform the conditions that would have to be created for photosynthetic microorganisms to be sustained within an uncontrolled interior setting. The paper will demonstrate a range of natural coatings and their effect on the metabolism of Chlorella *vulgaris*, a photosynthetic microalgae. In contrast to traditional forms of fabrication where the role of the designer is primarily concerned with generating a predetermined solution, when designing with living things the designer facilitates desirable natural processes that often unfold in unpredictable ways. Therefore, there is a need for a clear understanding of the natural requirements of living organism in terms of their metabolic functions so that we can guide their growth in a desirable way.

Figure 1. Living Algae on Porcelain by Assia Stefanova, part of Yggdrasil Exhibit, London Design Festival, 2019 [image by author]

Keywords: living materials, photosynthesis, bio-composites, ceramics, ecology

1 Introduction

Today urban areas account for 70% of energy consumption worldwide, with buildings being responsible for the majority of carbon emissions [1]. The built environment has contributed significantly to the environmental crisis facing humanity; from the sourcing and manufacture of materials to the energy required to sustain a high level of living comfort inside buildings. These relatively new standards of comfort are oftentimes met through the use of mechanical systems and manual methods, both contributing to higher building energy usage and heat losses [2]. However, there is a new trend of looking to natural processes in order to meet some of our needs as well as to establish a more balanced, closer relationship with nature by developing living building materials. The constant exchange between organisms that occurs in nature and the mutually dependent relationships present between species have created life as we know it. Within nature, organisms feed on each other's waste products to survive, creating symbiotic relationships that challenge widely accepted notions of individuality and separation [3]. It is these close relationships that serve as a blueprint for a new wave of living materials that sustain other species and that have the ability to utilize wastewater and carbon dioxide (CO_2) [4] and that produce vital resources for our survival.

The microorganisms that are the focus of this paper are microalgae, photosynthetic micro-organisms predominantly found within wet environments in both fresh and sea water [5]. In this paper we propose the integration of such organisms into unit based building components such as wall or ceiling tiles so as to reduce the need for ventilation. The algae cells would eventually be washed off and used as a natural fertilizer [6], feeding back into the food chain, whilst new cells would be introduced to populate the surface once again. The substrates would be reused in the cultivation of microalgae and would provide a complex, multifaceted geometry for maximum surface area. Algae provide a pertinent example of organisms that can sequester CO_2 whilst feeding on readily available waste products. They have evolved over time to survive within a variety of environmental conditions, altering their metabolic functions so as to meet their needs through the use of available resources. Today algae cultivation is finding application within the production of biomass [7], wastewater remediation [8], food production [9] as well as the sequestering of CO_2 [10]. Microalgae are typically cultivated within four main systems; open pond, closed pond, hybrid systems [11] and minimal moisture environments [12]. Photosynthetic algae utilize available light to process nutrients, suggesting applications within both internal and external building surfaces, depending on the species used. Within building applications algae have been integrated into biomass producing facades [13], photosynthetic lamps [14] as well as infill for flexible skins [15]. Within all those examples the algae are grown in suspension[1] within enclosed containers. From a design perspective integrating liquids into the building fabric poses challenges of maintenance, spillage and space requirements. The closed system of cultivation is also a popular method of cultivation for laboratory experiments as it ensures consistent results that only take into account a limited number of variables by limiting contamination from other chemical or biological entities and that reduces external stress. Testing within a controlled setting has been done with various types of phytoplankton on a variety of substrates, including, paper, timber, textiles and luffa. These studies have set out a simple screening method [16] of testing the performance of photosynthetic microorganisms with various materials. However, experiments conducted in a controlled environment provide data reflective of perfect conditions that are challenging to

[1] Suspension refers to growing algae within liquid nutrient media

meet within a regular building setting and therefore are not representative of how the material would perform within real world architectural applications. Therefore, before embarking upon fabrication with living organisms it is important to establish if their metabolic functions would be affected if exposed to an open interior setting and then devising ways to create a buffer that would offer a level of protection.

In this paper we are going to study living bio-composites consisting of an inorganic substrate (in this case various types of ceramics) in conjunction with a species of microalgae that is compatible with conditions typically offered by a range of interior environments such as offices or residential buildings. Nutrients and moisture are distributed through the unglazed, porous ceramic substrate, such that the structure becomes a distribution system capable of retaining moisture. We are able to sustain the algae in low moisture levels without the use of liquid tanks as long as minimal levels of moisture are maintained, as demonstrated within earlier experiments conducted. The benefit of this type of cultivation is in the level of flexibility in terms of architectural applications as well as the much greater cell density per area used and the reduced water demand for cultivation of algae.

The challenge in developing living bio-composite materials arises in the transition from a controlled laboratory setting to an uncontrolled domestic or office environment. Within our interior environments there are numerous bacterial and fungal species that would often find moist, nutrient-rich environments desirable and that are likely to colonize such exposed surfaces, attacking the algae and competing for space and nutrients. In order to minimize the detrimental effect of undesirable colonies and prevent rapid evaporation the experiments described below demonstrate a range of conditions that may enhance and support algae growth by employing natural coatings (i.e. Aloe vera, olive oil, lemongrass oil and chitosan) that have anti-bacterial and self-hydrated properties to protect the cells from water evaporation and foreign bacterial colonies. All the methods aim to utilize natural, low impact products and strategies that avoid artificial means of controlling the living population such as antibiotics or synthetic chemicals that potentially have detrimental effects on the environment.

2 Method

The experiments study the effect of an open setup on the development of microalgae that are highly efficient in sequestering CO_2 and that are compatible with conditions typically offered within interior environments, including light already utilized within interior spaces as well as a temperature that would not have a detrimental effect on the metabolic functions of the algae ranging between 18-25°C. The experiments test four types of ceramics, including; Porcelain, White Fleck (WF), Crank ES50 (ES50), Crank ES65 (ES65). The chemical compositions and texture of the clay provide differences in environmental conditions that can affect the response of the algae, hindering or helping growth in a variety of contexts. The species used was Chlorella *vulgaris* (C. *vulgaris*) a species that has a particularly efficient photosynthetic rate, with some chlorella species reaching an efficiency of more than 20% compared to the typical 1% efficiency of terrestrial plant species [17]. The cell viability was assessed using imaging pulse amplitude modulated-fluorometry (Imaging-PAM M-Series; Walz GmbH); that provides the level of chlorophyll fluorescence of photosynthetic cells [18]. Numerical and image data produced from Imaging-PAM were collected every 2 days for 14 days for each set of experiments. Liquid algae slurry (0.02ml per sample) that had been grown in full strength BG-11 medium (100% BG-11 contains; 1.5 g/L $NaNO_3$, 0.036 g/L $CaCl_2 \cdot 2H_2O$, 0.075 g/L

$MgSO_4 \cdot 7H_2O$, 0.04 g/L K_2HPO_4 and 0.02 g/L Na_2CO_3) [19] was placed in 50ml Falcon tubes and centrifuged at 1620 RCF (Relative Centrifugal Force) for 10 minutes to produce a dense algae slurry. Samples of 1.3g ceramic pieces were placed within 12-well-plate containers with 0.5ml of BG11 nutrient media. In each instance there were 3 samples with living cells of 0.05ml algae slurry and 3 samples without cells samples as per Fig.2, alongside control suspension samples with cells in suspension and empty BG11. The algae slurry and liquid consistency coatings were deposited using pipette tips whilst the natural coatings were deposited using a spatula, 0.5g per sample of gel or 0.05ml liquid consistency using pipette tips. The well plates were left open within an interior setting that was lit for approximately 16 hours a day and where a temperature of 18-22°C was maintained. The study was split into three stages conducted sequentially, each stage informing the next set of experiments.

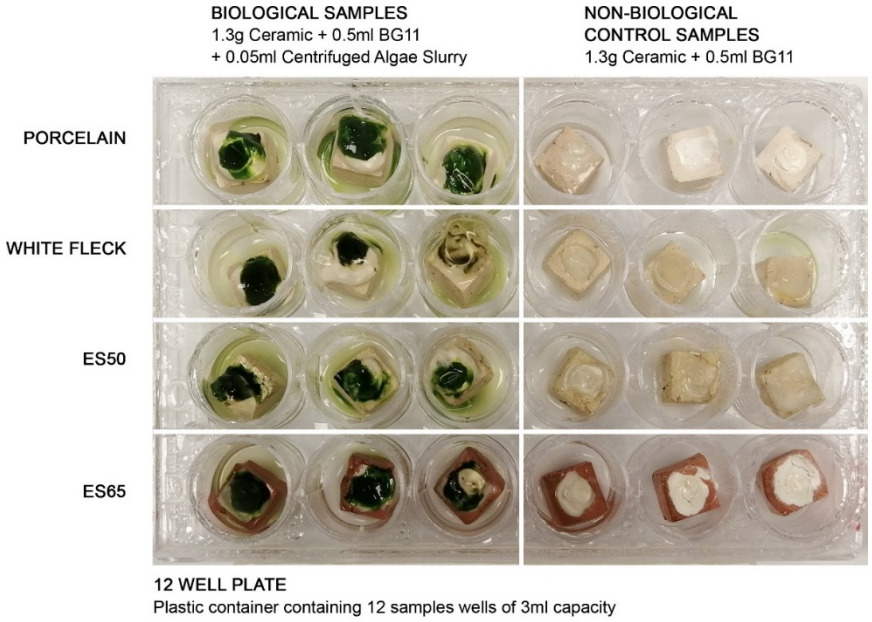

Figure 2. Example Samples Setup in 12 Well Plate- Ceramic Samples with and algae slurry and coating on the left, and control samples with coating without algae slurry on the right

1. Water Evaporation and Rehydration- This set of experiments assessed the metabolic functions in relationship to moisture reintroduction and evaporation. Three methods of moisture reintroduction were tested including; restoration of initial moisture levels every 48 hours, spraying the surface every 12 hours, 5 times per well plate using spays of 0.7ml water content and the use of a hydrogel as a top coating sprayed every 12 hours. A set of controls was used consisting of samples within a closed well plate that were not exposed to air to compare the performance of the exposed samples.
2. Protective Coatings – this set demonstrates the testing of a range of coatings that aim to provide a buffer from the open air or to enhance algae growth. The tested natural coatings include Aloe Vera, Chitosan (1.2%) / Acetic Acid (2%), Olive Oil, and Diatomaceous Earth[2].
3. Combined Protective Coatings– The combinations tested include; Aloe Vera and Diatomaceous Earth, Aloe Vera and Hydrogel, Chitosan (1.2%) /Acetic Acid (3%) / Diatomaceous Earth (1%), Olive Oil and Lemongrass Oil (10%).

[2] Diatomaceous earth (DE) is a type of sedimentary rock that is processed into a fine white powder that predominantly consists of the fossilized remains of microalgae.

3 Water Evaporation and Rehydration

In the first instance it was important to assess the survival rate of cells within an uncontrolled environment without any additional means of protection. The setup also highlights the difficulty of maintaining the minimal moisture levels necessary. In the first set of samples water was reintroduced every other day at a rate of 0.3ml to replace moisture lost due to evaporation, within the second set of samples water was introduced every 12 hours through spraying each plate five times with 0.7ml of sterile D.I. water. In the third set 0.6g of hydrogel powder were mixed with 20ml D.I. water and 2g of the gel mixture were placed over the algae slurry on the surface of the substrate. The last set contained samples that remained closed for the duration of the experiment to compare the performance of the algae when the well plate is left closed and evaporation occurs at low rates, in that set water was not added during the 14 days of testing.

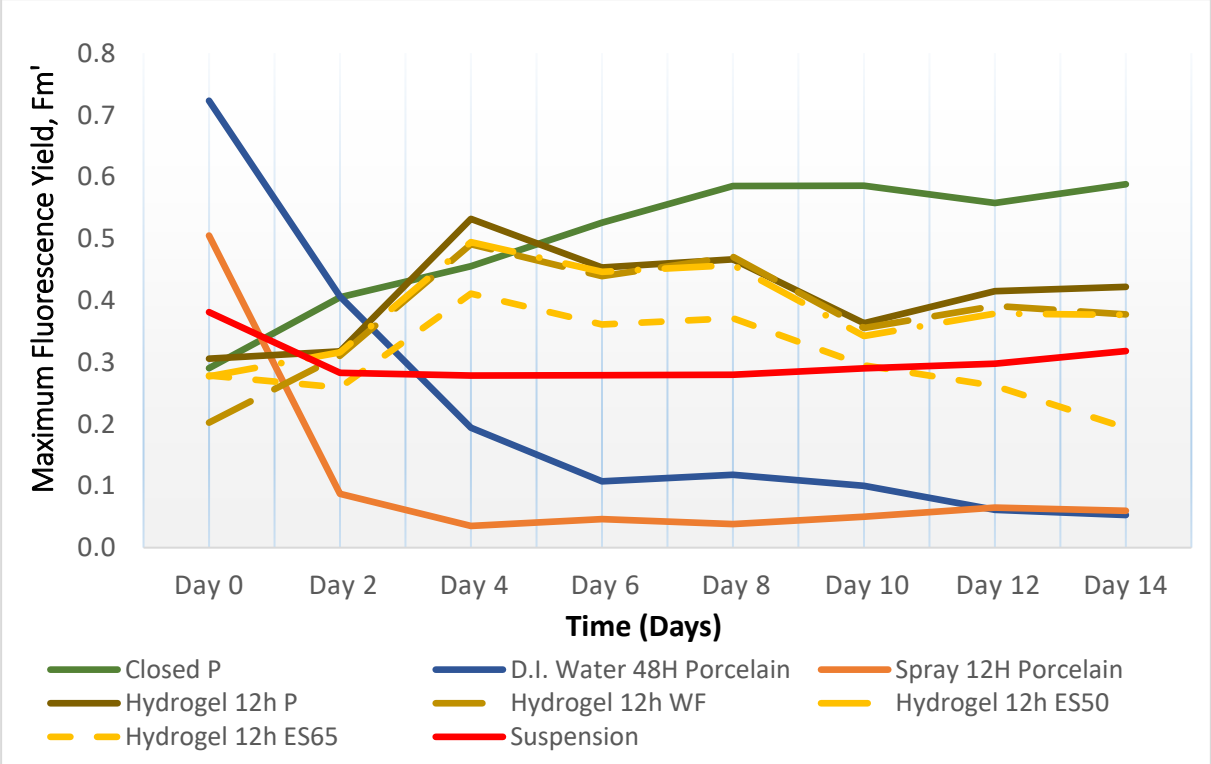

Figure 3: Maximum chlorophyll fluorescence yield of exposed to air ceramic samples and suspension samples using various methods of moisture retention and reintroduction

In this first group of experiments the results demonstrate a decrease in living cells, down to as little as 30%-7%, if we compare these results to results obtained within a closed setup where the cell culture continued to exhibit healthy functions and further favourable development it is obvious that exposure to an interior environment is highly problematic. The second set exhibits a steep decline and sustained low number of cells for the duration of the experiment likely due to the cells washing off into the surrounding liquid media during spraying suggesting the need to improve cell adhesion. The third set performed better however the hydrogel did exhibit a tendency to detach and would pose challenges if placed on a vertical surface. Figure 3 demonstrates the steep decline in chlorophyll fluorescence in uncoated samples. Porcelain is highlighted as it performed better than other types of ceramics.

4 Protective Coatings

Within nature organisms are often protected through a process of encapsulation [20], this natural phenomenon served as inspiration for the development of a natural antibacterial coating that would protect the algae by providing a film that may act as a barrier to the external environment as well as to provide an environment that would be less hospitable to undesirable species. In this next set of tests we used a number of coatings that aimed to slow down evaporation, providing a level of protection and helping to reduce contaminants through their natural antibacterial properties. In each instance the coating was delivered after the algae slurry was deposited onto the ceramic to cover the cells. The samples were sprayed with sterile D.I. water twice daily to ensure the coatings did not dry out. In this instance cell wash off occurred at a lower rate as the cells remained underneath protected by the coating layer. Porcelain and White Fleck displayed slightly better performance than Crank ES50 and ES65 (See Figure 4).

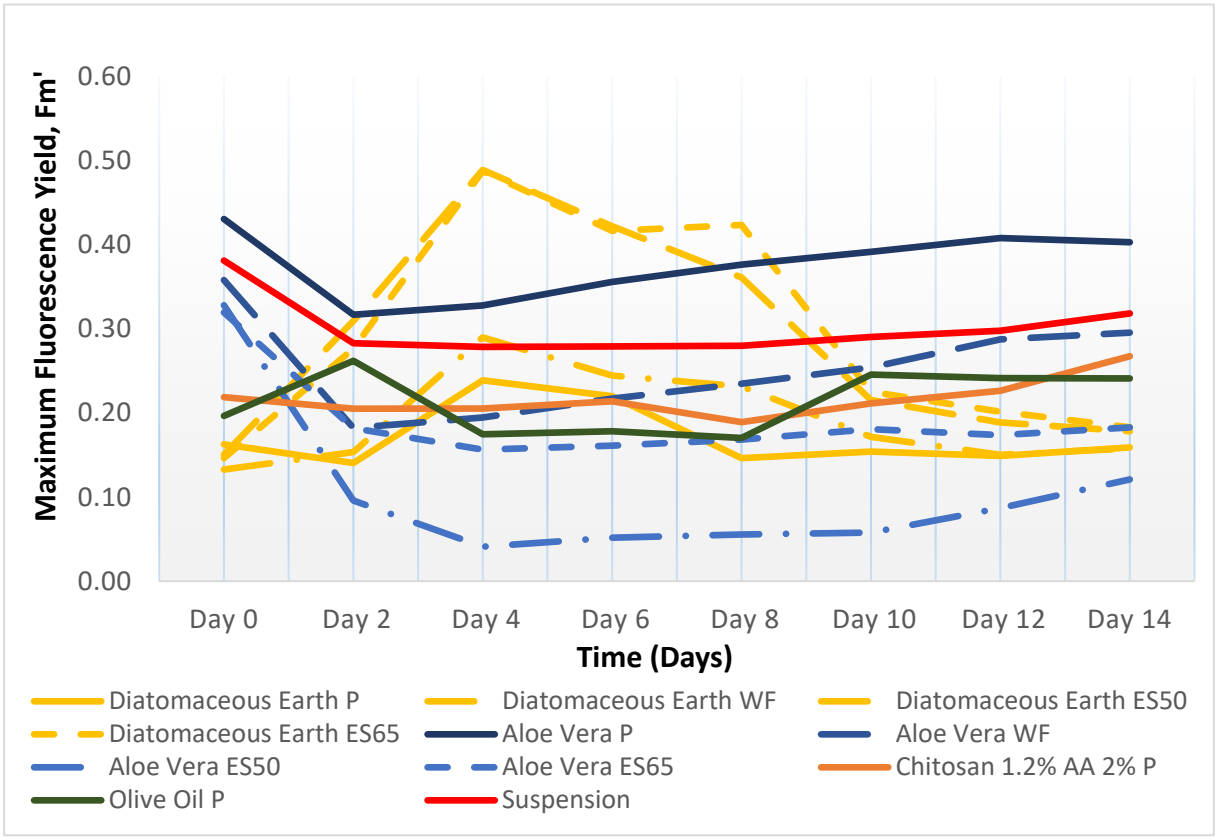

Figure 4: Maximum chlorophyll fluorescence yield of exposed to air clay base and suspension samples with protective coatings

This is most likely due to the higher variations within the composition of the later. The majority of samples displayed a slight decrease in chlorophyll fluorescence by day 2 followed by gradual increase that persisted for the duration of the experiment suggesting that cultivation within interior settings may be possible if the cells remain protected. A longer study is necessary to assess if the coating would have to be reapplied at certain times and to compare the longevity of the bio-composite within an open setup with that of closed samples. Previous closed experiments have been sustained within a closed setup for as longs as 100 days without a significant decrease of chlorophyll fluorescence. In the case of Diatomaceous Earth (DE) there is an increase of chlorophyll fluorescence by as much as 330% in certain cases by day 4, however that is followed by a decline likely due to the mixture not slowing down moisture evaporation on the surface. Aloe Vera, Olive Oil and Chitosan (1.2%)/ Acetic Acid (2%) display a steady increase in chlorophyll fluorescence providing greater consistency in chlorophyll fluorescence levels.

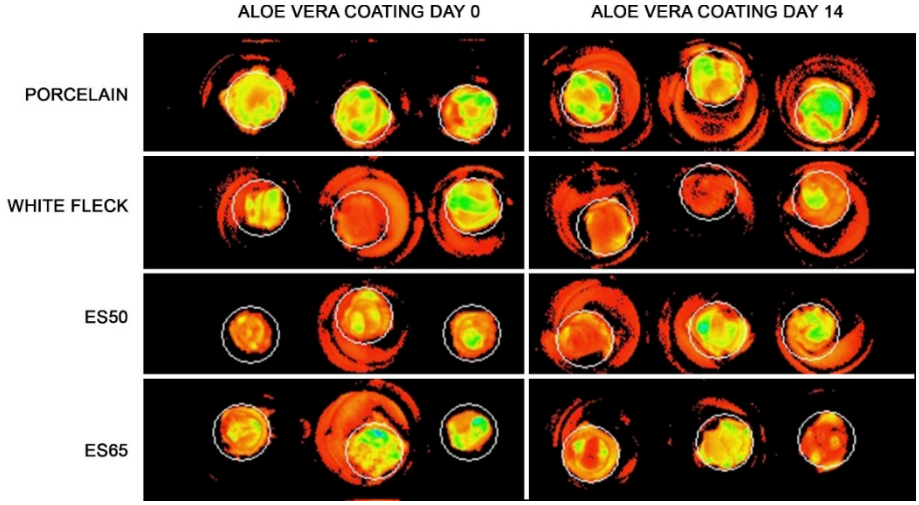

Figure 5: Aloe Vera samples on Day 0 and Day 14 Imaged using Image PAM- cooler colours indicate areas of greater chlorophyll fluorescence. From the image it becomes apparent that certain types of ceramic substrate are less likely to support C. *vulgaris* growth, with Porcelain showing an increase in chlorophyll fluoresce.

5 Combined Protective Coatings

In this group of experiments the previously tested coatings were combined and enhanced. Aloe Vera was combined with hydrogel at a ratio of 1:2, to assess if the moisture content could be increased. Olive oil was mixed with 10% Lemongrass essential oil in an attempt to reduce potential contamination and Chitosan (1.2%)/ Acetic Acid (4%) were combined with DE (1%) in an attempt to improve cell growth. Aloe Vera was also combined with a bottom layer of DE. The DE powder was mixed with water at a 1:1 ratio and 0.1ml of the solution was deposited on each sample using a pipette, 0.05ml of centrifuged algae slurry was deposited separately on top of the diatomaceous earth solution and the cells were sealed by a layer of 0.3g Aloe Vera. Within all other examples the coatings were applied over the algae slurry using a pipette or spatula depending on consistency. The results (Fig. 5) show a greater decrease in chlorophyll fluorescence at Day 2 compared to the single substance coatings and they also exhibit greater daily variation. The Chitosan (1.2%)/ Acetic Acid (4%)/ DE (1%) mimicked

closely the performance the changes of chlorophyll fluorescence of the suspension culture.

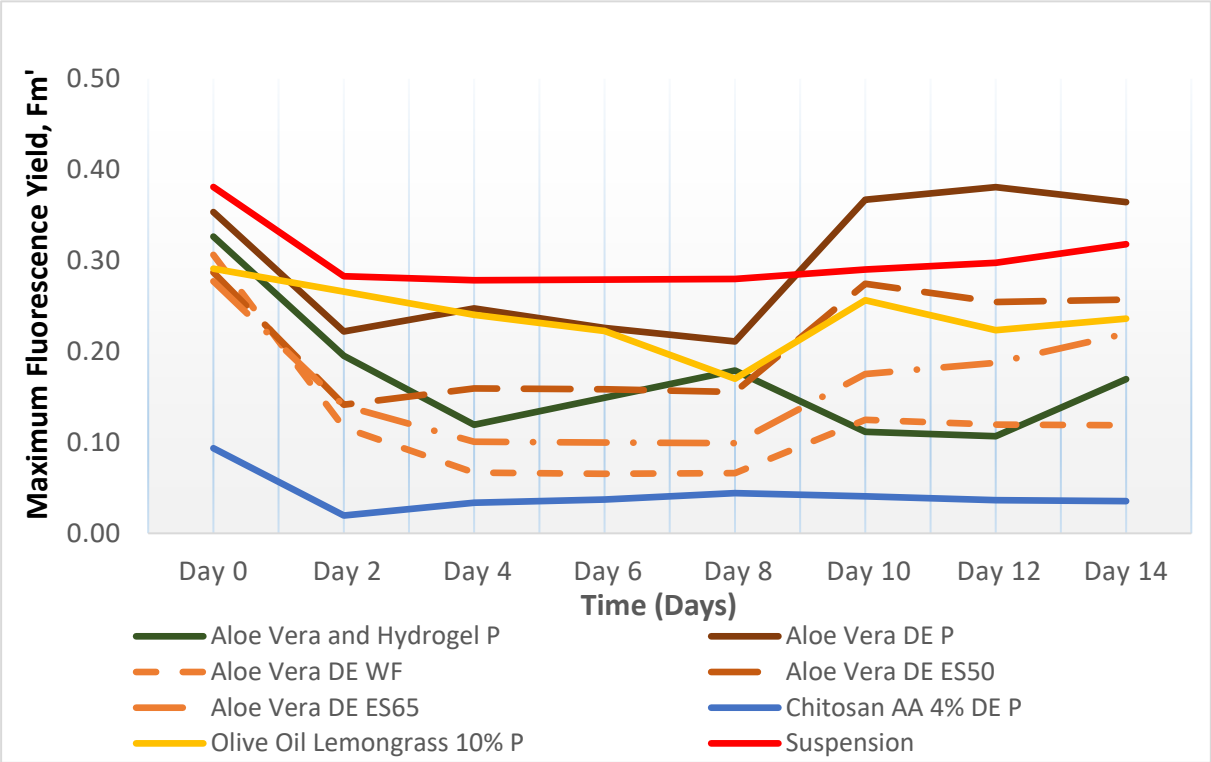

Figure 6: Maximum chlorophyll fluorescence yield of exposed to air ceramic base and suspension samples with various combined coating

6 Discussion

The experiments described above demonstrate the challenges of exposing living bio-composite materials within an uncontrolled interior environment. Whilst a decrease in cell numbers was observed in certain types of coatings within uncontrolled environments, living algae colonies were successfully sustained for the duration of the experiments suggesting that further testing through fabrication and live integration of such material is worthwhile. The results highlighted the need for a protective coating that acts as a buffer and that slows down the rate of evaporation. The testing also shows the importance of moisture distribution and the need for the development of a regime that maintains reasonable moisture levels as the surface of the ceramic tends to dry at a higher rate creating a hostile environment unsuitable for algae growth. The four types of ceramic presented different results, with Porcelain and White Fleck outperforming the two stoneware clays showing the effect of the substrate upon the chlorophyll fluorescence levels over time, with higher level of aggregate having a detrimental effect on the organism. The distribution of moisture throughout the ceramic samples would also be affected by the firing temperature of the ceramic affecting porosity with higher firing temperatures resulting in lower porosity (1100°C) with lower firing temperatures (e.g. 900°C) resulting in higher porosity and therefore better distribution of moisture and nutrients. In addition to that the shape of the sample would also have an effect with thinner layers of ceramic providing wetter surfaces if pockets of liquid could be locked inside the structure. Testing is necessary to assess the exact amount of moisture needed to maintain healthy algae growth in relationship to evaporation rates within different interior settings and the development of a building component geometry such as wall or ceiling tiles and a water distribution system would provide the next steps to integrating the living material within a building scenario. The coatings tested show significant improvement in performance

in the cases of Aloe Vera, chitosan and olive oil, in comparison to uncoated exposed samples. The coatings demonstrated an increase in chlorophyll fluorescence from the initial amount by the end of the experiments. A longevity test would have to be conducted to assess the lifespan of the bio-composite and the appropriate maintenance protocol that should take into account both the needs of the organism and what would be reasonable expectations to place upon inhabitants or mechanical systems as well as testing of the method for extraction of the dead algae cells so as to assess the viability of the whole product lifecycle.

7 Conclusion

By bringing materials and living organisms together we begin to form collaborative networks that foster closer relationships and open up new methods of cultivation which are necessary for addressing contemporary ecological issues. As is the case with all living things, the proposed materials require care and dedication and whilst that may be perceived as a limiting factor that places a burden upon inhabitants it is also an opportunity to establish a closer connection with our environment. By tending to other living things we develop a feeling of responsibility [21] and recognize needs outside of our own.

The research has identified the importance of protecting the living organisms from sudden environmental changes and unhospitable conditions through the introduction of an environmental buffer in the form of protective coatings. The choice of coating is of particular interest with more economical, local solutions offering a viable system for scaling and mass application. The choice of coating would depend on materials that are easier to source in particular parts of the world for example Aloe Vera would become an appropriate candidate in places where it is locally grown. However there is a wide range of factors that would have to be taken into consideration in addition to the type of coating, including cost of manufacture, maintenance and lifespan. Materials such as diatomaceous earth are of particularly interest, in the case of DE there is a close relationship to the living organisms being utilized. Creating a bio-composite using DE would in essence enable the construction of a habitat capable of supporting new life through the use of the remains of previous ancestors, creating a new network and opening up a dialogue as to the relationship between past and future within an ecological context.

The demonstrated design approach highlights the need to integrate laboratory testing and experimentation within design practice and to engage more closely with such testing so as to gain greater understanding and control necessary to develop viable solutions that can sustain living organisms for a meaningful period of time. The development of living materials opens up new possibilities of collaborating with nature to meet our needs in a sustainable manner. Tapping into natural cycles through creation of a living building fabric has potential to enable us to meet our needs through the use of living metabolic functions. The results suggest that microalgae could be cultivated within interior surfaces and applications may range from walls, ceiling tiles, partitions to decorative lighting fixtures. This new generation of products would be endowed with a natural intelligence in the form of responsive living behaviour and would require the same level of consideration as all living things.

8 Bibliography

[1] UIA, “UIA Durban Declaration 2050 Imperative - News & Media,” 2014. [Online]. Available: https://wp.architecture.com.au/news-media/uia-durban-declaration-2050-imperative/. [Accessed: 24-Dec-2019].

[2] M. Ma, X. Ma, W. Cai, and W. Cai, “Carbon-dioxide mitigation in the residential building sector: A household scale-based assessment,” *Energy Convers. Manag.*, vol. 198, p.

111915, Oct. 2019.
[3] M. J. Hird, *The origins of sociable life : evolution after science studies*. Palgrave Macmillan, 2009.
[4] P. Jajesniak, H. E. M. Omar Ali, and T. Seng Wong, "Carbon Dioxide Capture and Utilization using Biological Systems: Opportunities and Challenges," *J Bioproces Biotech.*, vol. 4, no. 3, p. 155, 2014.
[5] C. Reynolds, *Ecology of phytoplankton*, 1st ed. Cambridge: Cambridge University Press, 2006.
[6] A. Chatterjee, S. Singh, C. Agrawal, S. Yadav, R. Rai, and L. C. Rai, "Role of Algae as a Biofertilizer," in *Algal Green Chemistry: Recent Progress in Biotechnology*, Elsevier, 2017, pp. 189–200.
[7] A. Ilavarasi, D. Mubarakali, R. Praveenkumar, E. Baldev, and N. Thajuddin, "Optimization of various growth media to freshwater microalgae for biomass production," *Biotechnology*, 2011.
[8] S. Månsson, "Cultivation of Chlorella vulgaris in nutrient solution from greenhouse tomato production," Swedish University of Agricultural Sciences, 2012.
[9] I. Priyadarshani and B. Rath, "Commercial and industrial applications of micro algae-A review," *Res. Artic. J. Algal Biomass Utln*, vol. 2012, no. 4, pp. 89–100, 2012.
[10] A. Stefanova, B. Bridgens, R. Armstrong, P. In-na, and G. S. Caldwell, "Clay and Ceramic-Based Photosynthetic Biocomposites to Improve Interior Building Environments," *Technol. | Archit. + Des.*, vol. 4, no. 2, 2020.
[11] T. Fazal *et al.*, "Bioremediation of textile wastewater and successive biodiesel production using microalgae," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3107–3126, Feb. 2018.
[12] A. Stefanova, T. H. Arnardottir, D. Ozkan, and S. Lee, "Approach to Biologically Made Materials and Advanced Fabrication Practices," in *International Conference on Emerging Technologies In Architectural Design (ICETAD2019)*, 2019.
[13] K. Lofgren, "Algae Powered House Biofacade Splitterwerk ARUP Colt International SCC Green Power Building « Inhabitat – Green Design, Innovation, Architecture, Green Building," *inhabitat*, 2013. [Online]. Available: https://inhabitat.com/splitterwerk-architects-design-worlds-first-algae-powered-building-for-germany/algae-powered-house-biofacade-splitterwerk-arup-colt-international-scc-green-power-building/. [Accessed: 11-Jul-2019].
[14] Warisan Lighting, "10 benefits of Algae lamps," *Warisan Lighting*, 2017. [Online]. Available: http://warisanlighting.com/algae-lamp-2.html. [Accessed: 11-Jul-2019].
[15] Petra Bogias, "Algae Textile: A Lightweight Photobioreactor for Urban Buildings," University of Waterloo, 2014.
[16] A. Umar, P. In-na, A. D. Wallace, M. Flickinger, G. S. Caldwell, and J. Lee, "Loofah-Based Microalgae and Cyanobacteria Biocomposites for Intensifying Carbon Dioxide Capture," *SSRN Electron. J.*, 2019.
[17] M. Adamczyk, J. Lasek, and A. Skawińska, "CO2 Biofixation and Growth Kinetics of Chlorella vulgaris and Nannochloropsis gaditana," *Appl. Biochem. Biotechnol.*, vol. 179, no. 7, pp. 1248–1261, Aug. 2016.
[18] U. Schreiber, "Pulse-Amplitude-Modulation (PAM) Fluorometry and Saturation Pulse Method: An Overview," in *Chlorophyll a Fluorescence*, Dordrecht: Springer Netherlands, 2004, pp. 279–319.
[19] R. Y. Stanier, R. Kunisawa, M. Mandel, and G. Cohen-Bazire, "Purification and properties

of unicellular blue-green algae (order Chroococcales).," *Bacteriol. Rev.*, vol. 35, no. 2, pp. 171–205, Jun. 1971.

[20] I. Holzmeister, M. Schamel, J. Groll, U. Gbureck, and E. Vorndran, "Artificial inorganic biohybrids: The functional combination of microorganisms and cells with inorganic materials," *Acta Biomater.*, vol. 74, pp. 17–35, 2018.

[21] D. J. Haraway, *Staying with the trouble : making kin in the Chthulucene*. Durham: Duke University Press, 2016.