CHAPTER 11

Augmented Polycultures: Scaling up Algal Ecosystems and Design of a Biofouling Aesthetic

Brenda Parker and Marcos Cruz

Abstract

To lay the foundations for the Biocene, a potential future era of our Anthropocene human habitat, the infrastructure of our built environment should play a more active role in carbon mitigation and reduction. Algae and cryptogrammic species will become important elements of bio-integrated “photosynthetic cities”. However, to realise this, we will need to relinquish notions of monoculture and purity associated with highly maintained and controlled cultivation. This chapter will look back at the origins of contained microalgal culture in the realms of science and engineering to understand the basis for our current design language. We assume the position that in future, consortia-based approaches with direct exposure to the outdoor environment will be required in order to deliver the vision of algae for bioremediation or microbiome-inspired green infrastructure in a resilient way. Ultimately, our photosynthetic human habitat will embody a more provocative and disobedient condition. Reconciling with the abject nature of biofouling, overcoming disgust and ultimately reaching an acceptance of the sublime will be needed in order to form ecologically relevant and environmentally meaningful interventions. The role of design will be pivotal to introduce a new aesthetic which is based on how we embrace self-regenerative conditions while promoting heterogeneity and biodiversity in buildings.

Keywords

microalgae – polyculture – heterogeneity – symbiosis – biofouling – bioreceptivity – bioremediation – complexity – scale-up – aesthetics

1 Introduction

The concept of a “photosynthetic city” defines a radically new vision for the future human habitat whereby our spaces and structures become

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bio-integrated. It encapsulates two core, biologically-mediated, tenets: where buildings can become scaffolds for growth, or where construction materials are grown *ab initio*. The motivation for this is to reverse the devasting effects of climate change, and to create an environment for more ecologically-driven societies where we live in greater proximity to biodiversity. The process of photosynthesis underpins all ecosystems, and will be essential to the realisation of a shift from our current era of the Anthropocene to a future Biocene.

If we are to create such a photosynthetic city, how might it look? Unicellular photosynthetic organisms such as microalgae and cyanobacteria are frequently keystone species when transforming hostile landscapes. However, it is time to question what it might really mean to embed algae within our built environment and to look back critically at some of the underlying paradigms that have been established in previous design work. To understand how we might progress, it is worth reflecting on the methods of scaling up algal cultures for biotechnology, design and architectural purposes. Within the diversity of applications, this procedure has many common themes, including a focus on enclosed systems, monoculture and purity. While the appearance of algae as individual species has a greater social acceptability, this state is not reflective of natural ecosystems and as a result, considerable effort is required to maintain stability.

To move forward, this chapter will assume the position that in future, consortia-based approaches with direct exposure to the outdoor environment will be required in order to deliver the vision of algae for bioremediation or microbiome-inspired green infrastructure in a resilient way. Ultimately, our photosynthetic human habitat will embody a more provocative and disobedient condition. Reconciling with the abject nature of biofouling, overcoming disgust and ultimately reaching an acceptance of the sublime will be needed in order to form ecologically relevant and environmentally meaningful interventions. The role of design will be pivotal to introduce a new aesthetic which is based on how we embrace self-regenerative conditions while promoting heterogeneity and biodiversity in buildings.

2 An Initiation into Algal Biotechnology in the Built Environment – the B.I.Q. House

Following the construction boom in the late 20th century, the start of the 21st century brought about an awareness of the devastating carbon footprint of the built environment and the urgent need to find new sustainable solutions for our future human habitat. This coincided with rising oil prices, which created the drive to produce algal biofuels. In fact, these endeavours were reviving work started in the 1970's by the Aquatic Species Program where the research effort sought to create bioenergy from non-land based crops (Sheehan et al. 1998).

The heady mixture of highly funded and much-disseminated research in algal technology, coupled with the promise of lowering carbon emissions, gave architects and engineers a sense of opportunity to integrate such novel systems in buildings and urban infrastructures. Numerous projects were envisioned, but the first large functioning façade was designed by ARUP Engineering in collaboration with the Strategic Science Consult and Colt International in 2013 for the International Building Exhibition in Hamburg (Figure 11.1). Known as the BIQ House (Bio Intelligent Quotient), the building became the first of its kind to host a 200m^2 area of flat panel *SolarLeaf* photobioreactors (Wurm and Pauli 2016). The vision was the creation of a "bioreactive" façade that was capable of responding to light by the increased growth of microalgae. In addition, the panels acted as solar thermal collectors, and used to generate hot water. The design included the control and processing equipment needed to separate the algal cells in a facility located under the building (Figure 11.2). Biomass collected could be used to generate methane for electricity generation following a secondary conversion step. For the inhabitants the façade creates a self-cleaning and bioresponsive screen to filter light into the building. The initial sketches were formally more expressive, however budget constraints and practical considerations meant the engineering realisation of flat panels was the most effective means of construction. The building remains an important precedent in the history of applying living systems within our built environment due to the scale and ambition. Nonetheless, the project had a number of challenges. User experience of residents indicated that the noise from the airlift pumping system creates disturbance, and steps were taken to reduce the frequency. Materials of construction when handling algal cultures are important, even though algae are seen as benign. During certain phases of growth pH can rise significantly, resulting in corrosion of aluminium components. Also, incident sunlight within such thin film bioreactors can result in temperatures that challenge the physiological limits of algal cells. Despite this, the preliminary data from mass balances indicates that from the façade over 600 kg of microalgal biomass was produced in a year, and the net energy balance was favourable (Fraunhofer 2016). If this system was to be applied to many surrounding buildings, it could produce a significant amount of biomass in specific urban environments in a distributed manner.

The use of flat panel façades for culture of other, valuable microalgal species has been further explored in an architectural context by Jérémy Pruvost and

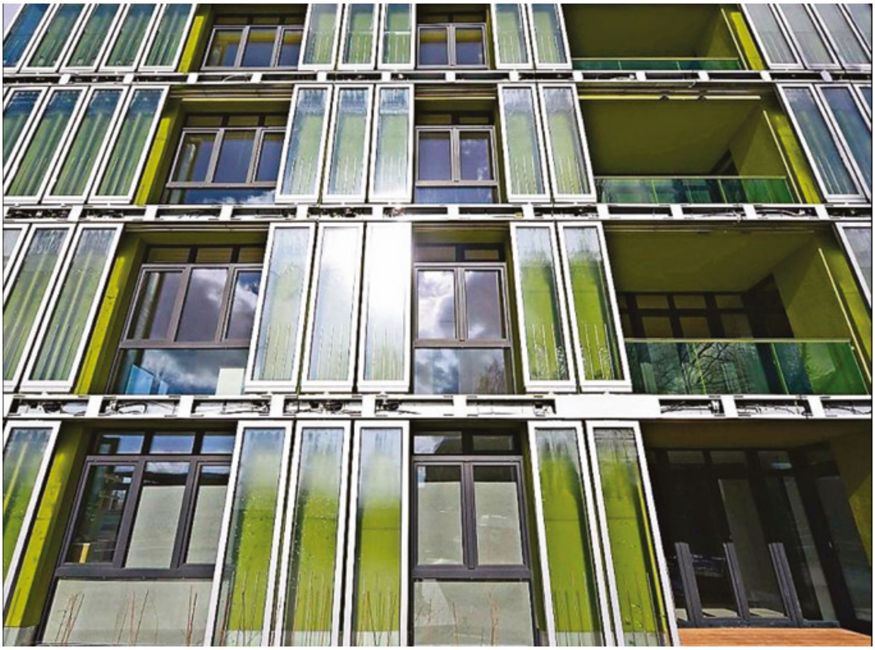

FIGURE 11.1 *Solarleaf* façade of *B.I.Q. House* with algae monoculture in flat bioreactors built on the occasion of the International Building Exhibition in Hamburg, 2013. Team: ARUP Engineering in collaboration with the Strategic Science Consult and Colt International
PHOTO CREDIT: MARCOS CRUZ

French architects from XTU (Pruvost et al. 2016; Todisco 2019). The engineering environment has been characterised and the patterns of growth examined in the photobioreactors designed. However, it highlights an interesting gap in our present thinking, and a dichotomy between two possible approaches. Should a reactor be designed for the species in a bottom-up manner, or if the species and its medium should be selected and designed to be able to deal with the conditions of the bioreactor as per a top-down approach? The comparison of both scenarios has not been exhaustively examined. Applied phycology has focussed on the phenomenon of algal growth within a pre-defined design, with the objective of understanding how it behaves in the vessel. For instance, scale up of species such as *Tetraselmis* for carbon dioxide sequestration has been evaluated in this manner (Pereira et al. 2018) using flat panels and tubular reactors. When considering an application within the urban landscape, the complexity of industrial photobioreactors (Figure 11.2) on the other hand offers little possibility for customisation or participatory design, as per the vision of an open source architecture (Ratti and Claudel 2015). Nonetheless, embarking

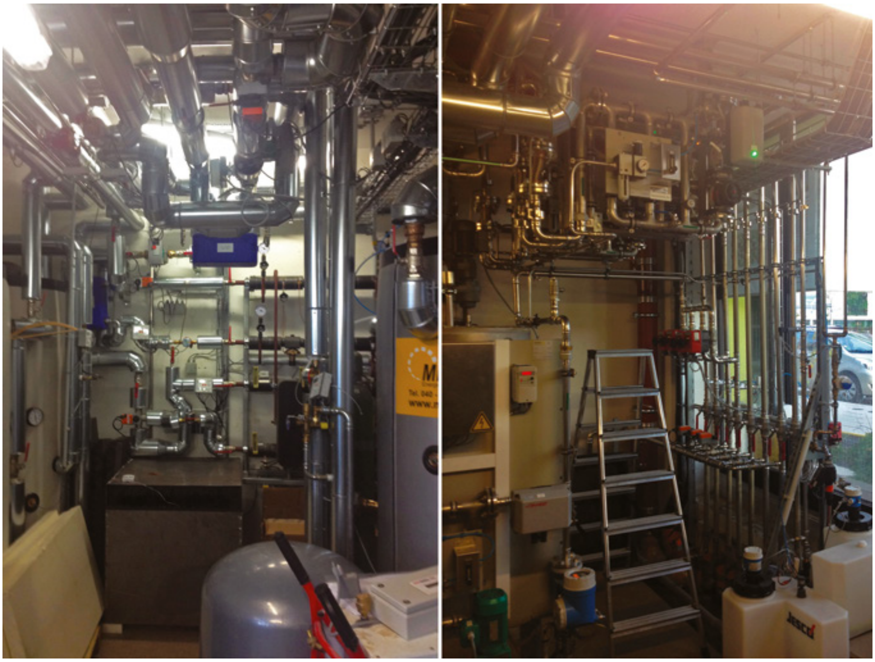

FIGURE 11.2 *B.I.Q. House* plant room to service and maintain bioreactor façade
PHOTO CREDIT: MARCOS CRUZ

on a design process for a photobioreactor to cultivate a single species could be perceived as a high risk endeavour relying on both an exhaustive knowledge of cell physiology and metabolism, as well as suitability for the environmental condition.

3 Photobioreactors and Engineering Cell Environments

To understand the challenge of photobioreactor design is worth going back to the origins of contemporary algal bioreactors, which echoes the development of mass cultivation of microbial cells in other forms of biomanufacturing. It has roots in the engineering of fermentation vessels and the evolution of industrial biotechnology since the 1940s. Geometries of stirred tanks have typically focussed on cylindrical models with modifications to the interior conditions to facilitate oxygen demand or decrease mass transfer limitations. The addition of spargers, impellers or baffles introduces mixing and turbulence, and through these interventions creates an environment amenable to cell growth. It has also established a conventional mode of manufacture based on standardised equipment and engineering heuristics in order to minimise risk. Largely driven by the pharmaceutical industry, the typologies of upstream cultivation vessels are inherently conservative. The strict procedures of validation leading to product approval have further cemented the approaches accepted for scale up of biological cultivation.

To scale up algal culture in closed systems requires a photobioreactor (PBR) – that is, a vessel capable of facilitating gas exchange, holding liquid and permitting light transmission. As noted previously (Pulz and Scheibenbogen 2007), light is the main limiting factor in scale up of algal cultures. The distance light must travel through the medium (path length) and exposure to sufficient solar energy to conduct photosynthesis is a primary concern. To this end, there are families of geometric forms based on two mechanisms: either bubble columns or airlift reactors, which comprise a specific compartment for the injection of gas. Both typologies may be cylindrical in nature.

Alternatively, scale up can also be achieved by maximising surface area to volume ratio. One approach for this in regards to contained photobioreactor systems was to move towards flat "plate" systems, a format first explored in the 1950s (Burlew 1953). The small path length and flat geometry has led to their inclusion in façade projects. While the internal mechanisms of flat panel PBRs may function as either bubble columns or airlift reactors, they crucially begin to break with biotechnology tradition as the format is rectangular. In microbiology, vessels are typically designed to have smooth junctions and rounded boundaries (cf. the petri dish) to minimise accumulation of matter or accommodate contaminating microbes. The principal advantage of the flat panel reactor is the high areal productivity. However, this is at the expense of capital expenditure and material usage given the low volumes they contain.

In the examples of bioreactors given above, the emphasis has been on cultivation of a single species. All forms of biotechnological manufacturing, from food to fine chemicals and pharmaceuticals, rely on reproducibility. Introduction of other organisms creates variable yields due to competition for carbon, nutrients and light; or can be lethal to the "desired" organism. Therefore, control mechanisms and sterile techniques are put in place to eliminate the potential for contamination. Interestingly, this approach does not apply when working with outdoor systems where biological systems are used to remove nutrients from wastewater. Water treatment facilities use membrane reactors and shallow raceways known as high rate ponds that work with mixtures of microorganisms, and even encourage flocs of algae and bacteria. While the exact species may vary with temperature or composition of wastewater, the functional structure is preserved despite taxonomic variability (Craggs et al. 2014; Louca et al. 2016). In this respect there is a divergence between biomass production (single species) and remediation (consortia). Herein lies the challenge for the built environment that so far inherited the aesthetics of the former, but for its wider use and application will have to benefit from the properties of the latter.

4 Monoculture and Purity

Monocultures in agriculture or biotechnology imply the growth of a single species, usually with either containment or preventative actions taken to prevent contamination with other species. Within algal cultivation these invaders may be benign, growing alongside the algal cells and feasting on organic carbon shed into the media. In some cases, these other organisms can be deleterious to algal growth. Viruses, bacteria, grazers in the form of ciliates or other zooplankton can rapidly decimate cultures and cause a “crash” (Day et al. 2017). This terminology hints at the precarious thermodynamic state of a monoculture. Energy is expended in the form of additional apparatus and precautions to maintain a single organism in a pure culture. A state of equilibrium is achieved through intensive human intervention, which could be interpreted as “Organisation [is] maintained by extracting order from the environment” (Schrödinger 1948).

The requirement for algal monoculture can be seen to stem from two origins which reflects the different communities who have been working within the phycology domain. Firstly, within the mindset of process engineers from biotechnology and pharmaceuticals where control over the organism is paramount to ensure safety of the product. Use of antibiotics, aseptic technique and genetic manipulation are cornerstones of this approach. While this can be successfully scaled up for valuable therapeutic products in other host organisms, there is an inherent challenge in trying to apply this mindset to outdoor culture in the volumes required (Carney and Lane 2014). Algal cultures have much lower cell density and much more extended elaboration times than bacteria or yeast typically employed in biotechnology processes. Maintaining the strain of interest has been important for yielding triacylglycerols for biofuel or astaxanthin for antioxidants in mass culture, and much of the tacit knowledge of scale up derives from these two applications. The second influential domain has been the need for pure culture to study the physiology of photosynthesis. Certain species, such as *Chlorella*, *Chlamydomonas* and *Phaeodactylum* have become model organisms thanks to the relatively facile cultivation. The choice to study a few model species intensively to gain translatable knowledge that can be applied to other species (Bolker 2019) has led to many advances in

FIGURE 11.3 *Algaegarden* – installation of steel and wooden frames, with hanging pods containing algal cultures. Exhibited at the Reford Gardens for the Metis International Garden Festival, Quebec, CA, 2011–13. Team: Wayward Plants / Heather Ring in collaboration with Brenda Parker and Synnøve Fredericks. Partners: Canadian Phycological Culture Centre, NutrOcean Rimouski, Martin Cooper (Engineer)
PHOTO CREDIT: LOUISE TANGUAY

our understanding of light harvesting and metabolism in algal species. Model organisms are typically easy to grow in monoculture, or have been demonstrated to be resilient within a laboratory environment. Nonetheless these algal species can be a source of anchoring bias whereby many phenomena observed in these experimentally tractable organisms elevates them to an enshrined status within applied phycology. In the 1930's at Harvard University graduate students formed "Chlorella club" – the members included Charles Stacey French and Peisong Tang who would go on to make enormous contributions to our understanding of photosynthetic processes (Zallen 1993). The vivid green of *Chlorella* is often a synonymous with the imagery of microalgal culture, and the study of this organism for biodiesel production has vastly expanded the expertise in mass cultivation.

In the contemporary sense, designers working with biology have inherited a legacy from these schools of thought regarding monoculture. There may also be ideas that to be accepted within an interdisciplinary field it might be advantageous to work with recognised organisms. In addition, there is a further aesthetic dimension to the use of monocultures. Separation of algal species enables a consistency and purity of pigment. In the case of green algae such as *Chlorella* this represents chlorophyll, or a blue-green mixture of chlorophyll and chromoproteins in cyanobacteria (Jeffrey et al. 2011). Diatoms are a rich brown because of carotenoids such as fucoxanthin (Kuczynska et al. 2015). Other pigmental changes are induced by stresses on the culture system, for instance beta carotene production is triggered in hypersaline conditions in *Dunaliella* creating a vibrant pink hue, and astaxanthin produced by high light or nitrate deprivation of *Haematococcous pluvialis* turns the culture crimson. Beside functional advantages of monocultures, an underlying, perhaps more unconscious, aspect to this lies in the expectation and drive towards sterility and cleanliness when producing any type of growth outside its original environment. The homogeneity of a monoculture instinctively implies a level of control – it feels safer than the heterogenous and potential hybrid biofilm where pathogens may breed.

5 The *Algaegarden*

The application of monoculture in a design context was tested in the art installation *Algaegarden* (Figure 11.3) created by Wayward Plants led by Heather Ring in collaboration with Brenda Parker and Synnøve Fredericks for the Métis International Garden Festival in Quebec in 2011 (Reford Gardens 2011). *Algaegarden* celebrated the beauty and productive potential of algae through a design that underlines its diversity and meaning. It deliberately presented individual species in hanging pods in order to invite a closer dialogue and understanding. The project aimed to create a narrative environment where visitors could experience and engage with algal cultures through the air pumps that enabled bubbles to race through the hanging tubes (Figure 11.4). Algae, often considered a nuisance, become an object of secret beauty and curiosity. The installation chose to amplify a selected number of individual species of algae through their presentation in rows to create an immersive sensation of being surrounded. Referencing an aquatic edge, the garden was lined with pond grasses to reference the types of ecosystems that one might encounter planktonic organisms such as algae. The interactivity invited the visitor to consider how to be more aware of the ecological roles of these organisms and their significance as well as evocative colouration.

The organisation of the garden by species taps into the human need for systemising nature – grouping by taxonomy. Botanic gardens have a long legacy

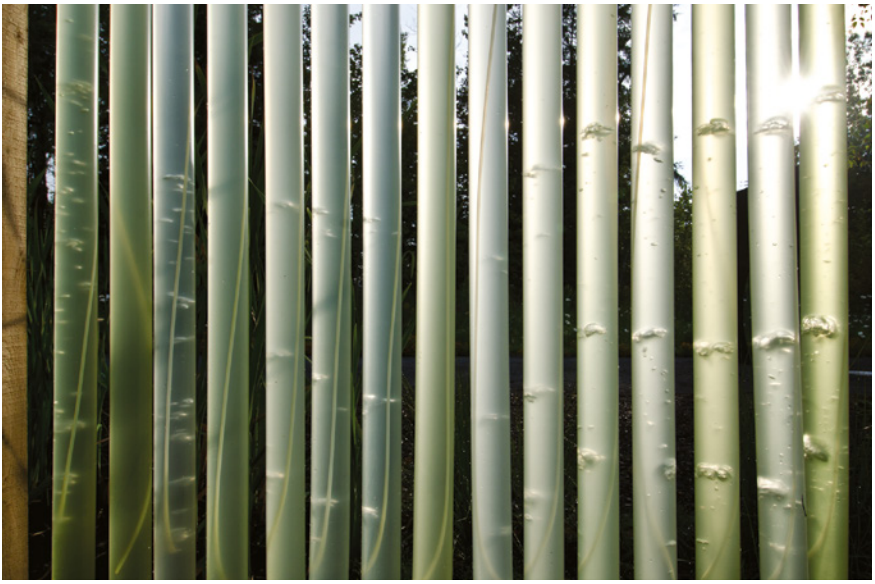

FIGURE 11.4 *Algaegarden* – detail of bioreactor tubes containing *Chlorella* cultures
PHOTO CREDIT: LOUISE TANGUAY

of systematic beds where plants are presented according to their evolutionary relationships. Here, in this case the colour spectrum was used as a proxy for biodiversity within the installation. Algal cultures collections enable us to understand an organism by the provenance: the location it was isolated from, by whom and what year. After the peak of the algal biofuel era, it felt urgent to reconnect humans to the vital role of algae in our ecosystems. Each algal species presented within the garden had a story illustrating its importance within ecology, commerce or our understanding of plant physiology. Golden brown *Pavlova lutheri* was supplied by a local aquaculture company who used it to feed oysters at a hatchery; a pink *Porphyridium purpureum* because of the pigment phycoerythrin, and CPCC 90 – the same species of *Chlorella vulgaris* used by Emerson to calculate the quantum yield of photosynthesis. Algae pods were prepared with media and nutrients to sustain the cells for a short season as the installation was a temporary one created for the festival without the goal of long-term culture maintenance. Therefore, preserving the organisms as single species within the pods was vital to the readability of the design and the message of the garden. Contamination was reduced through the positive pressure created from pumping the bags with the aeration system, but it was not controlled for.

6 Challenging the Format of the Bioreactor: INDUS

Taking the B.I.Q. House and the *Algaegarden* as valuable departure points for scale-up, the project INDUS, designed by Shneel Bhayana, Brenda Parker and Marcos Cruz for the A/D/O Water Design Futures competition in New York in 2019 (Figure 11.5), sought to question the format of a bioreactor entirely. By placing algal cells inside a matrix and circulating water over the surface it enables a departure from the mere design of a "vessel". In addition it offered the opportunity from a technical standpoint to understand how immobilisation might be used to reduce energy consumption and challenges of separating algal cultures from the liquid media. Building upon previous work on additive manufacturing of viscous membranes (Bhayana et al. 2020), hydrogels were used to maintain the algal cells in a favourable environment. Rather than printing the hydrogel layer-by-layer into three-dimensional morphologies, a ceramic scaffold was designed and moulded to host the hydrogel with immobilised algae. As an application, the issue of scalability in the outdoors was addressed in the context of water pollution. Bio-integrated design was used as a method (Cruz and Parker 2021) that offered a dual advantage wherein not only the material but also the scaffold for its growth was designed to embed this new living system.

The INDUS project was conceived as a tile-based, modular bioreactor wall with the goal of cleaning water through bioremediation. The design of INDUS reflected an interdisciplinary approach to the vast and nebulous issue of water pollution that poses a significant threat to human health (Landrigan et al. 2018). By embedding ethnographic research, scientific research, computational simulation and material studies it used a holistic approach to the design (Parker et al. 2022). The project evolved from a series of site visits, case studies and interviews between 2014 and 2018, including a community of artisans, a panchayat, who manufacture bangles in a region outside Kolkata, India. A case study site within the Howrah Domjur informal bangle and ornament letting industries, a two-room building with a soil pit for waste, became the departure point for subsequent design renders. The community reiterated the need for a simple, scalable and a sustainable system to treat heavy metal contaminated wastewater on a local level due to changing regulation from the Central Pollution Control Board. In response, the design made use of vernacular materials and traditional clay making methods. Inspired by the architecture of a leaf, water was envisioned to flow over a series of vein-like channels containing algae prepared in a seaweed-based hydrogel developed previously (Bhayana et al. 2020). The main objective was that pollutants such as cadmium were

FIGURE 11.5 *INDUS 1.0* – ceramic tiles with extruded algae-laden hydrogel, 2018–19. Team: Shneel Bhayana, Brenda Parker, Marcos Cruz and the Bio-Integrated Design Lab at UCL

PHOTO CREDIT: SHNEEL BHAYANA

sequestered by the algae and the hydrogel could then be processed to recover heavy metals safely.

In parallel to the design evolution, experimental validation of performance with a range of algal species and studied uptake kinetics of heavy metals such as cadmium was carried out. Building upon previous work (Scarano and Morelli 2003; Torres et al. 1998), laboratory tests (Stoffels et al. *unpublished data*) confirmed the uptake of cadmium by microalgal cells encapsulated in hydrogels as well as the production of cadmium nanoparticles by actively growing cells of *Phaeodactylum*. The aim was to enable the rural community of artisans to regenerate water for reuse within their manufacturing processes. The modularity of the system was deliberate as this enables the communities to construct this wall depending on the site availability along with the amount of water to be treated. INDUS was designed to be integrated within the existing community, which can be customised and also reflect the cultural identity of the region. Unlike conventional water treatment facilities, the leaf-like tiles complete with their "veins" when assembled into a wall add ornamental richness (Figure 11.6). This aspect of the decorative sought to instill pride and encourage visibility to what otherwise what could be a very alienating apparatus in a very rural context. Its morphological expression was aimed to generate a sense of empathy of users when engaging with its technology, while adding to the traditional pattern-like motifs of India. It could be supported on free-standing or existing walls of densely populated industrial clusters.

The long-term vision for such a bioremediation system is to understand the value of materials recovered. In the case of cadmium, metal nanoparticles synthesised by the algae can present a source of revenue (Cueva and Horsfall 2017). This can potentially create an incentive-based closed loop system, removing pollutants from the cycle entirely. INDUS has potential to become a precursor to existing constructed wetlands (Scholz and Lee 2007) or work in tandem with technologies such a microbial fuel cells or biophotovoltaics obtaining a higher efficiency of wastewater treatment. The visibility of the system encourages communities to engage with and consider the impacts of water contamination and environmental clean-up. Further, the design and fabrication of the wall gives a new dimension to traditional clay making practices.

A modular demonstrator wall of INDUS 1.0 was built outdoors for the Brompton Design District at London Design Festival in 2019. Tiles were computationally designed based on a generative algorithm which recreates biological patterns. From this, a mould was cast and tiles produced by hand pressing. A drip irrigation system was used to maintain moisture of the hydrogel component. It was apparent that while the deep channels and geometry of the tile enabled stable residency of the hydrogel, there was a need to decrease

FIGURE 11.6 *INDUS 1.0* – installation in exhibition at the Brompton Design District, London Design Festival, 2019. Team: Shneel Bhayana, Brenda Parker, Marcos Cruz. Collaboration: Bio-Integrated Design Lab at UCL. Ceramic casting: Richard Miller, Froyle Tiles, UK
PHOTO CREDIT: SHNEEL BHAYANA

the speed at which water flowed over the surface. A further design iteration of INDUS 2.0 considered the idea of *lentic* and *lotic* zones (Figure 11.7). Borrowing from riverine ecology, these terms define regions of still and flowing water respectively. In the lentic zone of INDUS, water flows more slowly and the contact with the hydrogel is longer. The lotic zones are faster, and more turbulent. To facilitate uptake of cadmium by the immobilised algae retention times would be extended through the lateral striations, increasing the proportion of lentic zonation to slow water flow over the surface.

In terms of architectural precedents that have explored the cultivation of a mixture of species, the concept of immobilisation had been explored in the *Alga*(*e*)*zebo* installation by the team marcosandmarjan – lead by Marcos Cruz and Marjan Colletti – for the London Olympics in 2012 (Figure 11.8) The design of the bioreactor vessels permitted the ingress of aerial organisms. Using a matrix of semi-solid agar, wild cultures could mix with laboratory strains of algae previously inoculated and viewed inside the transparent columns. The *Alga*(*e*)*zebo* intertwined human artifice with natural surroundings, working

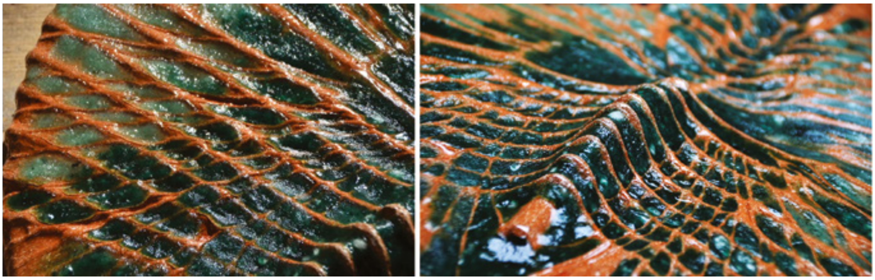

FIGURE 11.7 *INDUS 2.0* – ceramic tiles with extruded algae-laden hydrogel, 2019. Team: Shneel Bhayana, Brenda Parker, Marcos Cruz. Collaboration: Dali Alnaeb and Aurora Tairan Li. Ceramic casting: Richard Miller, Froyle Tiles, UK

PHOTO CREDIT: SHNEEL BHAYANA

FIGURE 11.8 *Alga(e)zebo* – photobiorector with multiple algae species from the surrounding embedded in double curved steel structure. Installation located at Euston Square Gardens built on the occasion of the London Olympics, 2012. Team: marcosandmarjan (Marcos Cruz and Marjan Colletti). Manufacturer: Formstaal / CSI, Stralsund Germany. Engineering: Bollinger, Grohmann und Schneider, Vienna Austria. Photobioreactor: Richard Beckett / DMC London with UCL Algae

IMAGE CREDIT: MARCOS CRUZ

from the microscopic scale to the interaction with vegetation and trees, examining the complex boundary negotiations that take place between architecture and nature in contemporary cities (Cruz and Coletti 2016). The provocation was to suggest architecture is behaving and looking more like a biological construct, whilst nature is manipulated via human interference. In one sense, the use of a viscous matrix for the immobilisation of algae unites both INDUS and the *Alga*(*e*)*zebo*. However, there is an important difference in terms of ambition and functionality. While the remit of INDUS was directed at the needs of a community facing water pollution in a resource-constrained site, the *Alga*(*e*)*zebo* was a highly elaborate construction located in central London. The challenge, yet also the paradox of INDUS, however, was that the design is celebrated for an aesthetic that relies on the installation staying pristine and clean despite the goal of treating polluted water. Although ultimately aimed for an outdoor environment, it did not encompass the effects created by the natural weathering process in which chemical changes of the material, dusts, the colonisation of new species or any ecological disturbances trigger profound changes of the overall surface. INDUS was conceived and designed with an immobilised single species relating to a biotechnological agenda of bioremediation performance that was supposed to maintain a permanent sense of newness, avoiding the unpredictable murky impacts of time.

7 Towards Polyculture and Interkingdom Interactions

> No claim for novelty can be made for mixed cultures: They form the basis of the most ancient fermentation processes. With the exploitation of monocultures having been pushed to its limits it is perhaps time to reappraise the potential of mixed culture systems. They provide a means of combining the genetic properties of species without the expense and dangers inherent in genetic engineering which, in general terms, aims at the same effect. (Harrison 1978).

In nature, monoculture is seldom found. While organisms may dominate a particular ecological niche, for instance extremophiles, this is usually down to a selection pressure. For instance, in the case of algae adapted to high pH levels they have relatively few competitors due to the niche environment. Availability of carbon, and other key nutrients is a limiting factor on the diversity a system can support. Mutualism in algal-bacterial systems and the formation of stable consortia is based on inter-kingdom exchange of resources (Rawat et al. 2021). Our understanding of the constant communication between trophic levels of the food chain is still nascent. Take for example, microalgae and bacteria trading Vitamin B_{12}, using a currency of carbon (Croft et al. 2005). We are beginning to unravel the metabolic exchanges – albeit painfully slowly via a process of eavesdropping on conversation and trade between organisms. The relationship between algae and bacteria facilitates tasks that either organism alone could not accomplish. For instance, in most aquatic environments, including wastewater, iron is scarcely bioavailable due to poor solubility. Bacteria have evolved pathways to secrete metal-chelating compounds called siderophores that can bind to iron and enable transportation within the cell. These public goods are the basis of a complex eco-evolutionary dynamic between heterotrophic bacteria and autotrophic organisms (Amin et al. 2009). Capitalising on fixed carbon from photosynthesis, algae shed polysaccharides and monosaccharides into the phycosphere (Seymour et al. 2017), an important region in the microscale relationship between cells. This dynamic proximity enables food security for the bacterial partner, while resourcing trace elements and vitamins for the phototroph.

This alliance may be invisible to the naked eye in a planktonic state, but frequently this takes on a physical presence between bacteria and algae in form of a biofilm. Biofilms are defined as 'aggregates of microorganisms in which cells are frequently embedded in a self-produced matrix of extracellular polymeric substances (EPS) that are adherent to each other and/or a surface' (Vert et al. 2012). EPS, or slime, is composed of various extracellular biopolymers which suspends the community, and enables the system to embody properties distinct from individual members (Flemming et al. 2016). Elaboration of biofilm-based structures requires an understanding of their formation and ecology, distinct from the single organism as described previously. Algal biofilms operate as intricate societies, with cooperation between some microbes and conflict with others (Queller and Strassmann 2009) while maintaining a resilience to environmental perturbances.

In the context of a future iteration of an INDUS bioremediation wall system based on consortia, cooperation exists at the microscopic level in order to maintain the overall community structure via mutualism, cross-feeding or syntrophy (Cavaliere et al. 2017) or through the formation of eco-evolutionary partnerships from environmental isolates (Borchert et al. 2021). Meanwhile at the macroscale, we must simultaneously consider how to design for a pattern of activity that is materially, morphologically and contextually determined. Autotrophy powers the biofilm community, and exchanges of nutrients within the slime manifold enable the system to create a very robust matrix, counteracting the forces of precocious decline or deterioration in fluctuating conditions. We are still in the process of understanding the myriad mechanisms

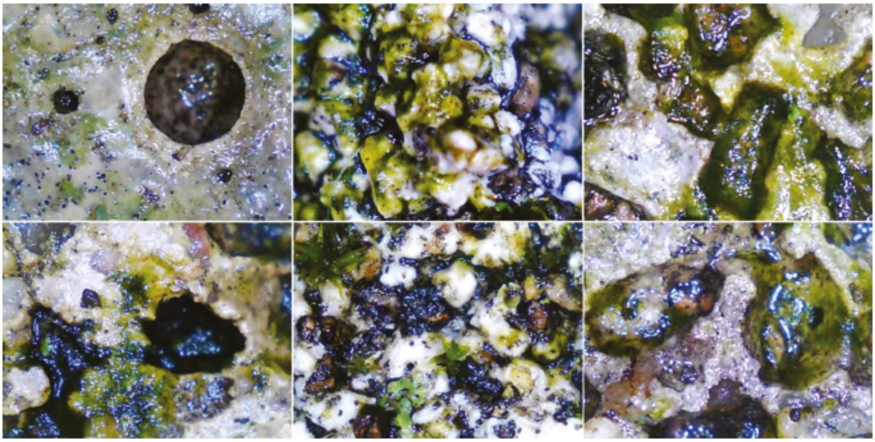

FIGURE 11.9 Algal biofilm formation on concrete scaffolds
IMAGE CREDIT: MARCOS CRUZ

of microbial cooperation (Buhmann et al. 2016; Nowak 2006; Villa et al. 2015) facilitating the emergent properties of the system. But what we do know is that these biodiverse algal biofilm communities create nutrient-rich substrates that in time are vital to the long-term and self-sustained nature of other forms of life that are integrated in large-scale constructions.

Design of algal ecosystems therefore navigates the boundary between the artificial and the natural. It has been previously stated that one should not confuse "biological" with "natural" when considering artefacts of our ingenuity (Simon 2019). Humans are profligate ecosystem engineers, through the modification of biotic and abiotic materials. In the previous case of INDUS we acted as allogenic engineers, as we modify materials such as clay to become ceramic and alginate to become hydrogel. Ultimately as we move to creating materials capable of bioreceptivity or biocolonisation we seek to create structural scaffolds in our built environment (Figure 11.9) to scale-up while augmenting biological performance, making us ultimately become "autogenic designers" (Jones et al. 1994). That is to say, we are capable of modifying our environment and resource exchanges through our own physical structures. This has significant implications for our methods of design and fabrication. While the overall ecosystem service of a building or an urban infrastructure may be agreed upon, the architecture will vary when considering designing in a microbially-centred manner vs a more traditional programme, space and form driven approach. We predict that here lies the tension, but also complementarity, of the bio-integrated design method (Cruz and Parker 2021), which negotiates the territory on an equal weighting.

8 Urban Abject Biofilms: The Preston Road Wall

In our aim to animate the built environment by promoting the biocolonisation of building surfaces, there is, however, a “germ of disequilibrium” to borrow a phrase attributed to MacNeice (Kearney 1979) where, despite the rationalisation of the biofilm as a highly sophisticated organisational unit that should appeal to our innate biophilia (Wilson 1984), it can invoke for most people very negative qualities, especially when grown into larger and more complex substrates. To understand this, it is worth looking at it from an aesthetic and cultural perspective. The biological hybridity and material viscosity of such humic strata create dark and slimy conditions, which potentially place it into the category of the abject (Kristeva 1982). Visually, they have formal associations with conditions that trigger our response to what is culturally mostly repressed in our body – excreta such as snot, pus, sperm, etc. Biofilms are filmy, scummy, curdly, mucky and viscid and therefore imbued with a sense of lowness due to their defiling appearance. This sits in close proximity to our boundaries of revulsion at the indeterminate and unresolved. The relationship of nature to body and mind creates ultimately a link to decay as a proxy for death.

Our built environment is exposed to a natural weathering process that makes all its outdoor surfaces prone to be receptive to biofilm formation. Encounters with such emerging biofilms are often signifiers of the unkempt and neglected areas of a city. Disrepair creates areas that are so common in our cities where pipework creates uncontrolled flows of water over brickwork, as for example seen at Preston Road Station in London (Figures 11.10 and 11.11). The presence of green, brown and black slime is a *memento mori* for the human observer. Leaking surfaces in city walls accumulate lots of growth, forming what could be considered highly unpleasant features that are associated with damp and decaying places. The presence of moisture enables the establishment of a complex biological infrastructure to form an ever-evolving “life soup” (Miller 1997). But in reality, these areas are saturated with vitality and the potential for growth. Successful establishment of the initial colonists by a process of adsorption triggers production of the EPS bioadhesive and an irreversible binding of a collective of cells (Bixler and Bhushan 2012). The final stage of biofilm colonisation involves dispersion and propagules colonise new habitats.

Microalgae are the most recognisable component of outdoor biofilms due to their abundance and pigmentation (Gaylarde and Gaylarde 2005). They form highly rich microbial, phycological or cryptogamic environments. This results in biodiverse polycultures full of excreting matter – soggy, clammy, slithery, sticky, tacky and dank. Soon, a synthetic biotope – an ecosystem created by

FIGURE 11.10 Synthetic biotope – leaking wall with biofouling at Preston Road Station, London, 2021
PHOTO CREDIT: MARCOS CRUZ

anthropogenic activity – is generated that is teeming with life, attracting inorganic sediments of dust particles, fibres and hair. Fed by humic matter, bacteria, cyanobacteria and algae, mosses and fungi proliferate to eventually form a rich microbiome that feeds the ecological succession of plants. For common architecture, however, this natural and highly site-specific phenomenon represents a fundamental challenge: the predictive dimension of design feels undermined and redundant when biology generates unpredictable growth conditions that are hard to forecast. At the same time, biofilm and biotope formations imply ugly states that are difficult to accept in a discipline that had for long as its ultimate goal the creation of beauty and purity. Our society has developed an intolerance towards 'dirty' and stained surfaces, especially when produced by nature's growth: it means that any visible biofilms in our immediate surroundings have to be removed – the result of a sanitation impulse that in our Western culture has symbolised for long a 'higher' status of civilization and cultural differentiation.

Design, in particular, has followed all-encompassing concepts of cleanliness (Vigarello 2008) and promoted hygiene aesthetics (Forty 1986) that has avoided heterogeneous, rough and viscous conditions in favour of more homogenous, smooth and matt finishes, a phenomenon epitomised with architecture's 'Modern whitewash' (Wigley 1996). In an ultimate instance, architecture has repressed any evidence of the abject in pro of clean-looking, clear and flat morphologies. In fact, our societal expectation has been constructed around an aesthetic and ecologic baseline principle in which biodiverse walls filled with messy growth are considered problematic, with too many irregular and patchy patterns. They contradict established norms and categorisations. As such, the scientific vocabulary switches to describing the biofilm as biofouling, with anthropocentric characteristics of stubbornness (Monroe 2007) and recalcitrance. The abject is here not an objective condition but instead a culturally constructed judgement of dirt and pollution where species and growth are mostly considered what the anthropologist Mary Douglas so famously defined as "matter out of place" (Douglas 1966).

At the same time, there is an inherent relationship with the uncanny (*unheimlich*) that has to be acknowledged when these biofilms occur in an overtly exposed context. Would they be inert or inorganic, they may not create too much of a problem, but anything that is alive in this form triggers a potential sense of disgust, and ultimately our innate fear that it all could overgrow and expand. Abject biofilms trigger an instinctive sense of defence from what could be polluting or contaminating matter that inflicts us harm. Ultimately, it is our visual perception and any possible smells that instigate our subconscious that is fed by our primal experiences of touch and taste. Geosmin and 2-methylisoborneol are compounds with musty and muddy aromas produced by members of the actinomycetes, cyanobacteria and green algae that can be detected by humans at low thresholds (Jüttner and Watson 2007). Viewing biofouling matter suggests the prospect of "unnerving touches, nauseating smells, foul odours" (Miller 1997). The real problem of putrefaction is not so much the biological content, but the simple phenomenon of being 'potential' which makes it all feel disturbing. One does not know what to expect and how much these biofilms and substrates could take over in time. There is also a problem with our difficulty to identify the filmy goo that will in time become overgrown with vegetation. There is a lack of terminology to objectively describe such conditions that seem to defy our orders of classification, challenging the aesthetic hegemony of a "specific model" of beauty (Eco 2011). Newly formed biotopes can have undefined and ambiguous contours and colouration. The more life they have the more they could feel like being too cluttered, disordered and uncontrolled. The biotope's lush ends up being uncanny because it is anomalous nature – disturbing, but highly vital.

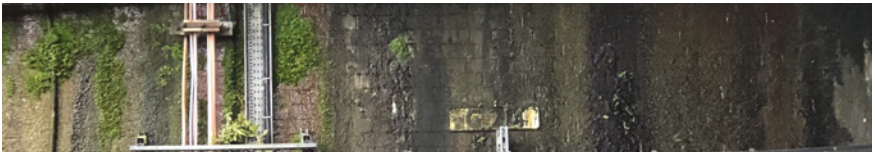

FIGURE 11.11 Synthetic biotope – abject biofilms at Preston Road Station, London, 2021
PHOTO CREDIT: MARCOS CRUZ

9 Biofouling and the Regenerative Power of Decay

Key to the formation of synthetic biotopes is the occurrence of biofouling in which biofilm formation and bacterial adhesion on a building surface produces a first phase of microfouling. This is then followed by an attachment of larger organisms which defines a second phase of macrofouling. This results in the decay of organic and inert matter which in turn has a vital regenerative power for the system to be kept alive. What was once fully growing will at some point fade away. Species and matter will age and degrade and in time shift to a yellowish, brownish or darkish hue; it may wilt or rot and gradually decompose, producing a nutrient-rich substrate to feed other forms of life. At the same time, alterations to physico-chemical parameters or temporal changes within the environment can promote heterogeneity within a biofilm (Wimpenny et al. 2000) In terms of aesthetics, on the other hand, the integration and scaling-up of polycultures and their life cycles in the built environment allows for a new type of design method where abject features define a basic “creative formlessness” (Douglas 1966) for growth and decay to become essential performative and formal parameters.

We need to assume the impacts of algal biofouling and the epibiotic accumulation of matter on building surfaces. Ultimately, it is important that we design for what is aging as opposed to our common expectation that buildings will look for ever new (Cruz 2021). Even more so does this apply to the homogeneous ever-green appearance of common green roofs and walls that, similar to monocultures in bioreactors, have been conceived to remain pure, therefore requiring a costly and unsustainable apparatus to be kept unchanged for long periods of time. On the contrary, we need to embrace a new approach to design that rejects two key aspects: architecture’s obsessions with the eternally stable, clean and geometrically controlled, and horticulture’s demands for a biological efficiency that is purely functional and mechanistic. We need to delve into a more spontaneous and surprising, also far more provocative and even disobedient aesthetic.

Historically, elements of the fecundity of crytogramic takeover of structures may be seen in the Gothic (Hughes et al. 2015), and mostly in Romanticism where the effects of time and weathering produced an existential cycle between the natural and synthetic. From the medieval fascination with the monstrous to nineteenth century obsession with imperfection, incompleteness and cyclic entropy, the return to the darkness and dankness of growth on buildings is abundant in these periods. The imagery is nostalgic, yet also exuberant and transgressive, invoking sex and death. It also speaks of unravelling, madness and the esoteric – characteristics later exorcised by the clinical treatment of twentieth century Modernism where stained, deformed and degenerated conditions became aesthetically unacceptable.

10 Phases of Bio-Integrated Design for Heterogeneity

How do we reconcile incongruous values of biofouling, the abject and ugly with the functional in our future cities, especially one with aspirations to be photosynthetic? To examine this, the phases of design in a biologically integrated manner has to be explored. Echoing the three stages of growth in cell culture – lag phase, logarithmic phase and stationary phase – the evolution of an outdoor bioreactor might be anticipated. The role of autogenic design is here to synthesise computation, fabrication and biology in a manner that can be augmented and "read", reflecting different stages of its lifecycle.

Considerations include the role of morphological variation and the intersection of environmental parameters, including moisture, light, nutrient level, etc. all of which are essential for the long-term creation of a synthetic biotope. This designed area offers environmental conditions providing ultimately a place for a specific assemblage of microbes, plants and animals. By developing a nomenclature to describe the phases of colonisation and development of sub-aerial biofilms on a designed substrate we may begin to understand how to interpret the lifespan of placing this outdoors. Here, we suggest three phases that can be actively considered and designed for, and a fourth phase where control is relinquished to the succession of organisms.

1. Inchoate phase of the design is an incipient, nascent stage, prior to establishment of visible algal biofilm growth. Here the material scaffold in form of a building roof or façade is presented. Depending on the context, a design may remain in this state for several months or years. Bio-colonisation of bacteria and algae and a shift from this latency period has been modelled previously for common architectural substrates such as brick (Quagliarini et al. 2021).

The rate of progression into the next phase may be through deliberate design, material choice or manipulation of environmental parameters as potential interventions for augmentation of bioreceptivity.

2. Burgeoning phase of the design focuses on the proliferation of growth in regions where surface roughness or water activity is favourable for growth, which may be predicted by Avrami's Law (Tran et al. 2013) to predict the temporal evolution of attachment and colonisation to a surface. This may not be uniform. It may be seen as the formation of a heterogenous patina of rich algal ecologies on the surface, or an accumulation of layers. The role of the scaffold is to support this and create desirable conditions of hydrodynamics and light exposure. In this phase materiality has a role to play in zonation – defining areas where growth is facilitated and limits where the scaffold surface is exposed.

3. Confervant phase of the design explores a moment of great intensity where the material has an abundance of growth that is well established. In this phase the design and biology work in tandem. The biofilm will have an internal heterogeneity of pH or light penetration, resulting in a dynamic system that may undergo taxonomic shifts at the community level but maintains functional structure. Here, the emergent properties of the system (Flemming et al. 2016), for instance bioremediation or nutrient uptake, become apparent. The algal biofilm will also have an external heterogeneity of colouration and texture, dependent on the composition and species associated.

4. Biocoenosis phase is the last stage in which the functional bioremediation process shifts towards a more uncontrolled bioreceptive moment. In this phase interacting organisms live together forming a highly complex ecological community with inter-species interactions shaped by evolutionary forces (Lee and Ryu, 2021). Cryptogramic and vascular species are established and intertwined in what is the emergence of a synthetic biotope on a building scale. This phase recognises that with biodiversity will come a multiplicity of forms, and will transcend the microbial.

Revisiting Guillette's work (Guillitte 1995), the term *quaternary bioreceptivity* has been proposed, where a structure may be coated to become more hospitable to colonisation (Sanmartín et al. 2021). A secondary material, such as a water retaining hydrogel (Snoeck et al. 2022), is applied or impregnated into the surface in order to enhance the ability to attract biological life. In this phase the materiality is paramount. Within the lens of design this may be considered in two ways. It may take form of seeding of algal biofilms through deposition directly, or through an initial phase of artificial biofilm created in a hydrogel structure. Parameters such as surface roughness, porosity and permeability will determine the rate at which a biofilm adheres or establishes. Designing with this mechanism of enhanced bioreceptivity in mind may accelerate the transition between initial phases to realise a performative ecosystem service.

11 The Future Human Habitat Lab of St Andrew's: Polyculture Design and Embracing the Abject

These design stages define the underlying methodology of the future lab at the St Andrew's Botanic Garden in Scotland – an experimental project aimed to create the prototype of a fully grown building that is tested and understood and ultimately applied to create a forthcoming photosynthetic human habitat (Figure 11.12).

Speculating on the evolution of such a project over a matter of years, we may anticipate how the phases described above may manifest over the various transitory states. In the initial phase, such a construction may embed elements

FIGURE 11.12 *Future human habitat lab / Bio.HAB* – sketch of building with merging synthetic biotope. Proposed location: St Andrew's Botanic Garden, Scotland, 2021. Team: Brenda Parker and Marcos Cruz
IMAGE CREDIT: MARCOS CRUZ

of photosynthetically biomineralised engineered living materials (ELM) which will follow the progression from *inchoate* to *confervant*, becoming progressively more structural (Tamuli et al. 2021). Comprising of cyanobacteria and silica aggregates, the ELM will provide a tectonic presence. The gradient of semi-translucent components allows for light to be embedded in the building in a variable degree of intensities without the need for traditional windows or openings.

Biocolonisation of other parts of the living lab will take place on designed synthetic biotopic zones, created through the intersection of materiality, porosity and water flow. Selection pressures from the ambient environmental conditions and seasonality may favour aerial, or poikilohydric organisms, which later become enmeshed in the exopolymeric material of an algal biofilm. The pristine walls will become murky and pigmented as regions of growth establish and augment over time. A disobedient ecology, as the botanist Mark Spencer would call it, is unfolding that blends surrounding landscape with the building's surface morphology. It results in a somehow creepy, but also extraordinarily alluring scene of unprecedented dimensions – engaging and immersive, the project starts defining a radically new aesthetic. The gradual formation of the biofouling repels and even provokes initial revulsion, yet compulsion to touch when experienced from very close. In this way the building confronts the limits of social acceptability. It may even elicit outrage provoked by disgust and fear of disease and the complex relationship of humans to what they may perceive as contamination (Davey 2011).

As our conception of humans as holobionts becomes more prevalent, this building may become a fascination, especially when viewed as a provocation of how we may envision a microbiome-inspired green infrastructure (MIGI) within landscape design (Watkins et al. 2020). MIGI promotes interactions between humans and environmental microbiomes, with explicit considerations for sustaining microbially-mediated ecosystem functionality and resilience. In this way, the ecosystem services provided by such a building as a hub for beneficial organisms for immunoregulation or bioremediation are placed at the foreground. Pathogens co-exist and are kept in balance via the presence of far more pervasive pre- and probiotic communities, creating a microbial equilibrium in the system that is beneficial to us. MIGI seeks to apply the "Old Friends Hypothesis" (Bloomfield et al. 2016; Rook et al. 2003) whereby dysbiosis is prevented through the creation of a varied exposome (Robinson and Jorgensen 2020) which could be generated by the *confervant* and *biocoenosis* phases of the design. The result is a scenario that is defined by its moist viscosity and a rather obscene biological beauty as well as a growing sense of connection to our own health (Flandroy et al. 2018). Over time, algae and microorganisms are no longer the only species present. The building flourishes and development of the *biocoenosis* becomes apparent. Common species give way to more rare species in a visual and dynamic display of biodiversity (Goulden 1969)' triggering a process of ecological re-wilding that makes it feel all rather rambunctious (Marris 2011). The scientific opportunity to examine inter-kingdom interactions and succession within this bioreceptive environment creates a bridge between the empirical and experiential. Considering our place in a microbial world (McFall-Ngai 2015), and our relationship in terms of the climate (Cavicchioli et al. 2019) will require an empathy and understanding of the "other".

A key aspect to achieve this positive shift in perception is the aestheticization of biofouling and abject biofilm formations. Several compositional features are important to help us engage and appreciate this living spectacle. The most important parameter is the overall readability of the biotope that acquires objectual qualities that are nonetheless interpreted in a highly subjective manner. The clarity of the building or wall tectonic is therefore crucial which can be achieved when applying Gestalt Psychology principles such as integral dimensions, emergent features, configural superiority, global precedence, primacy of holistic properties, law of *Prägnanz* (Wagemans et al. 2012). Most important are legible contours (macro geometry) and/or specific reference spots that are recognisable amongst the spooky and heterogenous micro landscape of algal biofilm formation. No matter what, our eye will look for anchor points within the filmy and vegetative clutter, making sense of inherent relationships in search for a reassurance of scale and intention of what is proliferating on the walls. This can be done by strategically setting intelligible features that can be understood amidst the overall wall composition. Familiar geometric forms or identifiable species, for instance, will enable this. At the same time, figurative qualities of the underlying surface morphology as experienced in figural ornaments of our past heritage help to overcome the predominant abstract dimension of biofouling. Especially when the surfaces have patchy gradients of intensity and colouration along with what looks like randomly scattered growth, figurative elements help mitigating the unfamiliarity of the biotope, in fact reversing our initial scepticism towards a growing attraction. Repetitive and single orientated protrusions or infolds will create topological variation as well as specific shadow plays that can further help the readability and enhance our curiosity. Amidst the unpredictability and unfamiliarity of the biotope, we are now not only able to validate the system but finally indulge with it.

In the applied sense the building surface may be considered an exo-bioreactor, or in the ecosystem sense it is a synthetic biotope. Regardless, the role of design is to negotiate the precarity of how the formal and poetic expression can overcome accepted norms of aesthetic presentation while maintaining scientific validity. The ugliness of the project offers a contemporary form of beauty and splendour – a contemporary sublime. In this context, the Burkean concept of sublime is distinct from beauty (Burke 1757). The sublime delves in the awe of the extraordinary but also contains elements of fear of the uncanny. It is a painting in a murky palette which transcends death and scale. The notion of the sublime encompasses the terrible to elicit a deeper response. In this way the infinite and irregular nature of such designs can be understood. But the sublime is here also grotesque due to the exaggerated and overtly visceral qualities that it implies. Design in this context offers a means to interpret the complex phenomena and allows the public to overcome loathing, towards a new acceptance of biological uniqueness and ever-changing complexion.

12 Conclusion

In this chapter we explored how algal monocultures are a well-established and highly efficient production system, with defined outputs and an inherent beauty of pigmentation. Nevertheless, they are dependent on complex apparatus to support purity. The B.I.Q house and the *Algaegarden* are examples of how such bioreactors have been applied to larger-scale constructs. The energy expended in maintaining the monoculture through mechanical procedures is unsustainable in the outdoor context. To achieve the ambitions of a truly bio-integrated architecture, there is a need to rethink our practice. Polycultures are more hybrid and less explored by design. Due to their multiple species cooperation and when exposed without any mechanical protection, they are more capable to survive in external conditions. They create resilient consortia that are self-regenerative and exist in constant exchange with the surroundings. In this context, algal biofilm formation is essential to establish such highly enriched ecologies. As a product of the design, algal-bacterial interactions are fostered, which when established exhibit emergent properties of bioremediation and/or microbiome-inspired green infrastructures. Yet the design and form cannot seek to emulate the monoculture, it requires its own aesthetic to deal with heterogeneity. Biofilms are viscous and become murky in time. They have an adverse visual impact that is associated to the abject. These conditions have been historically rejected as they reflect a sense of neglect, decay and disease that is supposed to be threatening us. Yet this perception is finally shifting, not only because of a recognition how ecologically rich and diverse these biofilms are, but also due to the emergence of a new design protocol that accepts the material impact of biofouling and decay as generative qualities.

In order to provide a way forward we posit a methodology to design for heterogeneity. The overall macro geometry or tectonic should have a sense of readability and/or figurativeness (not necessarily of bodies) so that it can handle the patchy irregularity of what grows on it. Here we have presented the various phases to be designed for: *Inchoate*, *Burgeoning*, *Confervant* and *Biocoenosis*. This is a form of bio-integrated design that already considers intermediary and indeterminate stages as valid parts of the life cycle. The intersection of materiality and geometry is key to lending the uncontrolled surface of growth some contrasting order. Material properties of charge, conductivity, porosity, roughness, wettability will interact with the physical environment: light, water, laminar vs turbulent flow, friction, etc. Geometry and form will give the uncontrolled surface of growth a contrasting order.

But this mode of design poses an inherent challenge: to integrate polycultures in architecture there is not only a problem of an unpleasing look and an *a priori* lacking readability and order, but also the problem of scaling-up itself. What is acceptable in a petri dish in a controlled lab environment feels threatening and overwhelming when applied and exposed outdoors. The sticky, slithering, wriggly, oozing, or slimy conditions that are large have the potential to multiply and expand even further due to its unprotected and sheer force of scale. It feels like it could ultimately engulf us. However, our contemporary awareness of the climate and biodiversity crisis is forcing us to embrace a radical change in how we envisage the future and rethink our technical approach to consider mixed, rather than mono-culture. We need to capitalise on emergent properties of algal ecosystems as the basis for our building-integrated biotopes – highly dynamic, diverse and vigorous. Our urban environments will depend and thrive on the augmentation of such polycultures and resulting ineffable aesthetics of biofouling so that we can ultimately realise the vision of a future photosynthetic city.

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