Architecture for the Holobiont

Designing Probiotic Interventions

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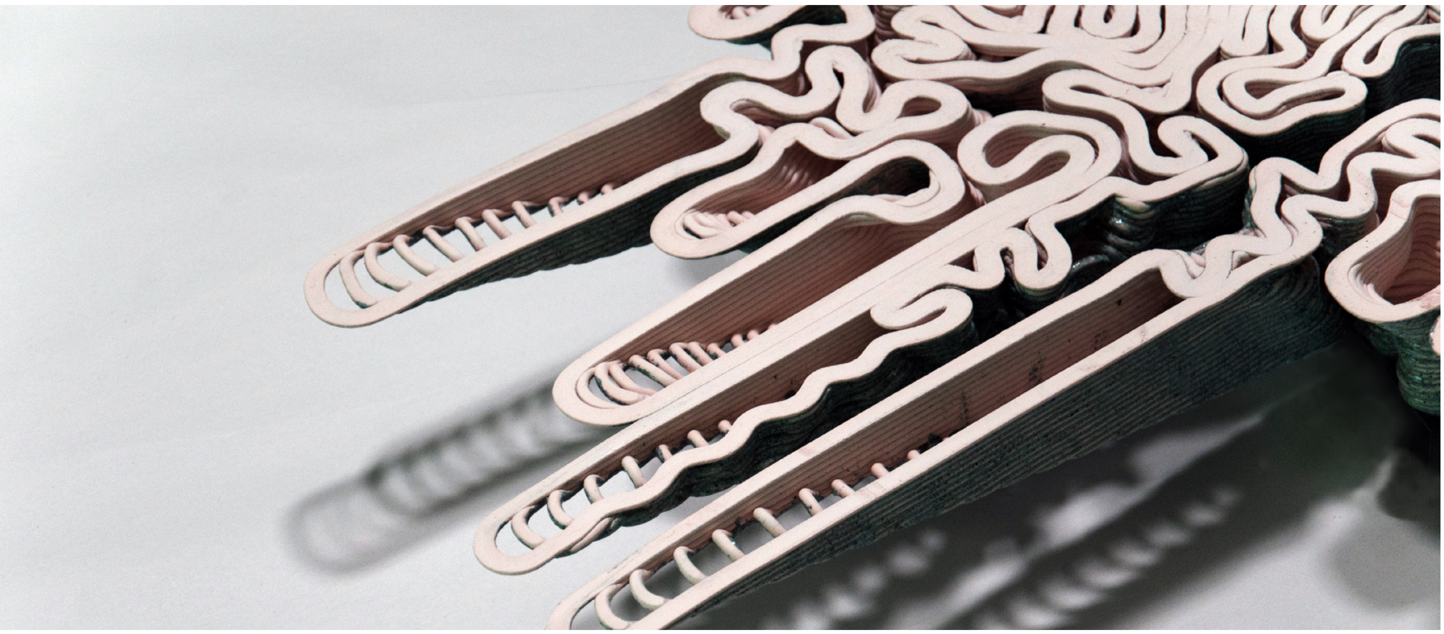

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1 Probiotic ceramic component,

ABSTRACT

This paper details a biodigital, probiotic design approach to creating biologically active material systems for buildings. These living materials are beneficial for the health of the human holobiont body through their impact on the human microbiome and potential to shape immunoregulatory health. I frame the research within the context of bio-integrated design in architecture and engineered living materials (ELM's), but with novel focus on microbiome health in urban environments. I introduce the discipline of microbiome science and its associated metagenomic technologies that show how it may be possible for bio-integrated design approaches to reshape the indoor microbiome of buildings. We propose a computational methodology towards designing and fabricating hybrid living building components that serve as both a niche and a source of symbiotically important microbes for buildings. A biodigital approach is presented, driven by current knowledge of the indoor microbiome and indoor environmental conditions that promote beneficial microbial transmissions via mechanisms of touch, ingestion, and respiration. This is presented through an experimental project which develops a human-machine-microbe fabrication process to create a living prototype which is then explored and assessed through an intervention study using a 16S metagenomic analysis.

INTRODUCTION

Biodigital and bio-integrated design approaches in recent years have seen an interest in designing and fabricating with living organisms for materials, components, and processes for architecture. To date, the majority of this work has operated mostly within the discourse of material sustainability and climate. A relatively unexplored area of research for these fields concerns how such materials could inform the types of microbes that exist in buildings and how they can shape human health. Specifically, this concerns the field of the 'Microbiomes of the Built Environment' (MoBE) and the sciences of the human microbiome. Over the last decade, these fields have revealed the symbiotic role that microbes play towards human health and offered a contemporary distinction between 'good' and 'bad' microbes. They have also made visible the relationship between design and the indoor microbiome yet, despite the long-held idea that buildings should be free of microbes, it is now clear that efforts to create increasingly sterile built environments are causing unintended, detrimental effects on human health. A lack of 'good' microbes in contemporary buildings and cities is now being associated with the observed increase in chronic and immune-related disorders over the last 50 years (Blaser 2014). The same strategies are increasing the resistance of microbes to medicines, as well as increasing the likelihood of further pandemics.

The emergence of these contemporary microbial pathologies suggests an important 'Habit of the Anthropocene' that we must challenge is one that assumes healthy buildings = fewer microbes. This 'antibiotic' architecture and obsessions with sterility became predominant in the mid-20th Century, in line with the antibiotic turn and little has changed in the early 21st Century. Furthermore, urbanization and the current energy discourse is exacerbating indoor environments that are increasingly separated from the outside and the environmental microbes that reside there. As we look towards the biocene, the design and application of living materials for buildings can offer new ways to challenge these approaches, as we seek to make buildings healthier through the concept of rewilding buildings with immune-relevant microbiodiversity. Engaging with this agenda offers new directions for the fields of biodesign in architecture, but also raises challenges to current approaches. In order to shape the indoor microbiome, the living components of such materials will likely need to remain alive upon application to buildings. Design focus must shift to consider indoor environments, as well as facades. The presence of living materials on their own may not be sufficient – important, too, will be the role they play in facilitating microbial transmission to other parts of the building, as well as facilitating these beneficial exposures to the holobiont body. This will also require a shift in focus from single organisms to broader, diverse communities of microbes. Importantly, to design, measure, and evaluate these phenomenon will require engagement with new techniques of metagenomics and new modes of expertise, including microbiome scientists and even immunologists. To do so will require new and novel approaches in computation and fabrication.

This work begins to address this agenda. Previous research into Probiotic Design (Beckett 2021) has presented methodologies to integrate beneficial microbes into materials for buildings that could survive over long periods of time. Building on these approaches, the work is extended here to explore if such biologically active materials and objects are able to impact the indoor microbiome and, subsequently, the inform the microbes that comprise the human microbiome. In this way, it explores the concept of an immune system for buildings, one that is not solely protective, but is also one which recognizes and facilitates microbial exposures that are beneficial for the holobiont body. In this paper, we present the methodology, design, and fabrication of a biologically active building component prototype (Figure 1) that can shape the indoor microbiome of a space towards a constitution that is understood as healthy for the holobiont body. The fabricated prototype is then tested as part of a microbiome study which is discussed and used to assess and conclude on this methodological approach.

BACKGROUND

The Human as a Holobiont

The term 'holobiont' describes a contemporary understanding of the human as a multi-species body, comprised of multitudes of other non-human microorganisms that operate in a combined, symbiotic model (Schneider 2021). This is radically different to the modern understanding of the human as genetically distinct from the non-human - a biologically discrete body. The concept of the holobiont has emerged from the sciences of the microbiome which has revealed how the microbes that exist on and inside us, and their genes, play important roles in bodily functions and, in particular, immune health. While some microbes are inherited, many are acquired from the environments we inhabit. The human microbiome is not fixed, but instead is constantly being informed by the microbes we are exposed to. As the built environment is now the predominant habitat of the human, the microbes that are present in buildings are of fundamental importance to health. Current building strategies do not provide the relevant exposures for immunoregulation (Rook & Bloomfield 2021)

The holobiont requires a fundamental shift in the way we plan and design buildings in relation to microbes. This must reject the idea that healthy buildings should be free of microbes and, instead, suggests that whilst we must continue to protect ourselves from harmful microbes, we must also design to ensure exposure to other, beneficial microbes. In line with the literature, design should focus on ensuring exposures to the types of microbes we have evolved alongside over millions of years (Rook et al., 2013). These are likely to be environmental microbes associated with natural areas, and possibly those associated with farm animals (Ludka-Gaulke et al. 2018).

Microbiomes of the Built Environment

Research into the MoBE has revealed how microbes exist everywhere in buildings, on all surfaces, in the air and in water systems. The techniques and technologies that measure the microbiome include metagenomics and DNA sequencing. These techniques are less about the presence of specific strains, and more about the dynamics of microbial communities. They offer, too, a new conception of buildings that are understood through big data sets of code and genetic information. Contemporary buildings are described as microbial wastelands. Dry, nutrient poor, and sterile surfaces mean only a tiny subset of microbes are able to survive. Most of these tend to be human microbes while environmental microbes tend to die. Design plays a key role in shaping these dynamics (Kembel et al. 2014) and so new design approaches are needed to increase environmental diversity. These will also require a shift in focus and methodologies for how to design and measure their performance. Within the literature, 'indirect' strategies have been suggested as ways to approach this (National Academies of Sciences Engineering and Medicine 2017). These include ventilation design and fenestration strategies to increase outdoor air coming into the buildings. Such strategies, however, may not be feasible in all cases, especially in urban areas of low environmental diversity and poor air quality. Highlighted within this literature is a need for novel strategies that can 'directly' add environmental microbes to indoor environments. Living materials and biodeisgn approaches offer significant potential here. Key areas for discussion include:

Engineered Living Materials

In the field of ELM's, the focus on growing and fabricating materials as an alternative to existing resource-intensive materials has particular potential to contribute to this agenda. However, while these approaches successfully innovate with the integration of living organisms into architecture, their aim is not typically to utilize the living agency of microbes as part of the building environment. In many cases the living agency of the materials are typically killed once grown, or prior to application. This has been the case with mycelium materials, and other materials produced as a by-product of specific microorganisms, such as bacterial cellulose (Zolotovsky 2017). Tied to this is how the agenda of material productivity and performance in this field has also seen a focus on single microbes, often grown under sterile laboratory conditions in line with the concept of optimization. These approaches are limited in their ability to offer microbial diversity to indoor environments. While this field could engage with broader species of organisms, its potential applications may lie more in its engagement with synthetic biology and ability to program cells at the level of DNA for specific functions. If these functions can be shaped towards health, or the resilience of organisms to function in indoor environments, such approaches might be revolutionary in this area.

Biodigital and Bio-Integrated Design

Explored predominantly through research driven by the contemporary climate challenges, research in these fields has seen a predominance of work exploring mostly green, photosynthetic organisms which have been utilized for their agency in absorbing CO_2 in urban environments. While in support of these agendas, this has resulted in a focus and prioritization on only a tiny subset of the millions of microbial species and strains that are now known to exist on the ever expanding tree of life that offer beneficial functions outside of CO_2 absorption. Work exploring algal strains has operated mostly through the concept of the bioreactor to maintain living agency (Wurm 2013). As this essentially contains the living microbes in a closed system, their potential to inform the indoor microbiome is relatively limited. Furthermore, as the aim of such systems is typically focused on growth to maximize CO_2 absorption, such systems favor single strains or monoculture growth which are limited in their ability to increase microbiodiversity in buildings.

Bio-Integrated designs, to date, have too focused predominantly on photosynthetic organisms, though in rejecting the container approach of the bioreactor, these approaches offer more potential for acting as a source of microbial exposures for buildings. To date, much of this work has been explored as outward facing, façade panels (Cruz 2021). Work remains to assess if these can significantly impact the indoor microbiome; however, the application of these approaches for indoor environments holds particular promise if they can be designed in line with indoor environmental conditions with limited moisture and nutrients. The work following this section utilizes bio-integrated design approaches, but crucially with a focus on indoor environments, and in line with the agenda towards increasing microbial diversity in buildings for holobiont health.

Laboratory Methodologies

Finally, the utilization of laboratory techniques and methodologies from the sciences, which has underpinned the broader biodesign discourse, requires discussion. To date, the field has mostly relied on approaches that focus on the growth of single organisms, under specific conditions, valued for a specific agency. This is, in part, a hangover from the field of bacteriology that emerged in the early 20th century that was solely interested in harmful microbes. By this definition, these approaches rely on techniques and processes that require sterility in order to isolate and separate the desired organism from undesirable others. In this way, the concept of desired 'growth' has become the defacto measure of whether biodigital projects are measured as successful. In projects where growth is not sufficient, experiments are seen as failed. In projects where contamination occurs, unexpected growth is also indicative of a failed experiment.

For the agenda of rewilding the indoor microbiome, the notion of 'growth' might not be the important factor in which to design for. Microbes can be merely surviving, or be dormant and still offer beneficial mechanisms, compounds or molecules. They may also never be visible in the way mosses or algaes are. Instead, the agency of these microbial communities can only be understood through the way they shape the microbiome, which needs to be understood through metagenomic analysis across various levels of information including, but not limited to, rates of metabolism and gene functions. For this reason, collaboration with microbiome scientists is fundamental to understanding how design can shape these conditions.

METHODS

Micro Scale: Experiments with Beneficial Soil Microbes

Previous experiments with creating biologically active materials containing beneficial bacteria focused on protection from harmful microbes. Building on these methodologies, the focus here switches from single microbial strains to broader communities of microbes that are beneficial for human health. In line with the discussion above, this research focuses on the types of microbes associated with natural environments that are important in shaping normal immune function. These microbes, associated with soils and vegetation, contain multitudes of strains of bacteria, as well as other organisms, including fungi, algae and even viruses. These diverse exposures populate the human microbiome and play important roles

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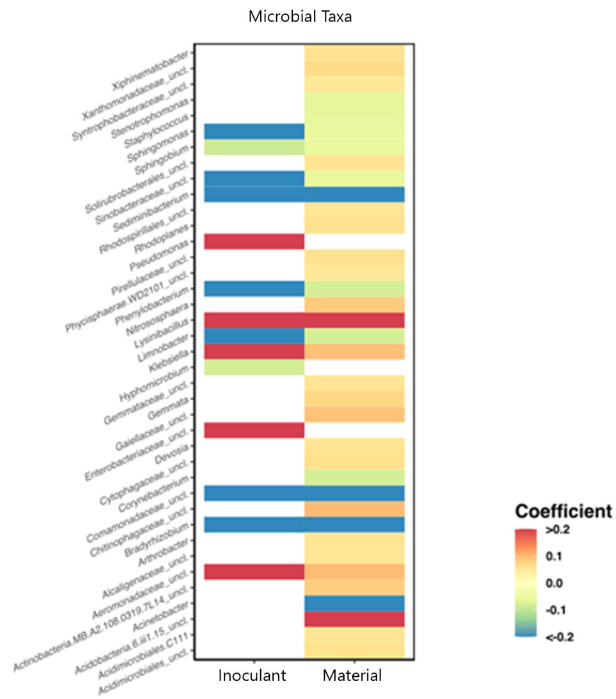

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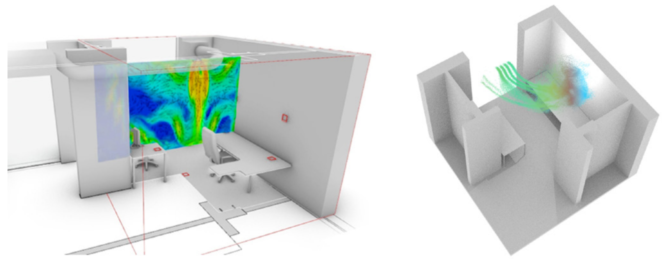
2 Fieldwork collection and processing of soil microbes.

3 16S sequencing - microbial taxa.

in selecting lymphocyte clones and other molecular signals that inform normal immunoregulatory control. This kind of microbial diversity in buildings can also play important roles in providing competition against harmful microbes, and has the potential to inform other mechanisms of volatile organic compounds (VOCs) and other pollutant absorption from indoor air. In this project, diverse communities of microbes were isolated from soil samples collected from a rural location in the UK (Figure 2a). Using laboratory methodologies, microbial communities were isolated from concentrated soil matter (Figure 2b) then processed with rainwater creating a liquid culture which was then inoculated into porous ceramic materials (Figure 2c). Clay, particularly in the form of porous ceramic, offers a bioreceptive niche for microbes in buildings, as it is chemically inert and its physical properties can be controlled during fabrication. Ceramics are abundantly used in buildings around the world, though mostly, in their hardened form following firing, and typically, made non-porous through glazing techniques which has origins in limiting microbial growth. A novel porous ceramic material was produced to achieve microbial bioreceptivity. Potential of hydrogen (pH) values between pH 7 and 8 were targeted as optimal for the soil microbes. Material porosity was then produced via a bisque firing process at low temperatures (800 – 900ºC). Material design here then is then driven by the needs of the microbes at the micro scale, but also by the requirements for robotic fabrication at the meso scale. This aims to ensure that the porous matrix can serve as a biologically compatible niche for the microbes to inhabit, and to remain biologically and structurally viable over time. These hybrid materials were characterized using 16S DNA sequencing to understand community structure in the material matrix (Figure 3). This understanding is less about the presence of any specific microbes, and more about the concept of microbial diversity which appears to be the important factor in shaping healthy indoor microbiomes.

Meso Scale: Geometry, Transmission and Exposures

Design of the prototype for this approach centered around the role that geometry can play in facilitating transmission of the microbes from the fabricated components to other parts of a building, and to the microbiome of the building occupants. Microbial transmission in buildings occurs predominantly through mechanisms of air transport and touch; therefore, the aim here is to design forms and geometries that facilitate these transmissions rather than limit them. The role of air flow is well understood as a key mechanism in relation to the spread of microbes in buildings (Kembel et al. 2012) and computational fluid dynamics approaches are being increasingly used as a tool to investigate the prevention and control of pathogen transmission (Peng et al. 2020). In a similar manner they offer the potential as a design tool to promote beneficial transmission. Computational methodologies which incorporate airflow simulations can inform and optimize geometries according to these criteria that are specific to a building environment. Alongside a data-driven approach, the project also explores the unruly aesthetics of biodesign investigations and robotic clay printing to create components that encourage curiosity and touch, in order to further facilitate the spreading of microbes. In this way, it rejects flat, smooth, white surfaces of the modern hygiene agenda, and instead, explores three-dimensional and geometrical forms that utilize these mechanisms to encourage microbial transmission.



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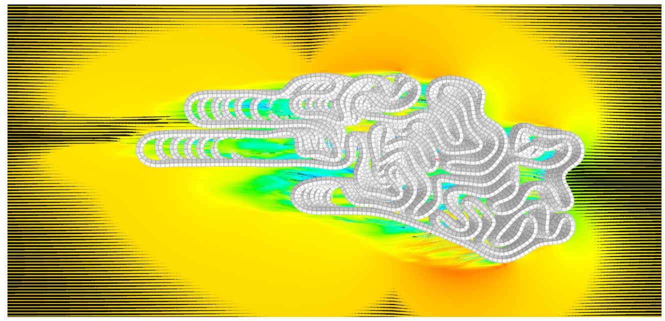

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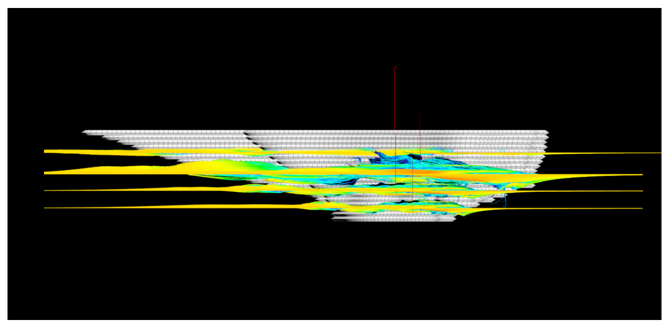

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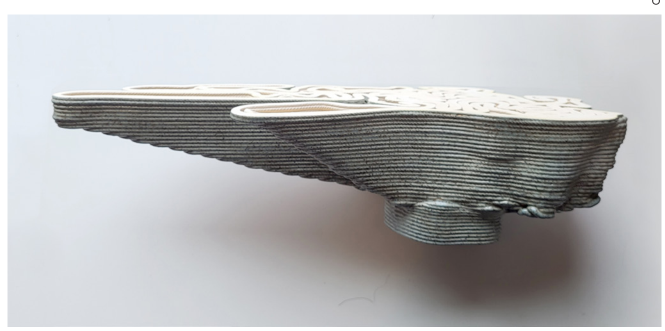

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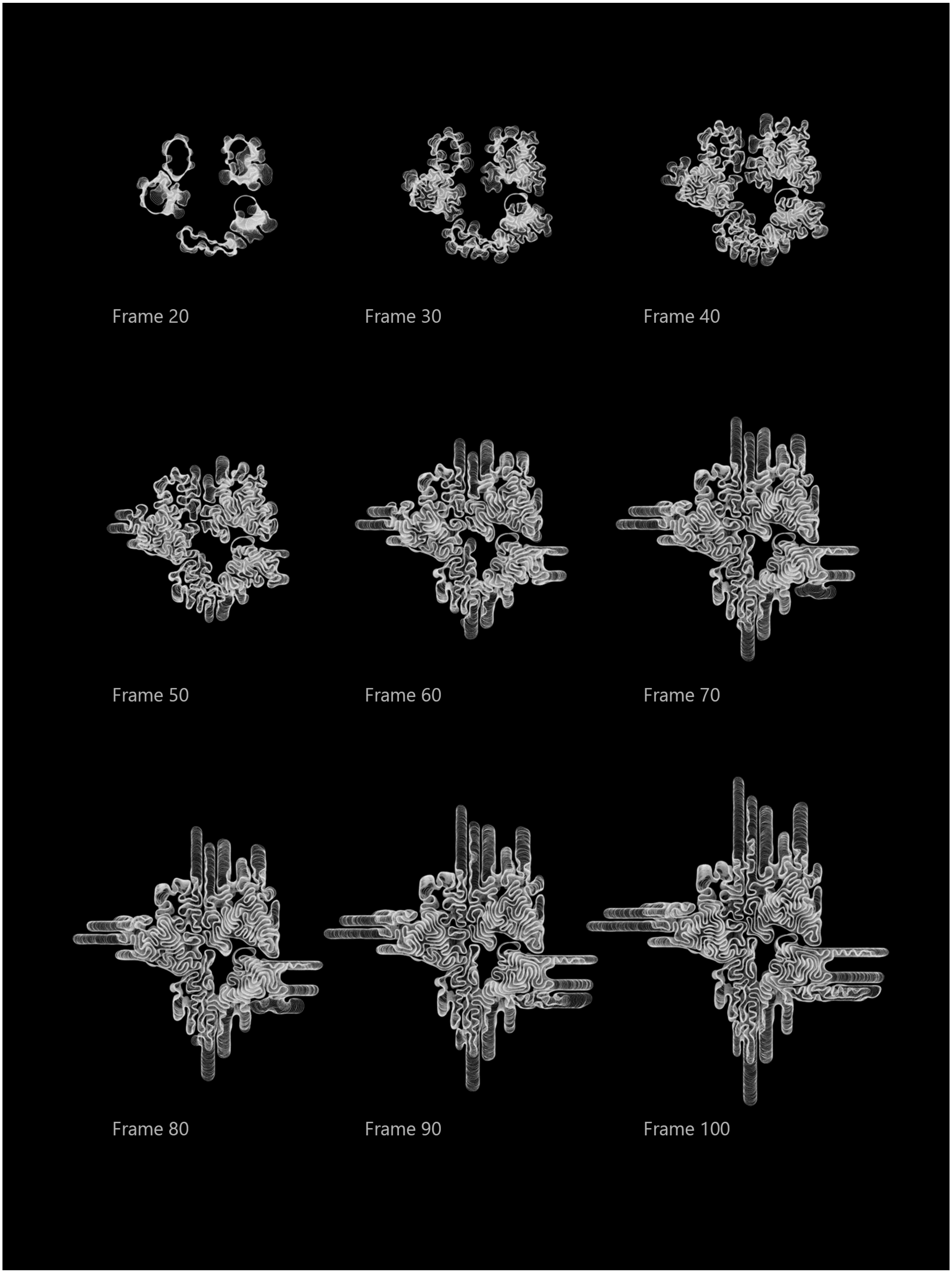
4 CFD airflow simulations of test space for intervention study.

5 Airflow simulation of component showing turbulence through the geometry in plan.

6 Airflow simulation of component showing turbulence through the geometry in elevation.

7 Photograph of fabricated component in elevation

8 Computational workflow using differential line growth to grow the component geometries through the CFD point clouds.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9 Robotic clay extrusion of component.

10 Photograph of front view of Probiotic Intervention.

11 Photograph showing the rear surfaces of the components, glazed and fired for structural stability.

12 Front faces of the components were unglazed, left in their bisque-fired state to exhibit material porosity.

13 Scanning Electron Micrograph image showing material porosity at 100um

14 Scanning Electron Micrograph image of soil microbes within the material matrix at 10um.

Previous Computational Fluid Dynamics (CFD) simulations of airflow of the test space (Figure 4a) were used to inform the location of the intervention. These were then imported into a procedureal design software, whereby using a particle approach, areas of air/surface collisions could be determined (Figure 4b). The use of airflow simulations incorporates a time-based process where each second of the airflow simulation creates a dataset that can then be used to inform a series of computational moves. Using these point clouds, a differential line growth algorithm was used to calculate paths through these point clouds in a way that results in single, continuous toolpaths which can be optimized and spaced directly for the robotic extrusion fabrication process.

This computational growth logic facilitates an unruly aesthetic through material sagging during fabrication, while facilitating the performative function of air-based microbial shedding. To augment this, the script was developed to grow forwards and outwards from the wall surface. Control of the density here played an important role in the functional performance. Central areas of density inform the structural stability of the component, defining solid areas for wall fixings and a creating large surface area of porosity for microbial inoculation. Points further away from this central area grew outwards in more linear forms, giving a directionality to the geometry. This also left gaps in the geometry, as well as spaces behind, where air can circulate. These were simulated and refined for their ability to create turbulence (Figures 5 through 7) in order to facilitate the desired shedding of microbes from the component. By using an approach that avoids collisions, the prototype was grown as five separate components that grow and intersect each other, hiding the notion of assembly joints within the geometrical lines of the aesthetic (Figure 8).

Fabrication

In designing architectural components at the meso scale, the method of fabrication becomes challenged by physical factors and limitations of the scales associated with microbiological methodologies and equipment. The design of the prototype was developed as a non-uniform typology in order to cover a specific area of wall surface. The size of the individual components were, however, limited specifically in order to still be manageable within the confines and instruments in the laboratory. Primarily, it was important that the components could still fit in the autoclaves, chambers, and fume hoods to facilitate the methodology. Components were scaled accordingly, and the toolpaths and nozzle width were recalculated for robotic clay extrusion purposes (Figure 9). Following clay extrusion, components were bisque-fired to achieve the desired porosity (Figure 13). They were, however, structurally weak for internal application; therefore a second kiln fire, with glazing only applied to the rear surfaces, resulted in a structurally strong component (Figure 11) while maintaining bioreceptive, porous-facing surfaces (Figures 10 and 12).

The high temperatures associated with kiln firing require that the microbes be inoculated post-fabrication. Previous experimentation had underestimated the time taken for inoculation of larger objects. The process of manually pipetting the microbial inoculant onto fabricated tiles was

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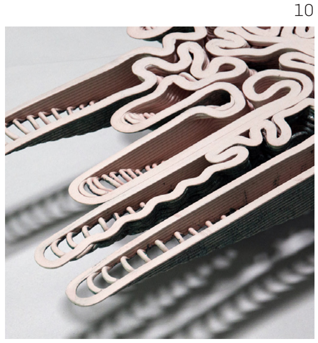

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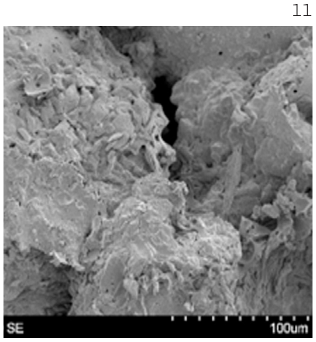

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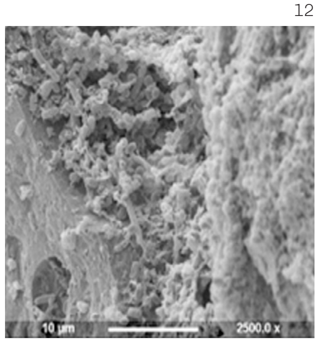

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extremely time-consuming and would not be feasible for applying to larger objects or wall areas. In situ spraying was discussed, but it brings risks associated with aerosolizing microbes, especially if done on-site, rather than in the laboratory. Therefore, the idea of utilizing this process was discounted. The development of an automated robotic workflow meant that the curves generated by the computational process, using the CFD simulations of the space described, could then be used directly as toolpaths for a robotic application for microbial inoculation. Using scale factors to compensate for shrinkage after firing, a syringe pump was used with a robotic end effector. The components could then be 'roboticallyl inoculated', allowing for accurate and repeatable applications of microbial cultures into the components (Figure 14).

RESULTS

The resultant intervention consisted of five biologically active ceramic components that were then assembled (Figure 15) and attached vertically, via fixings, to a wall within the test space. To test the feasibility of the intervention, an indoor microbiome study was then run over the course of nine weeks to assess whether the intervention could have a measurable impact on the microbiome of the space. The experimental approach involved swab-sampling 10 surface location sites located around the test space, which were then analyzed using a 16S sequencing approach. Sampling locations were defined by 10cm2 markers to ensure repeatability, and samples were taken using cotton swabs using a repeatable methodology. Samples were then analyzed using a 16S illumina amplicon protocol designed to amplify prokaryotes (bacteria and archaea) using paired-end16S community sequencing (Caporaso et al. 2018). Sample sites were selected to offer variation in terms of surface material, horizontal and vertical surfaces, and distance from the intervention. Swabs were taken once per week for three weeks to characterize the existing condition. The same location sites were then sampled for three weeks following installation of the intervention. At the six-week timepoint, the intervention was removed, and sampling continuing for 3 weeks after.

The work serves as a first attempt to use a direct design intervention to inform the indoor microbiome. Hopefully, this can serve as a basis for further research in this area. The full microbiome data will be published in a separate publication, as the specifics are beyond the scope of this paper. This also highlights the challenges of understanding this data from an architectural perspective. In summary, however, the results showed that the design intervention did serve to modify the microbiome of the space.

15 Final Assembly of Probiotic Intervention.

Clear differentiation in the alpha diversity of the microbial compsition of the space, following installation of the intervention, was observed. This remained, to an extent, following removal of the intervention. It was clear also that the microbes in the ceramic components were shed, and transported around the space, with microbes from the intervention found on other sampling points. The intervention was not touched during the study; therefore, this appears to be a result of air movements, as predicted.

Calculated, rarefied bacterial richness (the number of distinct bacterial genera observable in any sample when randomly selecting 2,000 reads from a sample), and normalized bacterial Shannon diversity (the measure of how evenly distributed relative abundance of each bacteria is across the samples), were assessed. Generalized linear models were built to assess the impact of material and sampling timepoint on observed bacterial richness and diversity. Results here showed that both timepoint and material had significant impacts on observed bacterial richness and diversity. The components had significantly greater bacterial richness than other surfaces over the course of the experiment.

CONCLUSION

This research outlines a bio-digital, probiotic approach towards creating biologically active, architectural-scale component assemblies that are able to measurably increase the environmental microbial diversity of an indoor space. Despite the long-held idea that our buildings should be free of microbes, the concept of the human as holobiont requires a recalibration of how we design buildings in relation to microbes. As we look to new ways to design healthy and resilient cities, designing for multispecies flourishing at multiple scales must become a fundamental habit in architectural efforts to secure the human. This work demonstrates that novel probiotic design approaches can contribute to creating healthy built environments by shaping beneficial microbial entanglements directly through the material condition of architecture. While these results need to be discussed within the context of the experiment, they serve as a proof of concept that biologically active design interventions can directly inform the microbiome of a space. While it is a very small step, this work has the potential to develop further as we learn more about how these microbes behave over time and whether they are able to offer any beneficial mechanisms towards health, either by limiting pathogens or in relation to immunoregulatory health.

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IMAGE CREDITS

Figures 1, 9, 10-12 &15: photographs by Cera Lab
All other drawings and images by the author.

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