Magnifying the Micro-scale: Thermographic-enabled Toolpath Engineering for Water Retention in Robotic Clay-3D-Printed Bioreceptive Facade

Conference Paper · November 2024

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Magnifying the Micro-Scale: Thermographic-enabled Toolpath Engineering for Water Retention in Robotic Clay-3D-Printed Bioreceptive Façade

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Abstract. Porous Clay is ideal for enhancing the bioreceptivity of facades due to its water retention and diffusion properties. Meanwhile, 3D printing allows for precise, scaffold-free fabrication of complex and highly performative façade structures. The application of clay-3D-printed-façades can help address the loss of urban biodiversity and public health issues caused by disconnection with diverse microbiomes. This research investigates the correlation between clay 3D printing parameters and microbial adhesion and growth, particularly focusing on tracking water behavior on façade surfaces. Furthermore, we explored controllable micro-habitats for microbiomes through additive manufacturing. The performance of clay 3D printing has been improved through toolpath engineering. Supported by digital simulation and thermographic data, the experiment outcomes elucidate the benefits and limitations of creating controllable micro-habitats for microbiomes through parametrically modelled robotic clay 3D printing toolpaths. The design and fabrication of prototypes with various bioreceptive features demonstrate the potential applications of our method in real-world contexts.

Keywords: Biologically informed disciplines, Bioreceptive facade, Clay 3D printing, Toolpath engineering, Analogous modelling, Thermal Imaging.

1 Introduction

Rapidly increasing urbanization has led to the deterioration of urban green spaces and a significant loss of biodiversity. The resulting disconnections between human and natural environments has caused numerous negative effects on public health, such as a notable rise in immunological disorders which occur frequently in urban contexts (Flies et al. 2017; Shanahan et al. 2016). One direct mechanism through which biodiversity benefits human health is the development of a healthy holobiont system, supported by the diverse symbiotic microbes within the human microbiome (Ruokolainen et al. 2017). However, industrial activities and current building practices, which often result in microbial wastelands, have disrupted this microbial diversity, leaving urban residents with fewer opportunities to encounter beneficial microorganisms (Beckett 2023; Marselle et al. 2021; Rook and Bloomfield 2021).

To promote biodiversity at various scales within the built environment, especially at the invisible microscopic level, bioreceptive façades offer a promising sustainable strategy for densely populated urban areas with limited space for direct greenery features. These facades can integrate natural elements while providing benefits, such as ease of installation, long-term self-sustainability, cost-effective maintenance. Additionally, they deliver environmental, social, and economic advantages, contributing to urban resilience at a large scale (Marsaglia, Brusa, and Paoletti 2023; Beckett 2021; Cruz 2020).

1.1 Bioreceptivity-Informed 3D Printing

Bioreceptivity refers to the ability of a material to be colonized by living organisms without necessarily undergoing biodeterioration (Guillitte 1995). To support biofilm growth, bioreceptive facades need to support the survival of these organisms once applied to buildings. Experiments have shown that key material factors influencing bioreceptivity include surface roughness, porosity, pH value, and chemical composition (Manso et al. 2014; Mustafa, Prieto, and Ottele 2021). Among these, surface roughness has the more significant impact on bioreceptivity, as it can retain water from the natural environment in capillary spaces formed by surface undulations, protect living organisms from sunlight, and gather nutrients on the surface (Mahrous et al. 2022; Jakubovskis, Malaiškienė, and Gribniak 2023; Sanmartín et al. 2021).

Distinct from traditional strategies that rely heavily on geometric design to enhance surface roughness, new fabrication technologies allow for simple geometries to exhibit visible bioreceptivity through subtle layer effects created by 3D printing. For example, Magnesium Phosphate Concrete (MPC) and Ordinary Portland Cement (OPC) panels can be made using 3D-printed formwork with bespoke casting toolpaths (Cruz 2022). Additionally, ceramic bioreceptive elements are often 3D printed (Diniz and Melendez 2023; Tietz 2021; Beckett 2023). These studies highlighted that the micro-scale geometries (around 5 mm) have a greater impact on bioreceptivity than larger-scale surface structures. For example, the studies of self-sustaining concrete system revealed that mosses preferred to thrive in micro-scale alcoves and ridges, where water retention and medium-resolution surface roughness are enhanced (Mustafa, Prieto, and Ottele 2021; Sochůrková et al. 2023).

1.2 Bioreceptivity for A Broader Range of Organisms

Recent bioreceptive research seeks to deepen the understanding of how the biological growth can be directed, with the presence of water being essential for bio-colonization (Bates 1998). As a result, highly detailed textures and geometries that affect water retention have become essential to this microbial-led design. The micro-morphologies of surface structures—including the variations in size, density, and texture shape—are critical from a bioreceptive point of view, as they influence the ability to retain and diffuse water on and within materials. Most bioreceptive designs, therefore, incorporate water behavior into their design considerations from different aspects. For example, the concrete panels with bespoke toolpaths create smaller-scale textural surface variances to slow water runoff (Cruz 2022). Similar studies have demonstrated the potential to direct the growth of specific epiphytes and bryophytes in targeted areas and with desired coverage (Crawford et al. 2022; Chadha et al. 2023). A more recent ceramic project focused on vertical branching patterns as water channels to guide water flow along the external printed surface toward designed cavities (Lim and Lharchi 2023).

Although micro-scale geometry has been proven to have a strong impact on shaping water retention on surfaces, the application of 3D printing in bioreceptive design, especially for bioreceptive ceramics, remains underexplored. In response, we propose a thermographic-enabled toolpath engineering method to enhance bioreceptive designs by leveraging the advantages of computational geometries, robotic clay 3D printing, and thermal imaging technologies. Through toolpath engineering for industrial robots, this approach enables precise and diverse clay 3D printing, allowing for the creation of intricate and functional surface structures capable of supporting microbial growth and biodiversity. This research aims to expand the scope of bioreceptive design beyond human-scale or building-scale architectural forms and explore feasible micro-scale design and fabrication methods for enhancing bioreceptivity in the built environment.

2 Methodology

This research explores how toolpath engineering in clay 3D printing affects water behaviors to enhance micro-bioreceptivity. The methodology consists of two parts: experimentation and prototype design. The experiments, conducted in parallel with the design of clay-3D-printed bricks, focus on evaluating the effects of geometrical and fabrication parameters on water diffusion, filtration, and eventual microbial growth. The experimentation is split into: (a) surface textures formed using different toolpath parameters, and (b) water behavior visualized using infrared thermal camera. All the experiments were set up in an indoor laboratory environment simulating rainfall on the bricks. Based on the results, a series of distinct geometric bricks are re-designed to cater to realistic environmental factors (Figure 5). All the bricks were printed with an ABB IRB 6700 6-axis robotic arm with a customized extruder of 5 mm diameter.

2.1 Geometrical Variations

The design process focuses on creating different micro-scale geometrical variations from the aspect of (a) toolpath control point offsets, (b) contour curve weaving loops, and (c) attractive forces in the design simulation model. Since the micro-conditions created by various toolpath parameters are the key focus for comparison, the base geometries were designed to be printable without unexpected overlaps or protrusions.

A preliminary test using a gradient pattern was conducted to evaluate the feasibility of visualizing water diffusion via a thermal camera. Subsequently, two types of geometries were developed based on a cuboid brick (10 cm x 16 cm x 10 cm) printed with fresh clay. Form variations were made on one side of the surface, consistently oriented to face the water distribution in the following experiments. The prototypes were designed to test different geometrical effects on water retention and diffusion.

Test A focused on different toolpath designs (elaborated in Section 2.2). The type-A base geometry in Test A was adapted from a pre-developed façade prototype and manipulated based on a customized generative algorithm (Herr and Li 2023). The second series of prototypes serves as the control group for Test A, and simultaneously explored the impact of medium-scale surface structure on water behaviors, so that various patterns were also tested, such as curtain, pocket, and bark (Figure 3).

2.2 Toolpath Engineering

A series of prototypes with varied surface patterns were designed and printed to understand the deviations between digital models and the final printed geometries, as well as their effects on water behavior. As part of a preliminary exploration into digital-physical relationships, three toolpath engineering strategies were tested: (1) different points-to-curve methods, such as Interpolation, B-Spline, and NURBS, (2) parametric control over point displacement on curves, such as varying loop periods, displacement distances, and attractor logic. While the applied generative algorithms are well known, no systematic experiments have yet explored their impact on water behavior on printed ceramic surfaces. The knowledge acquired from these experiments will inform future prototype designs, leading to a laminated design method. An attractor logic is also applied to the final toolpath design for the façade prototype.

2.3 Experimentation Procedures and Fabrication Settings

The fabrication settings, using 3D-printed clay, a printing speed as 200-250 mm/s, and nozzle diameter as 5 mm, remain consistent across all the experiments. This ensures that, with the same type of clay, the 3D-printed clay brick features a cross-section with a printing width of 6-8 mm per layer.

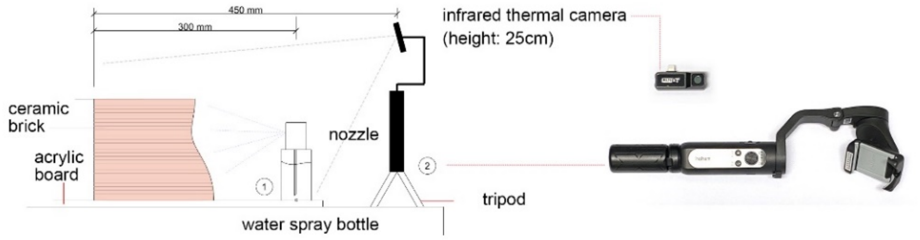

Figure 1. Experimental set-up: water is sprayed from a bottle specifically positioned on the table. The spray bottle is removed immediately afterward, and the thermal camera captures and analyzes the results. Source: Author, 2024.

Two types of experiments were conducted for comparison, with all experimental set-ups remaining the same. All clay-3D-printed bricks were placed on a non-absorbent acrylic board to ensure unbiased results. Additionally, the infrared thermal camera, with a 25 Hz frame rate, 120x90 infrared resolution, and 0.1°C temperature sensitivity, was positioned consistently to record the experiments. These preliminary tests aimed to visualize the short-term water behavior (Figure 1), recorded as thermographic videos, which will be compared and evaluated in the following section.

3 Results

The water behavior was analyzed by monitoring temperature changes across eighteen panels, including one pre-test and two formal test series. The analysis calculated the percentage of cooling surface coverage obtained from thermographic recordings.

Figure 2. Preliminary test results: (a) a 3D-printed ceramic brick with varying recess depths, (b) screenshots from thermographic recordings showing the water diffusion results (chronologically from left to right). Source: Author, 2024.

3.1 Pre-test for the Feasibility of Fabrication Settings

In the preliminary test, with recess depths varying from 5 cm to 1 cm (left to right) as shown in Figure 2, the chronological screenshots of the thermographic video reveal differences in water behavior based on the recess scale. Water behavior is visualized by the gradient color representing surface temperature. Upon spraying, the deeper recesses retained more water and thus cooled down faster. When the water diffused, the temperature of the smaller ridges on the right side cooled down within 30 seconds, as indicated by the purple areas.

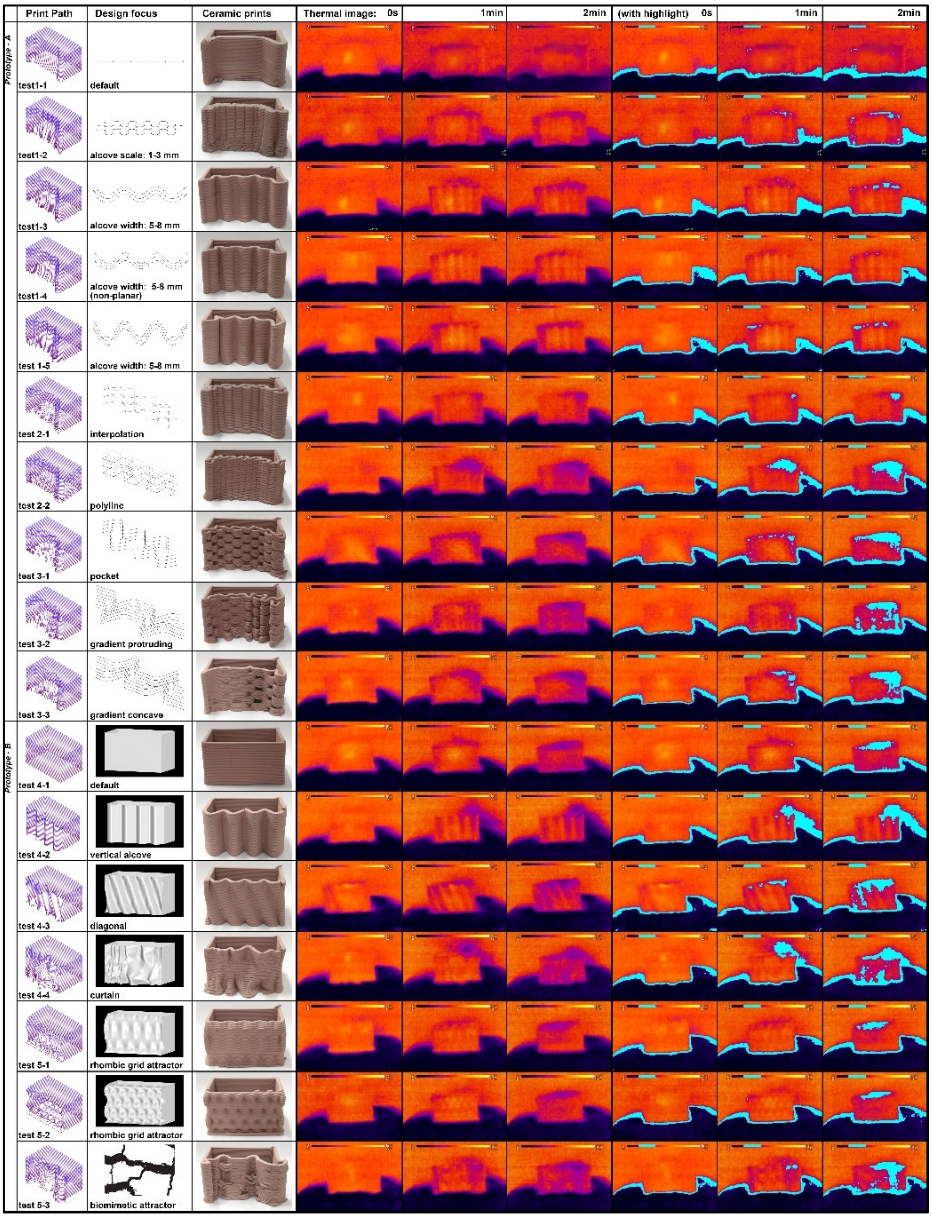

Figure 3. Results collection: prototype design, toolpath engineering, photos of the clay-3D-printed bricks and chronologically organized thermographic screenshots highlighting water diffusion from both experiments. Source: Author, 2024.

3.2 Results of the Water Behavior on Surface

Temperature readings were taken to observe the cooling effect of the ceramic bricks after spraying water. The detailed results are shown in Figure 3.

All bricks were placed in a constant-temperature, enclosed laboratory environment (27-28°C) for 48 hours to standardize their initial temperature. After five sprays of water, the brick surface temperature immediately dropped by 2-3°C. Over 1 to 2 minutes, areas with a temperature decrease of 0.5-2°C gradually expanded. These general trends were consistent across all bricks, likely due to the inherent properties of the clay. However, comparison between individual tests reveal that geometrical variations influence water behavior. Generally, macro-scale and micro-scale geometries directed the behavior of water on surface, as seen in the comparison between the default brick and others in both Test A and Test B.

Specifically, in Tests 1-2 & 2-2, weaving texture with 1-3 mm patterns enhanced water diffusion when the protruding patterns intersected. In contrast, in test 1-3,4,5, linear alcove width of 5-8 mm had a positive but less effective impact on the diffusion, compared to protruding pockets, especially for the concaves (test 3-3).

Beyond that, there was no significant effect from transitioning between planar and non-planar printed surface or point-to-curve methods. In Test B, two key findings emerged: (1) slightly inclined, diagonally continuous linear alcoves significantly improved water diffusion, and (2) linear alcoves perform better than spotted alcoves (compare the test 4-2,3,4 & test 5-1,2).

3.3 Façade Surface Prototype

The final robotic print path utilized a laminated optimization approach responding to two environmental factors. The optimization aims to improve water retention and protect organisms from direct sunlight and more gathering of nutrients. The key environmental factors are (1) simulated point-distributed nutrients, and (2) solar analysis in Grasshopper Ladybug library (Sadeghipour Roudsari, Pak, and Viola 2013), as shown in Figure 4-(b) and 4-(c). The experimental results showed that the geometrical variations resulted from toolpath engineering significantly impacted water retention, especially pocket and protruding geometries (Test 3-1, -2 and -3), which were applied to the façade prototype.

The optimization was driven by the distance between points on the original print path curve and the nearest simulated nutrient spot. For example, print 2-2, outside of the nutrient radiation range was optimized mainly by solar analysis, with less sunlight causing greater outward displacement of the weaving pattern. In contrast, print 3-3, where 90% of the surface falls within the nutrient radiation range, was optimized primarily by nutrient proximity, with weights of 0.8 for nutrients and 0.2 for solar analysis. Figure 4-(a) shows the final print paths for all nine bricks, and

Figure 5 presents the assembled physical prototype.

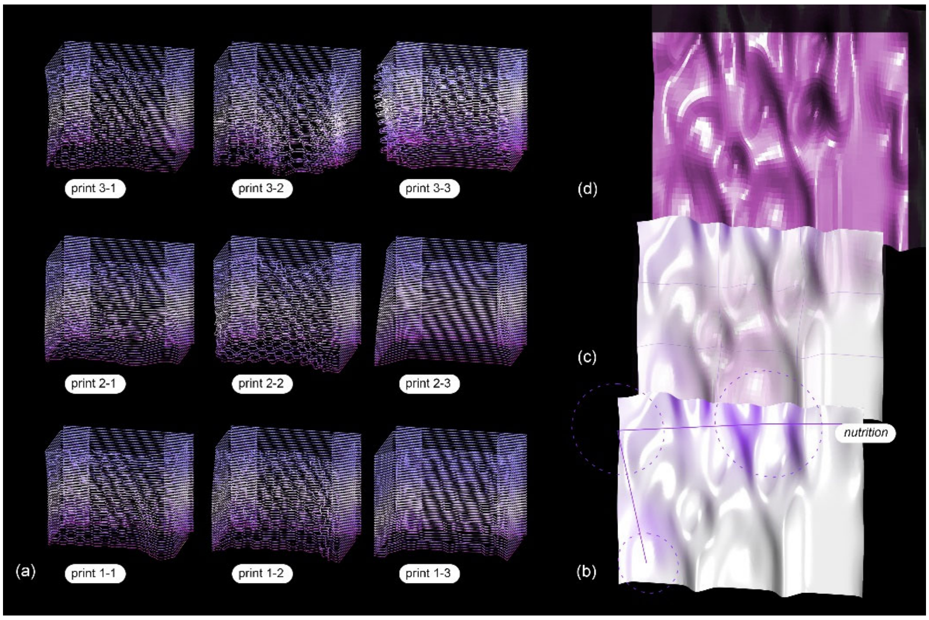

Figure 4. Façade surface prototype and final print path: (a) Final print path for all nine bricks, reflecting varying weight of digital environmental control; (b) nutrient simulation in purple; (c) laminated attractor logic responding to simulated nutrient and solar analysis; (d) mesh generated from the solar analysis shown in grayscale display mode. Source: Author, 2024.

4 Discussion and Conclusion

This research demonstrates a method for robotic clay-3D-printed bioreceptive facades that support microbial growth for a broader range of organisms, effectively combining aesthetic appeal with viable functionality. The experimental results highlight the significance of geometric variations created through robotic toolpath engineering, which can inform more efficient bioreceptive designs. While there are countless methods for designing bioreceptive geometries, the various print path parameters tested in this research serve as a guideline for evidence and reference. The research findings indicate that the micro-scale grooves created during fabrication process significantly influence water diffusion and retention, emphasizing the role of micro-scale geometrical variations in enhancing bioreceptivity.

Although the experiments provide essential data for the development of full system designs, some limitations exist. For example, the thermal imaging camera's low-resolution may result in the loss of subtle data. The temperature of fabrication laboratory environment does not strictly remain constant for extended periods, which may affect the initial temperatures of bricks and water. Therefore, the comparison in Figure 3 aims to show the trend of relative change.

Additionally, toolpath engineering results affect the final thickness of the bricks, potentially influencing water absorption. Some surface geometries, such as those in the test 3-2 and 5-3, feature partially suspended forms that can affect the structural integrity of the bricks and raise printing challenges. Investigation into structural aspects should be considered later in future research.

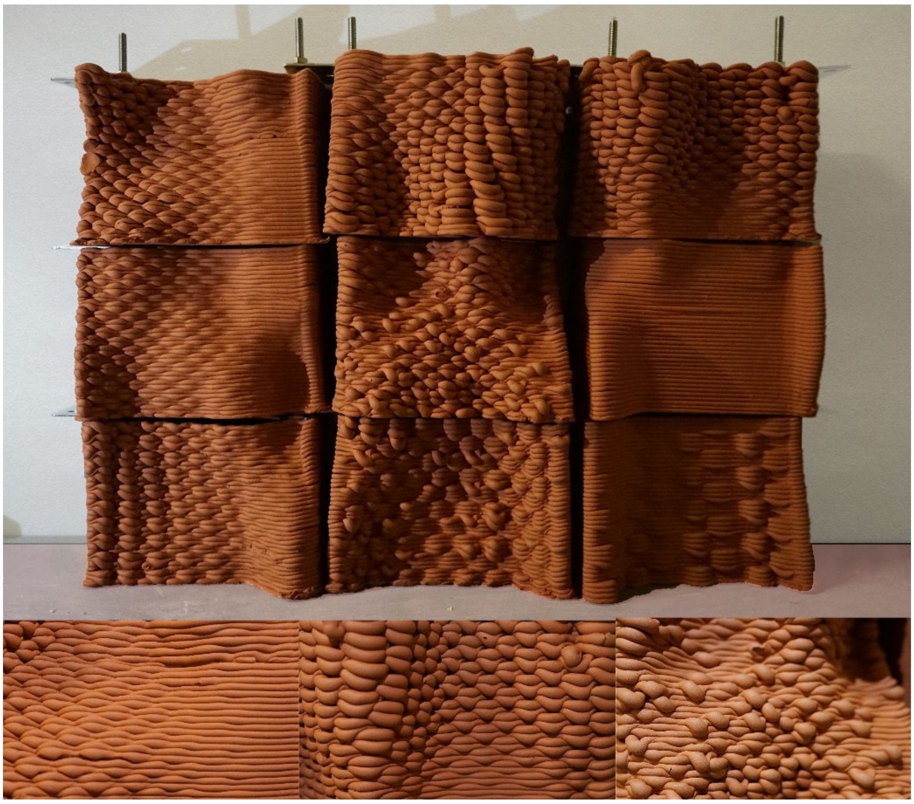

Figure 5. Physical prototype of bioreceptive ceramic façade system: the upper photo of the assembled model, and the bottom one is the detailed surface patterns of the print 3-1, 3-3 and 2-2. Source: Author, 2024.

As previously mentioned, surface humidity supports better biofilm growth, prompting the choice of clay for this investigation due to its inherent bioreceptive qualities. This focus allowed for design processes related to water behavior. However, additional building materials such as porcelain and concrete will also need to be tested for comparison in future research. The fabricated bricks made from various materials with different micro-scale surface variations will be investigated through experiments in natural environments, aiming to provide more general design guidelines for printing path engineering, which will be elaborated in future work as well.

In summary, while bioreceptivity is a natural phenomenon that cannot be fully predicted and controlled, a suitable environment can be facilitated through a biocentric strategy. Although more rigorous experiments are required to determine the conditional settings in robotic clay 3D printing toolpath engineering, the design and fabrication of facade prototypes with diverse bioreceptive features have demonstrated the potential for applying our research in real-world contexts.

Acknowledgements. This research was facilitated by the Robotics Fabrication Lab at The University of Hong Kong Faculty of Architecture, with support from Assistant Lecturer Mono Tung and Fabrication Media Labs Manager Jacky Chu in the clay 3d printing experiments.

References

Bates, J. W. 1998. “Is ‘Life-Form’ a Useful Concept in Bryophyte Ecology?” *Oikos* 82 (2): 223–37. https://doi.org/10.2307/3546962.

Beckett, Richard. 2021. “Probiotic Design.” *The Journal of Architecture* 26 (1): 6–31. https://doi.org/10.1080/13602365.2021.1880822.

———. 2023. “Architecture for the Holobiont: Designing Probiotic Interventions.” In *Proceedings of the 43rd Annual Conference for the Association for Computer Aided Design in Architecture (ACADIA)*, 2:220–29. Denver.

Chadha, Kunaljit, Natalia Ramos Montilla, Ingrid Maria Paoletti, and Olga Beatrice Carcassi. 2023. “Programmed Growth: A Living Mycelium and Clay Composite.” In , 311–20. Ahmedabad. https://doi.org/10.52842/conf.caadria.2023.2.311.

Crawford, Assia, Pichaya In-na, Gary Caldwell, Rachel Armstrong, and Ben Bridgens. 2022. “Clay 3D Printing as a Bio-Design Research Tool: Development of Photosynthetic Living Building Components.” *Architectural Science Review* 65 (3): 185–95. https://doi.org/10.1080/00038628.2022.2058908.

Cruz, Marcos. 2020. “Poikilohydric Design, towards a Bio-Integrated Architecture.” In *Design with Life*, Joachim, M. and Aiolova, M., 414–18. New York: Actar Publishers.

———. 2022. “Poikilohydric Living Walls.” In *Bartlett Design Research Folios*. http://bartlettdesignresearchfolios.com/cruz-poikilohydric-living-walls.

Diniz, Nancy, and Frank Melendez. 2023. “A Bio-Digital Fabrication Method for Large Scale 3D Printing of Bioreceptive Clay Modules and Automated Colonization of Lichen Communities.” In *Proceedings of the 43rd Annual Conference of the Association for Computer Aided Design in Architecture*.

Flies, Emily J, Chris Skelly, Sagri Singh Negi, Poornima Prabhakaran, Qiyong Liu, Keke Liu, Fiona C Goldizen, Chris Lease, and Philip Weinstein. 2017. “Biodiverse Green Spaces: A Prescription for Global Urban Health.” *Frontiers in Ecology and the Environment* 15 (9): 510–16. https://doi.org/10.1002/fee.1630.

Guillitte, O. 1995. “Bioreceptivity: A New Concept for Building Ecology Studies.” *Science of The Total Environment*, The Deterioration of Monuments, 167 (1): 215–20. https://doi.org/10.1016/0048-9697(95)04582-L.

Herr, Christiane M., and Chenxiao Li. 2023. “Articulating Facade Microbiomes at Human Scale.” In *Proceedings of the 28th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2023)*. CUMINCAD. https://papers.cumincad.org/cgi-bin/works/paper/caadria2023_339.

Jakubovskis, Ronaldas, Jurgita Malaiškienė, and Viktor Gribniak. 2023. “Bio-Colonization Layered Concrete Panel for Greening Vertical Surfaces: A Field Study.” *Case Studies in Construction Materials* 19 (December):e02394. https://doi.org/10.1016/j.cscm.2023.e02394.

Lim, Ariel Cheng Sin, and Ayoub Lharchi. 2023. “Parameters for Bio-Receptivity in 3D Printing.” In *Design for Climate Adaptation*, edited by Billie Faircloth, Maibritt Pedersen Zari, Mette Ramsgaard Thomsen, and Martin Tamke, 701–15. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-36320-7_44.

Mahrous, Rewaa, Emanuela Giancola, Ahmed Osman, Takashi Asawa, and Hatem Mahmoud. 2022. “Review of Key Factors That Affect the Implementation of Bio-Receptive Façades in a Hot Arid Climate: Case Study North Egypt.” *Building and Environment* 214 (April):108920. https://doi.org/10.1016/j.buildenv.2022.108920.

Manso, Sandra, Willem De Muynck, Ignacio Segura, Antonio Aguado, Kathy Steppe, Nico Boon, and Nele De Belie. 2014. “Bioreceptivity Evaluation of Cementitious Materials Designed to Stimulate Biological Growth.” *Science of The Total Environment* 481 (May):232–41. https://doi.org/10.1016/j.scitotenv.2014.02.059.

Marsaglia, Valeria, Guido Brusa, and Ingrid Paoletti. 2023. “Moss as a Multifunctional Material for Technological Greenery Systems.” *The Plan Journal* 8 (1). https://doi.org/10.15274/tpj.2023.08.01.3.

Marselle, Melissa R., Sarah J. Lindley, Penny A. Cook, and Aletta Bonn. 2021. “Biodiversity and Health in the Urban Environment.” *Current Environmental Health Reports* 8 (2): 146–56. https://doi.org/10.1007/s40572-021-00313-9.

Mustafa, Kazi Fahriba, Alejandro Prieto, and Marc Ottele. 2021. “The Role of Geometry on a Self-Sustaining Bio-Receptive Concrete Panel for Facade Application.” *Sustainability* 13 (13): 7453. https://doi.org/10.3390/su13137453.

Rook, Graham A.W., and Sally F. Bloomfield. 2021. “Microbial Exposures That Establish Immunoregulation Are Compatible with Targeted Hygiene.” *Journal of Allergy and Clinical Immunology* 148 (1): 33–39. https://doi.org/10.1016/j.jaci.2021.05.008.

Ruokolainen, Lasse, Jenni Lehtimäki, Antti Karkman, Tari Haahtela, Leena von Hertzen, and Nanna Fyhrquist. 2017. “Holistic View on Health: Two Protective Layers of Biodiversity.” *Annales Zoologici Fennici* 54 (1/4): 39–49.

Sadeghipour Roudsari, Mostapha, Michelle Pak, and Anthony Viola. 2013. “Ladybug: A Parametric Environmental Plugin For Grasshopper To Help Designers Create

An Environmentally-Conscious Design." In , 13:3128–35. Building Simulation. IBPSA. https://doi.org/10.26868/25222708.2013.2499.

Sanmartín, P., A. Z. Miller, B. Prieto, and H. A. Viles. 2021. "Revisiting and Reanalysing the Concept of Bioreceptivity 25 Years On." *Science of The Total Environment* 770 (May):145314. https://doi.org/10.1016/j.scitotenv.2021.145314.

Shanahan, Danielle F., Robert Bush, Kevin J. Gaston, Brenda B. Lin, Julie Dean, Elizabeth Barber, and Richard A. Fuller. 2016. "Health Benefits from Nature Experiences Depend on Dose." *Scientific Reports* 6 (1): 28551. https://doi.org/10.1038/srep28551.

Sochůrková, Petra, Daniel Sviták, Imrich Vaško, Shota Tsikoliya, Pierre Oskam, and Max Latour. 2023. "Bioreceptivity as a Factor of Additive Fabrication." In , 115–24. Graz, Austria. https://doi.org/10.52842/conf.ecaade.2023.2.115.

Tietz, Heather R. 2021. "Foreground for Mosses: Designing 3D Printed Clay Bryobricks to Enhance the Built Environment." 2021. https://www.asla.org/2021studentawards/3924.html.