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Cite this article: Melcore M, Vershinina A, Yücel I, Öğün Ramalhete E, and Armstrong R (2026). Comparative parametric methods for designing bio-receptive interfaces. *Biotechnology Design*. **4**, e31, 1–9. https://doi.org/10.1017/S2977905726100584

Received: 23 February 2026 UTC
Revised: 11 May 2026 UTC
Accepted: 21 May 2026 UTC

Keywords:
surface patterning; digital parametric fabrication; bio-receptivity; SPIKA; regenerative architecture

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Comparative parametric methods for designing bio-receptive interfaces

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Abstract

In recent years, bio-receptivity has gained increasing attention within regenerative practices. In the built environment, bio-receptive façades function as living interfaces that sustain cryptogamic and microbial growth, thus reshaping ecological interactions in urban areas. Although bio-receptivity has been studied by scientists for decades, architects and designers now play a critical role in advancing its application. This study investigates key parameters influencing bio-receptivity, including surface patterning, substrate composition, fabrication methods and spatial orientation. Parametric geometries were computationally developed to enhance hydrodynamic performance, while material variations were evaluated for their capacity to support moisture retention and biological attachment. The prototypes were produced through an integrated workflow that combined subtractive, additive and formative manufacturing processes and subsequently inoculated with a selected cryptogamic–microbial culture to examine growth dynamics. The research culminated in a nine-month full-scale installation entitled SPIKA, exhibited at the Milan Triennale, serving as a public demonstrator of bio-digital fabrication and ecological integration.

Impact statement

This research advances bio-digital design by establishing a preliminary, replicable framework for bio-receptive architectural surfaces, validated through the *SPIKA* installation at the Milan Triennale. It delivers a process-oriented comparison of three fabrication paradigms – subtractive (CNC-milled wood), formative (mould-cast concrete) and additive (3D-printed clay) – documenting parametric workflows and material-specific parameters that link manufacturing processes to potential ecological performance. By demonstrating promising initial biological colonization across all substrate types within 75 days of on-site inoculation, the project validates the feasibility of moving bio-receptive design from laboratory settings to real-world architectural applications as an exploratory prototype. *SPIKA* reconceptualizes the architectural façade as a dynamic ecological interface, offering a transferable model for regenerative practices that integrate computation, material science and microbiology. This work provides designers with practical strategies for enhancing urban biodiversity and supporting ecological succession, while acknowledging the need for future quantitative validation.

Introduction

Contemporary urban environments increasingly recognize the need to integrate ecological performance within architectural design. However, practical methodologies for developing building surfaces that actively support biological life remain underexplored. This paper addresses this gap by asking: How can subtractive, formative and additive fabrication paradigms be systematically compared in the production of bio-receptive architectural surfaces, and what are the limits of such a comparison in the absence of quantitative biological monitoring?

It presents *SPIKA*, a bio-digital design project that develops and explores strategies for bio-receptive architectural surfaces. Drawing inspiration from defensive natural morphologies and self-organized biological patterns such as reaction-diffusion, the research translates these principles into performative surface geometries. Importantly, existing literature has established that morphological parameters such as porosity, rugosity, pH and surface texture significantly influence bioreceptivity (Abdallah and Estévez, 2023; Guillitte, 1995; Pollini *et al.* 2023). However, the specific relationship between digitally fabricated spike geometries and colonization dynamics remains underexamined. This study does not isolate morphology as an independent variable but instead examines how fabrication constraints shape achievable morphologies and their initial ecological responses. It is limited to indoor conditions and does not address long-term ecological succession or outdoor environmental variability. Accordingly,

the focus remains on early-stage growth behaviour and material–geometry interactions rather than full lifecycle ecological outcomes.

Through a systematic design-to-fabrication workflow, sixty-eight panels were produced using three distinct manufacturing methods with three corresponding materials – CNC-milled wood, mould-cast concrete and 3D-printed clay. Following fabrication, all substrates were inoculated with a cryptogamic-microbial culture collected from Parco Sempione, Milan. Validated through public exhibition at the Milan Triennale, *SPIKA* establishes an exploratory framework for reconceptualizing architectural façades as dynamic ecological interfaces that can support urban biodiversity and regenerative design practices. The primary contribution of this pictorial is the detailed documentation of fabrication parameters and workflows. The biological observations are presented as preliminary and qualitative rather than as a controlled comparative experiment.

Digital 3D modelling

A tessellated assembly of sixty-eight panels was digitally modelled using Rhinoceros 3D software in combination with the Grasshopper parametric modelling extension and AutoCAD software.

Spiky surface pattern

The computational workflow allowed precise control over panel geometry, subdivision and surface articulation. The resulting surface pattern draws inspiration from the defensive mechanisms found in natural systems, translating adaptive, survival-driven morphologies into performative bio-receptive surfaces (Figure 1).

Reaction-diffusion surface pattern

Figures 1–3 outline the computational development and digital simulation of bio-receptive surface geometries generated through Rhinoceros3D, Grasshopper and AutoCAD workflows. Figure 1 presents the parametric modelling process used to create the spiky surface pattern for the wood and concrete panels, characterized by pointed protrusions distributed across a tessellated geometry to increase surface complexity. Figure 2 demonstrates the resulting digital simulation of the façade system integrating both wood and concrete panels. Figure 3 further complements this topological investigation through the incorporation of softer geometries combined with reaction–diffusion patterns for the clay panels.

Unlike the spiky surface pattern, the clay tiles adopt softer geometries inspired by beetle carvings on wooden surfaces. These macro-geometries are analogous to reaction-diffusion patterns, where local interactions produce self-organized surface formations, reflecting principles of biomimicry and parasitic ecological interactions (Figure 3).

Parametric fabrication methods

Panels were fabricated from three different materials – wood, concrete and clay – to qualitatively explore the biological growth supported by each under similar indoor environmental conditions. Subtractive, formative and additive manufacturing methods were employed. Each material is characterized by a distinct surface geometry directly informed by its respective fabrication method, thereby establishing a relationship between manufacturing process and material expression.

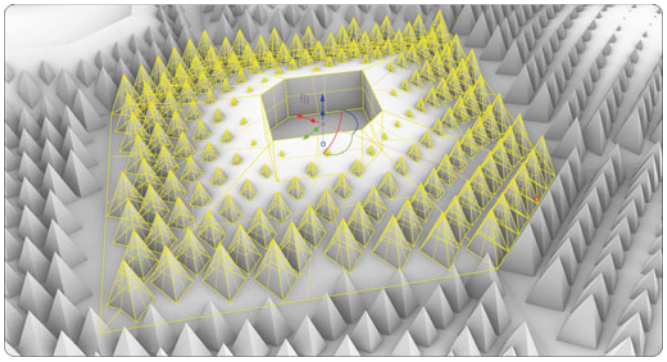


Figure 1. 3D modelling of the spiky surface pattern (Rhinoceros3D and Grasshopper).

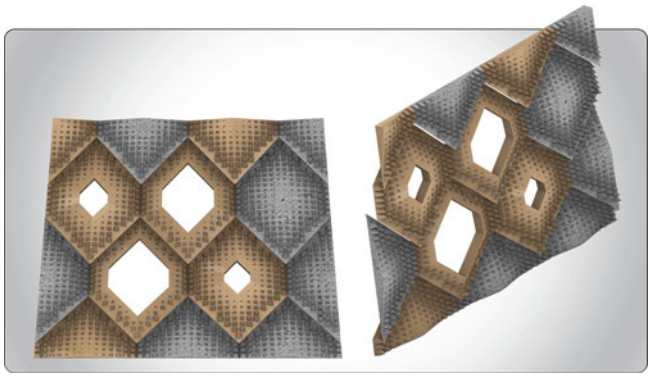


Figure 2. Digital simulation of the spiky surface pattern (Rhinoceros3D).

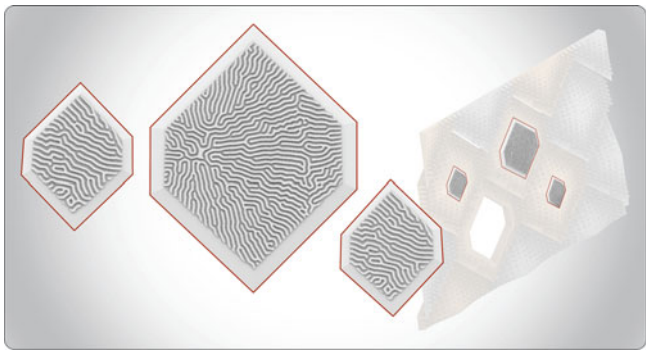


Figure 3. Digital drawing of the reaction-diffusion surface pattern (AutoCad and Rhinoceros3D).

Figure 4 provides a side-by-side visual comparison of the resulting surface textures at 20× magnification. Figure 12 (see page 6) summarizes the key fabrication parameters, material properties relevant to bioreceptivity (porosity, pH, surface roughness), and the specific geometric outcomes achievable per method.

Subtractive manufacturing: CNC milling

Two softwood species were selected for this study: Douglas fir (*Pseudotsuga menziesii*) and spruce (*Picea abies*), both in their chemically untreated construction-grade form. These species were chosen because, as softwoods, they exhibit higher porosity and lower density than hardwoods – properties that are known to enhance bio-receptive potential. Their selection was also motivated by their widespread availability in Europe, particularly in Belgium,

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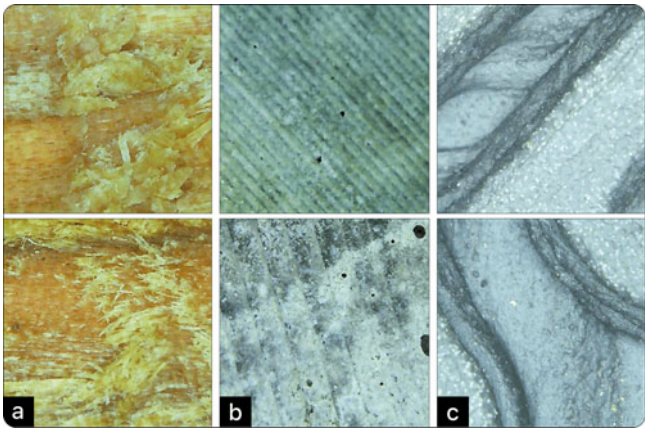


Figure 4. Surface textures of (a) CNC-milled wood, (b) mould-cast concrete and (c) 3D-printed clay substrates. 20× magnification.

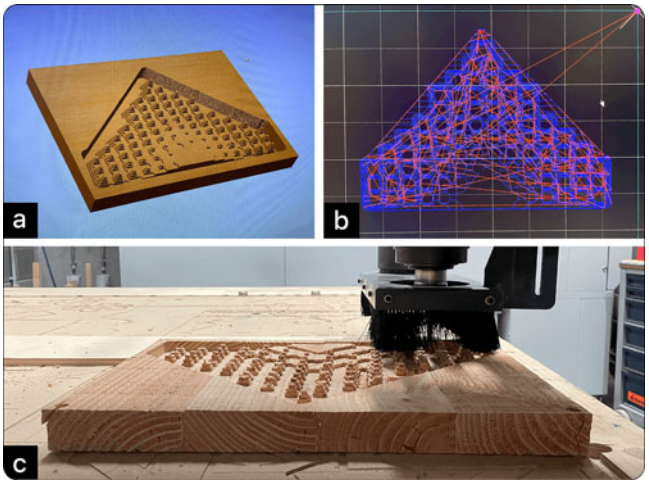


Figure 5. Programming CNC machine: (a) Tool-path simulation in Aspire software, (b) G-code progression on controller screen, (c) CNC milling on wood block.

where subsequent experiments are planned. The wood samples were procured in March 2025 from Hanssens Hout, a wood supplier based in Ghent, Belgium.

The wood panels were fabricated using a subtractive CNC-milling process. All panels were prepared in the Wood Workshop facilities of the LUCA School of Arts. The wood planks were initially cut using professional woodworking equipment and subsequently glued with Rectavit 210 Classic wood adhesive to produce blocks suitable for CNC milling. The 3-axis CNC milling was performed using a Colinbus machine, manufactured by CNC Studio (Figure 5).

The parameter combination found to be most effective for both Douglas fir and spruce consisted roughing path, a 5.94 mm step-over (99.00%), a 6 mm flat-end drill bit and a spindle speed of 20,000 rpm. These settings provided an optimal balance between detail fidelity, structural integrity and surface quality across both wood types. As a result of these parameters, the initial 3D-modelled spiky geometry was slightly modified across the wood panels (Figure 6).

Figures 5–7 present the transition from computational fabrication workflows to the production of tangible bioreceptive prototypes through CNC milling processes. Figure 5 presents the

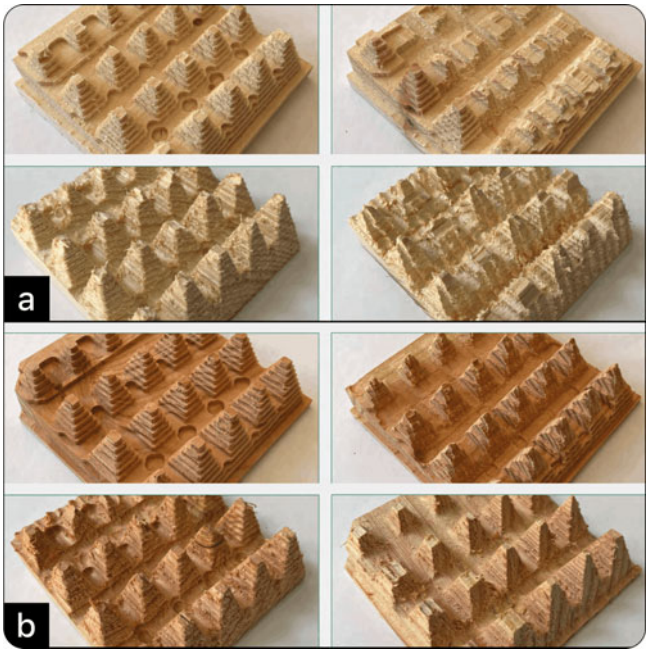


Figure 6. Evaluation of G-code parameter variations to optimize pattern fidelity and surface roughness on (a) spruce pine and (b) douglas fir woods.

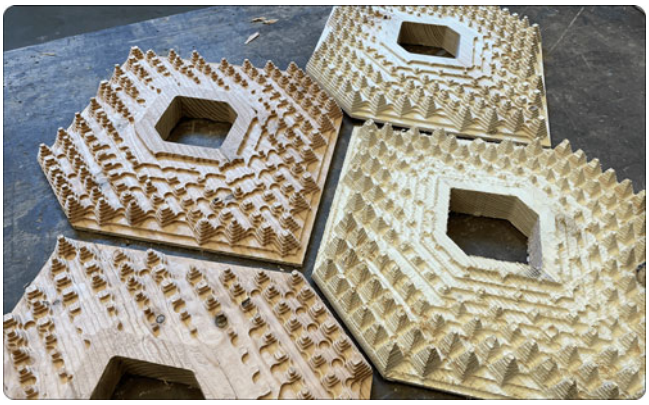


Figure 7. Overview of the final series of CNC-milled wood panels (Douglas fir on the left side and spruce pine on the right side).

digital preparation and machining sequence, including the tool-path simulation in Aspire software, the visualization of G-code progression on the CNC controller interface and the milling process performed on wood blocks. Figure 6 documents the evaluation of different G-code parameter variations used to optimize pattern fidelity and surface roughness on spruce pine and Douglas fir specimens, assessing the material response to fabrication constraints and textural resolution. Figure 7 provides an overview of the final series of CNC-milled wood panels, comparing the resulting prototypes produced in Douglas fir and spruce pine and demonstrating the translation of computational surface geometries into physical bioreceptive architectural components.

Formative manufacturing: mould-casting

Concrete panels were fabricated using a two-stage workflow: (1) silicone mould production from 3D-printed positives and (2)

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Figure 8. Silicon mould-making and casting processes of the concrete panels.



Figure 9. Overview of the final series of casted concrete panels (CEM I or CEM III).

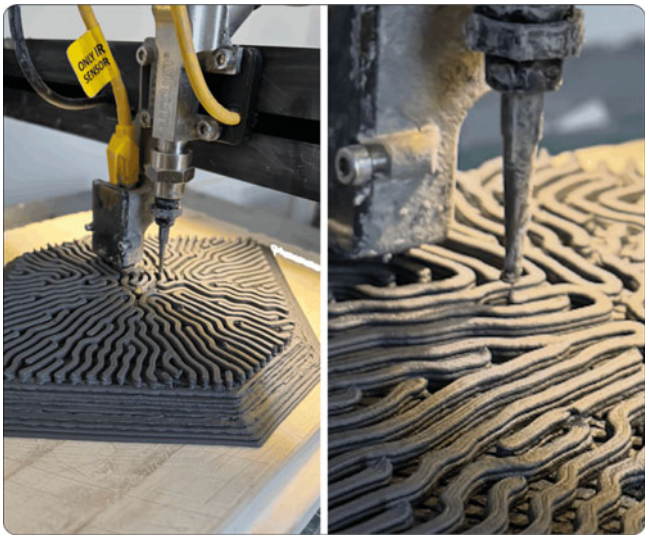


Figure 10. Evaluating clay consistency for the 3D printing process on LUTUM 5 printer.



Figure 11. Kiln firing process of the 3D-printed clay panels (stoneware).

repeated concrete casting in two cement types (CEM I and CEM III) to generate a full set of tiles.

The moulds were made from 3D-printed positive tiles produced at LUCA School of Arts. Positives were printed in PLA on Prusa and Ultimaker printers. Each mould was prepared on a laser-cut MDF base, with temporary cardboard borders constructed around the perimeter to contain the silicone during casting.

Before pouring silicone, the printed positives were coated with a brushed layer of Pattex wood glue diluted with water. This layer was left to dry completely and served as a separating/sealing layer between the PLA and silicone to support clean demoulding.

Silicone moulds were then cast using "Siliconen Rubber Shore 25, Mallen gietsiliconen (A+B)," mixed according to 100:30 ratio. An initial plan was to apply the silicone in multiple layers to reduce material use; however, due to the steep spike geometry and time constraints, the process was changed to a full-pour method. Cardboard borders were therefore set to create an approximately 1 cm-thick silicone body around the mould, and the silicone was poured in one complete cast. The moulds were left to cure at room temperature for approximately 2–3 days and then demoulded carefully using hand tools to avoid damaging fine spike features.

Concrete tiles were produced by casting into the silicone moulds. Prior to casting, the silicone surfaces were coated with polyvinyl alcohol (PVA) as a release agent and left to dry.

Concrete was mixed without additives using a simple ratio of 1 part cement (either CEM I or CEM III), 2 parts sand and approximately 0.6 part water (adjusted slightly as needed to reach workable consistency). The sand used was Rivierzand (river sand) with a 0–4 mm grading (25 kg bag, Hubo).

After mixing, concrete was poured into the moulds and compacted using a manual vibration technique: each mould was placed on a dedicated MDF support board, and after pouring the board was repeatedly lifted slightly at one edge and slammed down onto the table to vibrate the mould and help the mix settle into fine details and release entrapped air. This was repeated frequently for approximately 10 minutes per cast (Figure 8).

Panels were left to cure at room temperature and demoulded after approximately 2–3 days, followed by continued air curing (Figure 9).

Figures 8 and 9 document the transition from mould fabrication to the production of cast concrete bioreceptive prototypes. Figure 8 presents the silicone mould-making and casting processes developed for the concrete panels, highlighting the translation of digitally generated surface geometries into reproducible casting systems. Figure 9 shows the final series of cast concrete panels produced using CEM I and CEM III cement formulations, enabling a comparative evaluation of their material characteristics, surface resolution and potential bioreceptive performance.

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Comparative Synthesis Table

Fabrication Method	Subtractive (CNC)	Formative (mould-cast)	Additive (3D print)
Material	Douglas fir (*Pseudotsuga menziesii*) and Spruce (*Picea abies*)	Concrete (CEM I, III)	Stoneware clay
Porosity (qualitative)	High (softwood)	Medium (capillary pores)	Low-medium (after firing)
pH	~5–6 (acidic)	~12–13 (alkaline)	~7–8 (near neutral)
Surface Roughness (relative)	Medium-high (tool marks)	High (mould texture + formwork)	Medium (layer lines)
Achievable Geometry	Steep spikes, but truncated	High fidelity to positive	Soft, reaction-diffusion geometries
Key Limitation for Bio-receptivity	Tool access limits undercuts; wood acidity may inhibit some microbes	High pH inhibits early colonization; requires weathering	Layer lines create directional micro-habitats; shrinkage cracks may aid or hinder

Figure 12. Comparative summary of fabrication methods, material properties relevant to bioreceptivity and geometric outcomes.

Additive manufacturing: 3D printing

The clay panels were fabricated at the LUCA School of Arts facilities using a LUTUM 5 clay 3D printer supplied by VormVrij Factory. Stoneware clay was chosen for its strength and versatility for outdoor and architectural uses. The clay was purchased from Colpaert, Ghent, and was NIGRA 20/02 chamotte clay (0–0.2 mm grog, 10 kg bags).

To achieve a consistency suitable for syringe loading, the clay paste initially prepared with 15% water content was found to be excessively viscous for clay-based 3D printing. The formulation was therefore adjusted by increasing the total water content to 30% (by weight) relative to the dry clay mass.

Geometry of the clay models were developed in AutoCad and Rhinoceros 3D, exported as STL files and processed using PrusaSlicer, following a workflow adapted for paste-extrusion clay printing. The LUTUM 5 printer was equipped with a 3 mm nozzle, with print speed set to 110% of the machine's default profile and extrusion flow adjusted between 60–70% to stabilize bead width and layer adhesion. All clay panels shared a long hexagonal morphology; three nominal heights were used, approximately 144.13, 264.58 and 127.44 mm and each dimension was scaled 12% larger in the digital model to compensate for drying and firing shrinkage.

Figures 10 and 11 document the development of the clay fabrication workflow, from material preparation to the thermal transformation of the final prototypes. Figure 10 presents the evaluation of clay consistency for the extrusion-based 3D printing process using the LUTUM 5 printer, assessing the material's printability, structural stability and capacity to retain complex surface geometries. Figure 11 shows the kiln firing process of the 3D-printed stoneware clay panels, highlighting the transition from raw printed components to durable ceramic prototypes suitable for bioreceptive applications.

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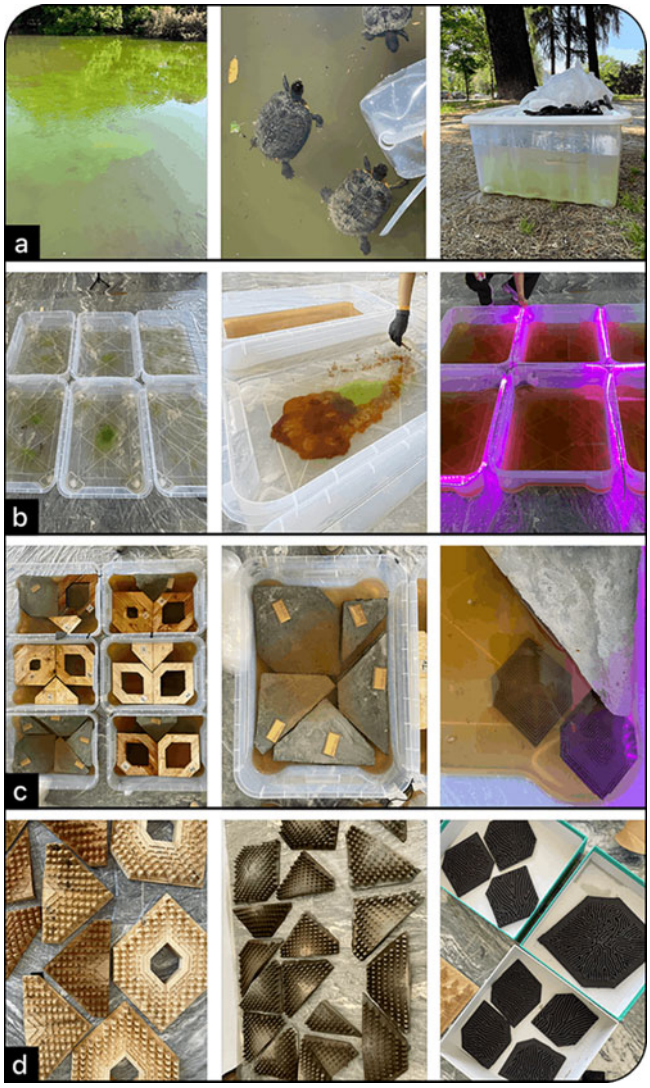


Figure 13. Cryptogamic-Microbial inoculum collection and inoculation process on the different panels: (a) collection from pond water at Parco Sempione, Milan Triennale Park. (b) Baths set-up with nutrient and LEDs lighting. (c) Inoculation of the panels in soaking baths for 15 hours. (d) Maintenance of the panels with water spray after the inoculation.

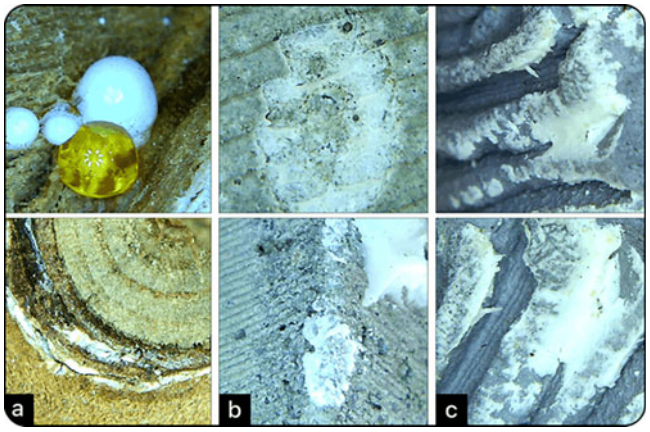


Figure 14. Initial biological growth observed across the different substrates after a two-month period: (a) wood, (b) concrete and (c) clay. 20× magnification. **Annotations**: On the wood samples (a), whitish nodular formations and biofilm development are observable along the natural wood grain. On the concrete samples (b), patchy white colonies appear preferentially on rougher cast surfaces, suggesting localized surface conditions favourable to biological attachment. On the clay samples (c), filamentous whitish growth follows the layered deposition patterns generated through the 3D-printing process. Samples were collected from the north-facing side of the installation, where solar exposure and light was lowest. As no longitudinal or time-series documentation was conducted during the growth period, the images presented here should be considered endpoint observations only.



Figure 15. Bio-receptive panels tessellation as part of the overall biological garden in the *SPIKA* installation (Microbial-Hydroponics [Mi-Hy] project). Photograph by Rachel Armstrong during the exhibition "*Inequalities. We the Bacteria. Notes Toward Biotic Architecture,*" Milan Triennale, 2025.

Biological inoculation and preliminary observations

The collection site, a pond at Sempione Park, was selected for its ecological relevance due to its proximity to the Milan Triennale. The water samples were collected *in situ* from the southeast side of the pond, where the intensity of the greenish water colour indicated higher algal concentrations. Sampling focused on the surface layer, where light and oxygen availability promote microbial growth.

Biological component

The undefined mixed culture was placed in six plastic boxes, supplemented with a nutrient solution and exposed to UV LED light for six hours. All of the panels were then immersed in these inoculation baths for a minimum of ten hours.

Figure 13 details the collection and inoculation process of the cryptogamic–microbial inoculum applied to the different panels. The inoculum was collected from pond water at Parco Sempione, in the vicinity of the Triennale Milano (a). Subsequently, soaking baths were prepared with nutrient solutions and LED lighting to promote microbial activity and growth (b). The panels were then immersed in the inoculum baths for approximately 15 hours to ensure effective colonization of the surface (c). Following inoculation, the panels were maintained under semi-controlled conditions through regular water spraying to support the establishment and development of the cryptogamic–microbial communities (d).

After seventy-five days, all substrates – wood, concrete and clay – exhibited initial biological growth, indicating promising colonization. However, due to the constraints of the exhibition setting, no quantitative monitoring (e.g., percentage coverage,

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Figure 16. Surface patterning details of the bio-receptive panels tessellation. Photograph by BioFaction team.

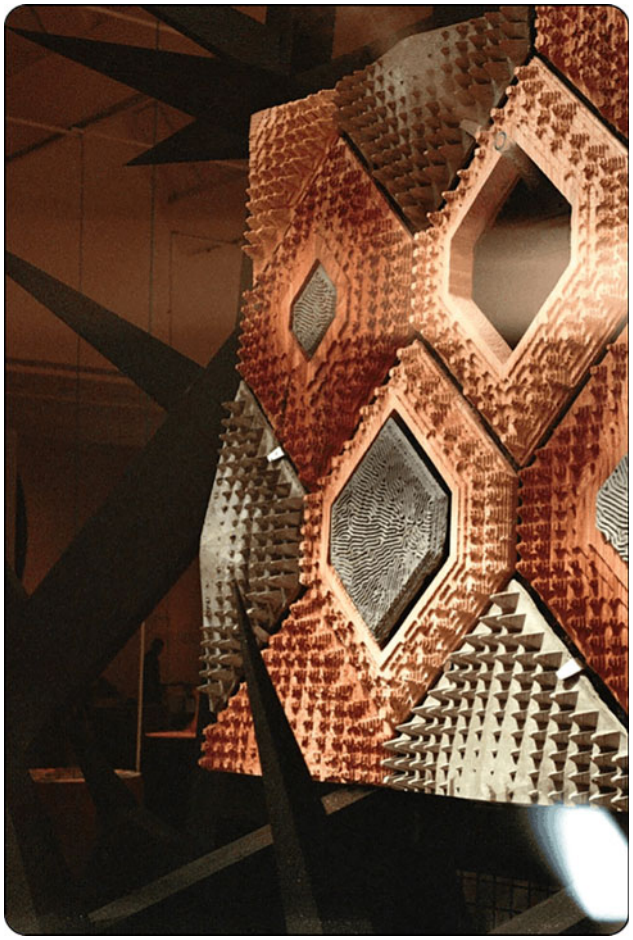


Figure 17. Surface patterning details of the bio-receptive panels tessellation. Photograph by Işıl Yücel. Milan Triennale, 2025.

species identification via microscopy or DNA barcoding, chlorophyll fluorescence measurements) was performed. The observations reported here are therefore qualitative and visual.



Figure 18. *SPIKA* overall prototype setup of the Mi-Hy system, including the series of bio-receptive panels. Photograph by Işıl Yücel. Milan Triennale, 2025.

SPIKA installation

The installation of the panels adhered to the architectural logic of the *SPIKA* composition, with the panels systematically distributed across the four vertical façades of the structure (Armstrong, 2025; Modesto *et al.* 2026). Each façade accommodated seven concrete panels, seven wooden panels and three clay panels. This spatial configuration was intentionally designed to reflect not only the aesthetic composition but also the indoor environmental exposure conditions. Panel positioning accounted for variables such as solar orientation, which was expected to influence biological growth processes over the duration of the exhibition.

Figures 15–20 present the SPIKA installation within the Microbial-Hydroponics (Mi-Hy) project, presented as part of the exhibition "*Inequalities. We the Bacteria. Notes Toward Biotic Architecture*" at Milano Triennale in 2025. Together, the images illustrate the spatial and material organization of the bio-receptive system, from the integration of panel tessellations within the broader biological garden (Figures 18 and 19). They further document the full-scale *SPIKA* prototype, where the bioreceptive panels system was deployed across four vertical façades, arranged in a structured modular grid (Figures 15–17). The four vertical façades of the structure each accommodated seven concrete panels, seven wooden panels and three clay panels. The south-facing façade received the highest solar exposure, while the north-facing

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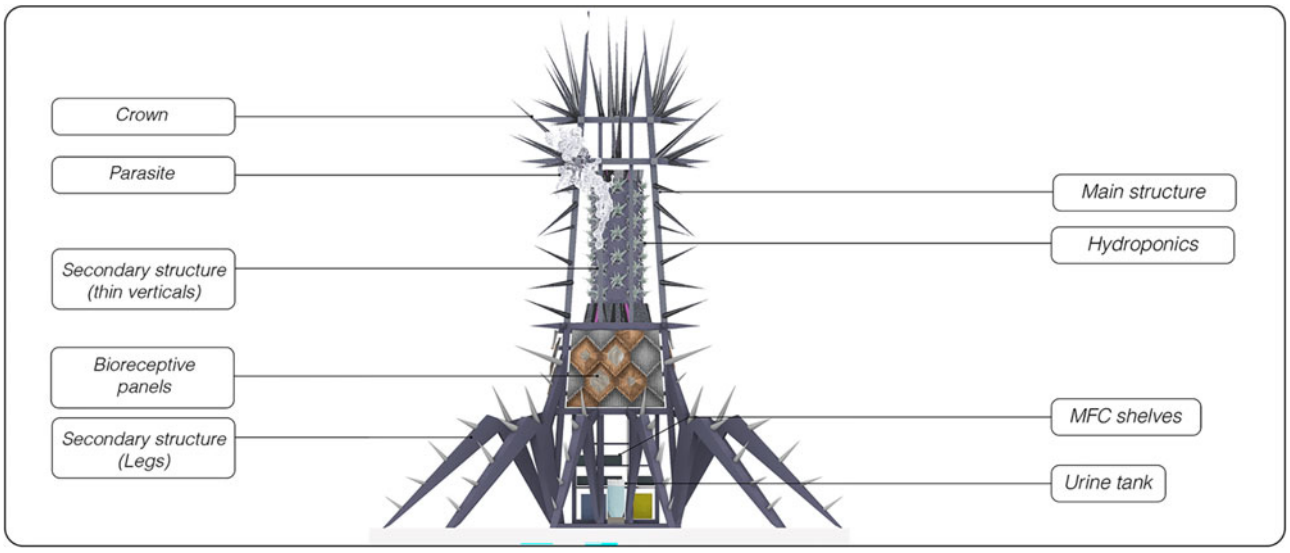


Figure 19. *SPIKA* diagram showcasing the vertical garden and its ecological and functional components.



Figure 20. Front view of *SPIKA*, a 7-metre-tall installation, showcasing the overall prototype setup of the Mi-Hy system. Photograph by Işıl Yücel during the exhibition "*Inequalities. We the Bacteria. Notes Toward Biotic Architecture*," Milan Triennale, 2025.

façade received the least. Panel positions were recorded to allow future correlation with growth patterns, but the current study does not analyse orientation-dependent effects due to the absence of quantitative growth data. Figure 19 provides an overall frontal view of the installation, consolidating the system's architectural assembly and its integration of bio-receptive surfaces within a coherent experimental structure.

Conclusion

SPIKA demonstrates an exploratory integration of computational design, parametric fabrication and ecological inoculation within an unified architectural installation. By comparing subtractive, formative and additive manufacturing methods across wood, concrete and clay substrates, the project qualitatively documents that diverse fabrication paradigms can support initial biological colonization under indoor environmental conditions. The observed initial growth across all material types validates the proposed design-to-fabrication workflow as a replicable model for future, more controlled studies of bio-receptive architecture.

Limitations and future work

This study does not claim to be a controlled comparative analysis of biological performance. Key limitations include: (1) no quantitative measurement of colonization (e.g., % coverage, species identification, biomass), (2) no replication or statistical treatment, (3) no isolation of morphology from other variables (porosity, pH, material chemistry) and (4) no time-series monitoring. Future work will involve laboratory-controlled experiments with standardized inocula, replicate samples and systematic measurement protocols. Additionally, the relationship between specific geometric features (spike density, curvature, layer-line orientation) and colonization success requires dedicated parametric variation studies.

Reconceptualizing façades as dynamic ecological interfaces, *SPIKA* offers a transferable pathway toward regenerative design practices that actively support urban biodiversity and ecological succession, while recognizing that rigorous quantitative validation remains the necessary next step.

Data availability statement. The authors confirm that the data supporting the findings of this study are available within the article.

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Acknowledgements. The authors would like to thank: Beatriz Colomina and Mark Wigley, curators of the 24th International Exhibition "*Inequalities. We the Bacteria. Notes Toward Biotic Architecture*" for inviting the RAAD research group to showcase its work at the Milan Triennale from May 13 to November 9, 2025; Maurizio Bisi (Medbcreateam Srl) and his entire construction team for their support during the installation's construction.

The Microbial-Hydroponics (Mi-Hy) research team for their guidance and collaboration, including Prof. Yannis Ieropoulos and Natasha Tait (University of Southampton, UK), Prof. Peter Hanappe and Dr. Lenon Romano (Sony Computer Science Laboratories, Paris, France), Prof. Jorge Barriuso and Dr. Ignacio Barriuso (Spanish National Research Council, Madrid, Spain), Prof. Markus Schmidt, Uliana Reutina, Camillo Meinhart and Ines Sarazin (BioFaction, Vienna, Austria) and Prof. Neil Willey and Dr. Mukesh Sharma (University of the West of England, Bristol, UK).

Milan Polytechnic University (Politecnico di Milano) for facilitating this research, including Prof. Valentina Rognoli (Department of Design), Dr. Salvatore Viscuso, Dr. Anna Dalla Valle and Lorenzo Rota (Department of Architecture, Built Environment and Construction Engineering, DABC).

Mahsa Davaraza, Ph.D. exchange researcher, for her advice on clay 3D printing (University of Aveiro, Department of Environment and Planning, Aveiro, Portugal).

All technicians from LUCA School of Arts (Campus Sint-Lucas, Brussels and Ghent, Belgium) who contributed to prototyping the panels: Robin Berrewaerts, Sam Van Gils, Bart Aertsen, Ambet Manalo and Elie Desmet (Wood Workshop, LUCA Construct); Glenn De Cock, Julia Hadassa Cumaru and Amy Beaulisch (LUCA 3D Printing) and Sabine Deroo (LUCA Ceramics).

Author contributions. Conceptualization: Marie Melcore, Anna Vershinina, Işıl Yücel and Rachel Armstrong. Methodology: Marie Melcore, Anna Vershinina, Işıl Yücel and Ezgi Öğün Ramalhete. Data curation: Ezgi Öğün Ramalhete. Visualization: Marie Melcore, Anna Vershinina and Işıl Yücel. Writing – Original draft: Marie Melcore (initial manuscript draft); Anna Vershinina (subsection 2, *Formative Manufacturing: Mould-Casting*); Işıl Yücel (subsection 2, *Additive Manufacturing: 3D Printing*). Writing – Review and editing: Rachel Armstrong.

Financial support. This research was supported by the European Union's Horizon Europe EIC Pathfinder Challenges research and innovation program through the Mi-Hy project (Grant Agreement No. 101114746); the Bio+Wood FWO Junior Research Project; and the Bio+Concrete FWO Doctoral Fellowship. This work was additionally facilitated by an Erasmus award between KU Leuven and Milan Polytechnic and supported by Johan Verbeke Belgium funding.

Competing interests. The authors declare that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics standards. The authors declare that no ethical approval was required for this study as it did not involve human or animal subjects.

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