THESIS FOR THE DEGREE OF LICENTIATE OF ARCHITECTURE

Matter in transition: From underutilized biomass to robotically fabricated architectural material for resource-efficient renovation

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Abstract

Architecture is increasingly required to operate across disciplinary boundaries in response to an urgent transition shifting from fossil-based construction systems toward resource-efficient and renewable alternatives. While emerging biobased materials offer such possibilities, they also challenge predictability and standardization, demanding new, interdisciplinary, material-driven design methodologies. In this context, this licentiate thesis aims to investigate how a novel biobased material, derived from underutilized biomass, can be developed, fabricated, and translated into architectural applications.

Focusing on the formulation and upscaling of a yeast-cellulose hydrogel, the thesis positions material as an active element whose behaviours must be negotiated during design and fabrication. This highlights the architect's role as a mediator at the crossover of biotechnology, material science, and architectural design. Therefore, the study employs a research-by-design methodology in which making serves as inquiry, establishing an iterative workflow in which material formulation, computational toolpath design, and robotic fabrication are studied together through iterative, micro-, meso-, and macroscale prototypes. This framework addresses three interconnected inquiries: the formulation and characterization of the yeast-cellulose hydrogel (RQ1); the development of fabrication strategies that respond to material agency (RQ2); and the exploration of architectural applications enabled by this co-development (RQ3).

The research findings lead to two proof-of-concept, architectural applications: a tiling system and an early-stage timber coating. These prototypes reveal how the material’s aesthetic and physical characteristics translate to spatial, tactile, and visual architectural expressions. Moving beyond laboratory conditions, the research situates the material in context through public exhibitions and testbed installations, providing early observations on environmental exposure and user perception.

Overall, the thesis proposes an alternative approach in which interdisciplinary knowledge, material response, and digitally mediated craft reshape how architecture addresses environmental challenges. Future research will build on these findings through further optimization of the yeast-cellulose hydrogel and fabrication parameters, investigating material performance, environmental aging, and user perception, supporting the development and architectural integration.

Keywords: *Yeast-cellulose hydrogel, Bio-based materials, Robotic 3D printing, Architectural design, Material-driven computational design, Biofabrication*

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List of Publications and Research Dissemination

This thesis is based on the following appended papers and other research communication outputs:

Paper A

Bektas, Y., Zboinska, M. A., Geijer, C., Nypelö, T., & Hefny, Z. (2026). Novel 3D printable yeast-based materials for architectural applications. Frontiers of Architectural Research. https://doi.org/10.1016/j.foar.2026.01.003

Paper B

Bektas, Y., Zboinska, M., Skånberg Dahlstedt, T., Geijer, C., Nypelö, T. (2026). Digital crafting of architectural biomaterials: Computational geometric design and robotic 3D printing of yeast-cellulose hydrogels. In Humanistic computation and intelligence: Proceedings of the 31st annual conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2026) (Vol. 2, pp. 205-214. Hsinchu, Taiwan.
https://papers.cumincad.org/data/works/att/caadria2026_353.pdf

Exhibition

Mycotecture: Sustainable Architecture from Yeast Materials
Helsinki Design Week - Designs for a Cooler Planet,
Aalto University, Helsinki, Finland, 2025.
Bektas, Y.; Zboinska, M.; Nypelö, T.; Geijer, C.

Testbed Installation

Evaluation of Yeast-Based Tile Performance under Environmental Exposure
Sankt Kors, IMA Testbed, Linköping, Sweden, 2025.
Bektas, Y.; Zboinska, M.

Author’s Contributions

The author contributions presented follow Elsevier’s CRediT (Contributor Roles Taxonomy) framework, specifying the roles and contributions of each author in the included publications and research dissemination outputs.

Author initials:

YB = Yagmur Bektas
MAZ = Malgorzata A. Zboinska
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TSD = Toste Skånberg Dahlstedt

Paper A

Conceptualization: YB, MAZ; Methodology: YB, MAZ; Software: YB, MAZ; Validation: YB, MAZ; Formal analysis: YB; Investigation: YB, ZH; Resources: MAZ, CG, TN; Data Curation: YB; Writing - Original Draft: YB, MAZ; Writing - Review & Editing: YB, MAZ, CG, TN, ZH; Visualization: YB, MAZ; Supervision: MAZ, CG, TN; Project administration: MAZ.

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Testbed Installation

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Glossary

Additive Manufacturing (AM)	Layer-by-layer fabrication of physical objects from digital models.
Bioink	A printable biomaterial formulation designed for extrusion in additive manufacturing.
Biomass	Organic material derived from biological sources, including plants, microorganisms, and industrial side streams such as agricultural or food-processing waste.
Biopolymer	Naturally occurring polymers such as cellulose, chitin, alginate, or starch are used as binders or structural components in biomaterials.
Computational Design	A design approach that uses algorithmic and data-driven methods to generate and manipulate form through digital workflows, enabling iterative, performance-informed exploration.
Crosslinking	Chemical or ionic bonding within a material that increases stiffness or stability.
Deposition Sequence	The order in which lines or layers are printed.
Digital Fabrication	Computer-controlled manufacturing processes, such as CNC milling, robotic assembly, and 3D printing, are used for producing architectural components.
Direct Ink Writing (DIW)	A high-precision, extrusion-based technique where viscoelastic inks are deposited through fine nozzles to create 3D structures.
Extrudability	A material's ability to pass smoothly through a nozzle without clogging or structural collapse.
Extrusion Pressure	The applied force driving material through a nozzle; influences flow rate and print fidelity.
Extrusion-Based Additive Manufacturing	A form of AM where materials are extruded through a nozzle in continuous strands.
Flow-Based Fabrication	Additive manufacturing that relies on controlled continuous material flow, influenced by pressure and material rheology.
Hydrogel	A water-rich polymer network that flows under shear stress but maintains shape after deposition.

Lignocellulosic Fibres	Plant fibres composed of cellulose, hemicellulose, and lignin, commonly used as reinforcement in composites or as substrates for microbial growth.
Nanocellulose	Cellulose-based material at the nanoscale with high strength and surface area. Forms include nanofibrillated cellulose (NFC), microfibrillated cellulose (MFC), bacterial nanocellulose (BNC), and nanocrystalline cellulose (NCC).
Rheology	The study of material flow and deformation, relevant in the extrusion of hydrogels and pastes.
Robotic Fabrication	The use of industrial robots to carry out manufacturing tasks with high precision, enabling complex toolpaths, multi-axis deposition, and spatial printing while integrating material and geometric constraints within computational workflows.
Shear-Thinning Behaviour	A rheological property where viscosity decreases when shear is applied, enabling smooth extrusion through nozzles.
Toolpath	The programmed route that a printhead or robotic tool follows during fabrication, defining where and how material is deposited.
Viscosity	A measure of a material’s resistance to flow.
Wet-to-Dry Transformation	Changes in geometry, thickness, translucency, colour, or stability occurring as water evaporates from hydrogels.
Yield Stress	The minimum stress required for a material to begin flowing.

Contents

Abstract

Acknowledgments

List Of Publications and Research Dissemination

Author’s Contributions

Glossary

1. Introduction

1.1. Background and Research Context

1.1.1 Context

Human societies are fundamentally shaped by their relationships with material, ecological, and biological systems. For most of human history, survival depended on direct engagement with local environments, making the limits of resources and the consequences of their use immediately visible. Technological development, industrialization, and globalized production have gradually transformed this relationship. Over 20th century, biological and material production increasingly came to be mediated through engineering practices, industrial infrastructures, and specialized scientific knowledge, reframing living processes as technologically managed systems rather than direct objects of everyday experience (Bud, 1991). Energy, food, and materials have consequently become abstracted from their origins, as advancements reorganize agriculture, industry, and medicine through economic, regulatory, and institutional frameworks that facilitate everyday engagement with life-sustaining processes (Bennett, 1998). This distancing has not eliminated humanity's dependence on the Earth's resources, but it has altered how that dependence is perceived. "Humanity is on a journey in which we are rediscovering just how connected we are with other members of our species and with the world around us" (Krogh & Johansen, 2020), foregrounding the need to reacknowledge connectedness across social, environmental, and the more-than-human systems. Yet, contemporary biological and ecological conditions are not simply distant, but they are increasingly shaped by the aftermath of industrial interventions, generating new forms of life that emerge from and respond to these systems of control (Landecker, 2025).

Architecture operates at the centre of this condition. The built environment materializes societal choices through "extractive impacts and human violence" across a building's lifecycle, including site choice and acquisition, design and review methods, material selection and sourcing, to end-of-life decisions (Kiechel, 2021). Buildings are designed with long-term material commitments that shape environmental relations beyond the moment of construction (Fallan, 2025). In this sense, architecture functions as an interface between human activity and the ecological systems on which it depends (Picon, 2024). Recognizing this role requires architectural thinking that accounts for material origin, transformation, and environmental consequence as integral aspects of design.

1.1.2 Planetary Impact and Circular Perspectives

The cumulative effects of human activity on land use, material extraction, and atmospheric composition now operate at a planetary scale. These transformations are not the result of isolated actions but of long-term patterns of production and consumption that have altered Earth systems in persistent, often irreversible ways. Within this context, scholars have described the present condition as one in which human activity functions as a geological force, and architecture is an active participant in planetary material cycles, referred to as the Anthropocene (Yigit-Turan et al., 2022; Crutzen, 2000; Lewis & Maslin, 2015; Rickards, 2015).

The built environment is a major contributor to global environmental degradation, material depletion, and carbon emissions (UNEP, 2025). Architectural practice remains largely dependent on fossil-based, finite, energy-intensive materials whose extraction, manufacturing, and disposal intensify ecological imbalance (Beim, 2023). At the same time, global urbanization continues to increase, with the proportion of the world's population living in urban areas significantly rising, reflecting ongoing growth in cities and their associated infrastructure (Ritchie et al., 2024). Commonly used building materials rely on extractive practices and energy-intensive processing prior to use, representing 16% of global greenhouse gas emissions in 2019 (Kane et al., 2025). Construction and demolition activities further generate large waste streams, many of which remain unrecovered or are downcycled, reinforcing a predominantly linear material economy.

In response to these conditions, circular perspectives have gained increasing attention within architectural and construction research. These approaches emphasize the management of material flows across the entire life cycle of buildings, including construction, renovation, and end-of-life phases, rather than focusing solely on operational performance (Pomponi & Moncaster, 2016). As each building lifecycle contributes to environmental impacts, material reuse and recovery should be prioritized through planning, assessment, and routing to enable continuous circulation (Ashrafi et al., 2025). Within this framework, buildings are understood as temporary material configurations embedded within broader systems of extraction, transformation, and recycling.

Moreover, the "Butterfly Diagram" developed by the Ellen MacArthur Foundation in 2019 provides a widely referenced conceptual model for circular material flows by distinguishing between technical and biological cycles. Technical cycles prioritize reuse, repair, and renovation to extend material lifespans and reduce the demand for new resource extraction. Biological cycles focus on renewable and biodegradable materials that can safely return to ecological systems after use. In architectural discourse, this distinction has been interpreted both as categorization of "material systems" and as a design framework that aligns material selection with design strategies for reuse, remanufacturing, or disassembly (Hubmann & van Maaren, 2022). This process aligns with Material Driven Design (MDD), a method that emphasizes the role of material experiences, focusing not only on what a material is, but on what it does, what it expresses, and what it makes people do (Karana et al., 2015). As emerging materials often lack an established domain, to facilitate their adoption, MDD provides a structured approach to exploring their technical properties, experiential qualities, and potential uses across scales, through tinkering with the material, user characterization, and envisioning future applications (Sicher et al., 2023). So, renewable materials are evaluated beyond environmental impact, but for the forms of interaction, perception, and value when applied in architectural contexts.

Within the biological cycle, underutilized biomass, which includes organic materials derived from plants, animals, microorganisms, and side streams such as agricultural residues, forestry by-products, and organic industrial waste, is not fully exploited or is often discarded (Guo et al., 2024; Cuadrado-Osorio et al., 2022). However, these sources can be processed and upcycled into building materials, emerging as potential material alternatives (Tripathi et al., 2019); as they can lower carbon footprint and reduce greenhouse gas emissions (Chen et al., 2024); are biodegradable and can break down naturally and reduce the burden on landfills and provide varying mechanical properties which can be tuned according to specific requirements (Gowda et al., 2023). Despite their potential, bio-based materials still face challenges, including cost-competitiveness, upscaling, material control, and performance, which require further research and development (Ghosh et al., 2023). Additive manufacturing addresses these issues by enabling the creation of complex geometries and allows precise control over material distribution for regulating chemical and biological activity (Mogas-Soldevila & Zolotovsky, 2025); offering material efficiency and customization via precision in fabrication; reducing material waste during manufacturing (Wijk et al., 2015); improving cost efficiency and enabling the integration of novel materials in both new and existing architecture (Banica et al., 2024).

1.1.3 Architectural Framing

In response to the environmental and material challenges, architectural discourse repositions material behaviour as a design driver. Work in material computation demonstrates how form and performance can emerge through interactions among material properties, environmental input, and fabrication processes, calling for design methods that engage matter's agency (Lallemand, 2021). This approach situates materials as active systems, whose properties unfold over time, influencing architectural form, performance, and lifespan. This understanding aligns with theoretical perspectives that frame matter as processual and relational, emphasizing how materials act, respond, and exhibit forms of agency rather than how they are shaped (Dade-Robertson et al., 2023).

This shift is connected to emerging discussions of material temporality, which evaluates materials not only for spatial performance, but also across their lifecycles of extraction, production, use, and degradation. While biomaterials have gained increasing attention across disciplines, their architectural application remains limited by challenges related to variability, durability, and scalability. They often exhibit behaviours such as growth, decay, transformation, shrinkage, and moisture sensitivity that challenge conventional architectural expectations of permanence and standardization (Ramsgaard & Tamke, 2022; Tumerdem & Gul, 2023). This characteristic highlights the need for alternative material approaches that reframe transformation as a quality that can inform architectural design.

Recent frameworks expand this temporal understanding by situating materials within extended material ecologies. The concept of "Matterscapes" proposes a comprehensive view of matter that traces materials from their geological or biological origins through industrial processing, architectural use, and eventual re-entry into environmental systems (Mantz et al., 2024). Architecture therefore operates within overlapping temporal scales, ranging from geological time to the short lifespans of buildings and it's components. Understanding materials as temporal agents is particularly relevant in the context of renovation, transformation, and disassembly. Studies in heritage and material practice highlight that buildings often consist of multiple material layers, each reflecting different moments of construction, repair, use, and their role in negotiating temporalities (Bangstad, 2020). Within this context, biodegradability can be reframed as an architectural asset rather than a liability. Research on adaptive reuse and circular renovation demonstrates that materials designed for limited lifespans can support performance-driven interventions where long-term structural permanence is neither required nor desirable (Roark, 2023). Such approaches align with circular practices that emphasize material reversibility.

Architecture has long drawn inspiration from nature, initially through biomorphic approaches focused on visual resemblance and later through biomimetic approaches emphasizing functional transfer (Nasir & Kamal et al., 2022). Coherence between form and function can arise from material-environment interaction rather than top-down control (Chayaamor-Heil, 2023). Advances in biology and biotechnology enabled direct engagement with living systems at molecular and cellular scales. Rather than transferring biological forms or functions through analogy, bio design engages biological processes as generative and time-based systems (Liu et al., 2022). Drawing on biological understandings, architectural form and performance are conceived as outcomes of interactions between material properties, environmental conditions, and temporal change.

Recent architectural discourse has also framed materials as active participants in design rather than passive carriers of form. Oxman's Material Ecology positions material systems as inseparable from biological processes, computational design, and environmental performance, and within this framework, architectural form emerges through material behaviour and interaction rather than through predefined geometries (Oxman, 2012). Mette Ramsgaard Thomsen's work on eco-metabolistic architecture further informs this positioning by understanding fabrication as an ecological process; digital and robotic fabrication are both tools for precision and mediation, engaging with material variability, feedback, and adaptation (Thomsen & Tamke, 2022). Fabrication thus becomes a site of negotiation between material behaviour and architectural intent. Theoretical contributions by DeLanda, New Materiality, contribute to this material-driven perspective by conceptualizing materials as non-linear systems with their own capacities and tendencies (DeLanda, 2012). Karen Barad's theory of agential realism extends this understanding by framing materials, tools, and designers as entangled agents, producing architectural knowledge through material-informed practices where experimentation, fabrication, and observation actively shape outcomes (Barad, 2007). Together, these positions establish an architectural framework in which material behaviour is engaged rather than controlled, and within which biomaterials become architectural matter rather than technical novelty.

The increasing complexity of interactions between built and natural environments has prompted questions regarding the disciplinary relationship between architecture and biology (Kenza, 2024).

Addressing this complexity requires approaches that operate across scales and integrate diverse forms of knowledge. Materially driven bio design emerges as a synthesis of biological insight, computational methods, and material intelligence (Marom & Buehler, 2025). Computation functions as a mediating framework that supports feedback-driven design, adaptation, and transcalar interaction (Menges & Ahlquist, 2011). Digital and robotic fabrication further enable this shift by coupling computational design and construction, informing material processes and shaping what Gramazio et al. (2014) describe as digital materiality in architecture. Robotic fabrication, therefore, forms an important part of the research context. Through controlled deposition and manipulation, fabrication becomes a site of experimentation where digital precision coexists with biological variability. This shifts fabrication from a final production phase to an active design process, in which material feedback informs architectural decision-making.

The architectural relevance of this research is grounded in the renovation and transformation of the existing built environment. Renovation offers opportunities to reduce the extraction of new materials by extending the lifespan of existing stock and minimizing demolition waste, thereby enabling adaptive and reversible interventions (Amini et al., 2025). This focus reflects both the environmental significance of working with existing structures and the suitability of biomaterials for non-load-bearing applications such as environmental modulation, spatial articulation, and responsive architectural layers. The work is inherently interdisciplinary, situated at the intersection of architecture, material science, and biotechnology, with architecture functioning as a mediating discipline between biological processes and spatial performance.

1.2. Objectives and research questions

Within this research context, a novel yeast-cellulose hydrogel is introduced as a 3D-printable material system, serving as a medium for exploring questions of material agency, robotic fabrication, and architectural applicability. Architectural applicability, in this thesis refers to indoor contexts, including newly constructed environments as well as those in need of sustainable renovation, replacement, and aesthetic upgrade of existing architectural materials, elements and surfaces, with focus on wall claddings and tiling assemblies, surface finishes, and room divider elements that function as ultra-lightweight claddings, finishing layers in wall systems, and spatial formations for decoration, rather than load-bearing structures.

The background established that architecture is entangled with material and ecological systems, that circular perspectives reframe buildings as temporary material configurations, and that material agency and temporality open new design logics. Within this context, renovation has become a primary strategy for reducing environmental impact and extending the lifespan of existing buildings. Yet renovation practice continues to rely on fossil-based and energy-intensive materials. At the same time, extensive amounts of underutilized biomass from industrial side streams remain unexplored as resources for biobased architectural materials. In this thesis, biomass refers to organic material derived from biological sources, including plant matter and microorganisms. The term underutilized is used to describe residual or side-stream materials generated through agricultural, industrial, or food-processing activities, which are typically treated as by-products or waste. Although such biomasses may have established applications in other fields, their potential as resources for architectural fabrication and material upscaling is limited. Their sourcing from industrial or agricultural side-streams is particularly relevant, as it aligns with circular principles by redirecting abundant material toward new applications. While a growing body of architectural research on biobased solutions has focused on fungal material, i.e., mycelium, most commonly applied as insulating or acoustic panels and bricks, this thesis instead introduces, for the first time, spent and underutilized yeast biomass from beverage and food production sectors and cellulose biomass from forestry industries as available resources for architectural materials. Unlike filamentous fungi, yeast exhibits predictable behaviour that aligns well with computational design and robotic fabrication, enabling precise control over material rheology, deposition, and geometric articulation in architectural material systems.

Granting that these materials present opportunities for circularity, biodegradability, and reduced embodied energy, their architectural uptake is constrained by three interrelated challenges. First, bio-derived materials often lack design frameworks that link their material behaviour to geometric and fabrication strategies. Without methods to systematically integrate material properties with toolpath design and fabrication logic, their application remains limited to experiments or prototypes rather than architectural systems. Second, as each novel material presents unique properties that generalized robotic 3D printing systems remain insufficient to address. Without material-specific toolpath strategies that account for rheology, deposition stability, and drying transformations, the scalability of such systems is limited. Third, the architectural integration of emerging biobased materials is limited, particularly in terms of how their mechanical and aesthetic properties can contribute to architectural materiality.

This licentiate thesis aims to investigate how a novel yeast-cellulose biomaterial, derived from underutilized biomass, can be developed and integrated into architectural applications through research by design, emphasizing robotic fabrication and the design of new material systems. Positioned at the intersection of architecture, material science, and biotechnology, the research does not seek to master these disciplines individually. Instead, it works within the spaces where material behaviour, fabrication constraints, and architectural intent intersect. Engaging with the material across scales, the research seeks to contribute new knowledge to the emerging field of biobased material, enabling scalability and future integration into sustainable renovation practices.

“How can a novel biobased material be developed, fabricated, and translated into architectural materiality through research-by-design to support circular renovation and aesthetic transformation of the built environment?” To address this main question, the study is structured around three interrelated research questions:

1. **RQ1 Materiality**

How can underutilized biomass be transformed into a novel yeast-cellulose biomaterial whose emergent behaviours and properties inform its architectural applicability?

2. **RQ2 Robotic Fabrication**

Which material properties and toolpath parameters need to be optimized to develop a robotically 3D-printable yeast-cellulose hydrogel that negotiates material agency across micro through meso to macro scales for architectural design?

3. **RQ3 Architectural Potential and Integration**

How can novel biobased materials be translated into possible architectural applications through robotic 3D printing, and how do their functional and aesthetic qualities shape this translation?

To address the research questions, the study objectives are to:

1. Develop material formulations from baker's yeast and cellulose biomass, and characterize their rheological, mechanical, and aesthetic properties relevant for architectural applications.
2. Establish methods for robotic 3D printing of yeast-cellulose hydrogels by identifying key toolpath parameters and material-geometry interactions required to achieve shape fidelity and expressive deposition.
3. Fabricate and evaluate micro-scale material samples, meso-scale prototypes, and macro-scale architectural demonstrators to reveal how the material's functional and aesthetic qualities can contribute to renovation practices, spatial transformation, and aesthetics.
4. Propose and validate an early-stage design framework that supports material-informed and fabrication-aware decision making for developing architectural components from yeast-cellulose hydrogel.

1.3. Research Design

This research is conducted from the disciplinary position of architecture and is situated within the field of architectural design research, with relevance to architectural material systems, computational design, and robotic fabrication. It adopts a research-by-design methodology, in which architectural design practices function as the primary means of inquiry. Rather than treating design as an outcome, design functions as a method for generating knowledge through iterative making, testing, and reflection. The design is inherently interdisciplinary, engaging with disciplines such as materials science and industrial biotechnology, yet it does not seek equal proficiency across all disciplines. Knowledge from other fields is deliberately borrowed at specific stages to support architectural exploration rather than to advance disciplinary research within those fields. In this context, the role of the architect is positioned as a mediator, aligning material behaviour, fabrication logic, and architectural intent. The author leads the decision-making process for defining research questions, material selection, planning of experiments, design of robotic toolpaths, conducting fabrication, and evaluating outcomes, while drawing on supervision and technical guidance from experts in adjacent disciplines where necessary.

As illustrated in Figure 1, the workflow follows a non-linear and iterative framework in which different disciplines become central at different moments. Biotechnology informs material development by supporting the cultivation of yeast biomass, metabolic activity, and viability considerations necessary for forming the yeast-cellulose hydrogel. Material science contributes methods for understanding printability-related rheology, material transformation during drying, adhesion, and mechanical properties. All material formulation experiments, toolpath design, bioprinting, robotic fabrication, and assessment of experiments were carried out by the author. Mechanical and biological tests were also performed by the author, with methodological guidance, training, and technical assistance from researchers in relevant fields to ensure the correct application of protocols and the interpretation of results. Through all phases of research, supervisory input from subject-specific experts, informed decision-making, or evaluation, but did not replace the author's responsibility.

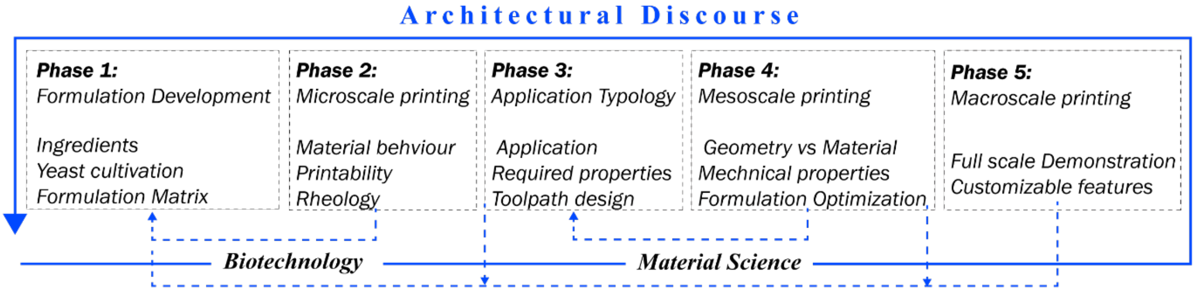


***Figure 1**. Decision-making workflow illustrating progression across scales, in which architectural discourse guides the process and knowledge from biotechnology and material science is borrowed at specific stages to inform material development.*

Architectural questions such as spatial expression, surface articulation, aesthetic potential, and applicability within interior renovation contexts govern why specific properties are explored and what is tested next. Architectural insights often emerged early in the experimental stages. For example, observations of material pliability or two-dimensional formations at the micro scale suggested architectural potentials related to surface-based applications, as wall assembly systems conceived through tiling logic, prompting targeted meso-scale material testing focused on tensile properties, continuity, and deformation behaviour. In this way, architectural intent actively redirects material development, according to architecturally defined criteria established by the author. The research, therefore, operates as a continuous loop of discovery, in which material behaviour, fabrication outcomes, and architectural intent inform one another. Unexpected material behaviours are treated as productive design drivers rather than constraints, reinforcing an architectural mode of inquiry grounded in exploration rather than optimisation.

A central structuring principle of the research design is the intentional investigation across micro-, meso-, and macro-scales. This scale logic is architectural rather than technical. Micro-scale experiments enable close observation of biological activity, material behaviour, rheology, extrusion stability, and drying transformation. Meso-scale prototypes allow these behaviours to be negotiated through patterned toolpaths, layered deposition, and repeated fabrication logic. Macro-scale prototypes and installations test how the material performs and is perceived at architectural scale, engaging gravity, light, spatial presence, and handling. Working across these scales allows architectural questions concerning surface behaviour, geometric articulation, and spatial expression to be continuously assessed and refined, ensuring alignment between material development and architectural relevance. Decisions regarding which outcomes were considered informative or successful were made by the author based on architecturally motivated criteria, including shape fidelity, geometric clarity, surface expression, translucency, and the capacity of the material to convey design intent at scale. Evaluations were conducted through systematic comparison across iterations, supported by critical reflection and supervisory dialogue.

The included publications and accompanying research dissemination are positioned within an architecture-led research trajectory. Paper A addresses the establishment of the yeast-cellulose hydrogel as a 3D-printable material system, drawing on biological and material-scientific methods instrumentally in service of architectural aims. Paper B shifts the disciplinary centre more clearly toward architecture, investigating robotic fabrication strategies, toolpath logic, and tile-based assemblies as architectural material expressions negotiated through spatial, geometric, and aesthetic considerations. The exhibition and test-bed installations extend this trajectory further, functioning as architectural implementations of the developed material system and situated architectural demonstrators. Knowledge is therefore generated through comparative analysis of iterative experiments, reflective interpretation of material and fabrication behaviour, and situated observations from prototypes placed beyond laboratory conditions. Conclusions are derived by identifying patterns, constraints, and opportunities that emerge through making and architectural evaluation.

1.4. Scope and Limitations

While the work engages with methods and tools from multiple disciplines, the scope of the thesis in architectural research. As such, the focus lies on exploring architectural materiality, engaged through design, fabrication, and spatial prototyping, rather than as a building material evaluated through standardized criteria of technical performance, durability, and regulatory compliance for construction. Contributions to material science or biotechnology as independent disciplines lie outside the scope of this work. The investigations presented therefore should be read as an exploratory in nature and should be read as formative rather than conclusive. The research introducing a novel yeast-cellulose hydrogel, demonstrating its fabrication through robotic 3D printing, and establishing its architectural potential through prototypes and spatial applications. It does not aim to make claims regarding structural performance, long-term durability, or industrial scalability. These aspects are out of scope and remain important directions for future research.

At the time of writing this licentiate thesis, a parallel study is ongoing, that investigates the potential of yeast-cellulose hydrogels as decorative biobased coatings for timber surfaces. This work includes preliminary, pedagogy-based material observations, prototyping and design explorations that reflect restoration as an application domain. As the investigation remains in its initial phase, it serves to identify opportunities rather than establishing finalized methods or applications. Accordingly, the coating study included in this licentiate thesis is presented as work in progress and will undergo further development where the final outcomes will be reported in the final doctoral dissertation.

Accordingly, the primary contribution of this work is not technical optimisation, but the development of architectural knowledge concerning how a biobased material behaves within design-driven and fabrication-oriented processes, how robotic 3D printing can negotiate and express the material's agency, and how its aesthetic and spatial qualities can inform architectural applications. In summary, the study provides initial findings, proof of concept prototypes, and an early conceptual framework for working with yeast-cellulose biomaterial in architecture. The results are exploratory, iterative, and open-ended reflecting both the novelty of the material system and the architectural focus of the research.

1.5. Overview

The compilation thesis is organized into five main chapters, followed by supplement documentation. Chapter 1 introduces the research by outlining the background, positioning, research objectives, questions, and scope. It establishes the relevance of investigating biobased materials in architecture and clarifies the architectural standpoint from which the work is conducted. Chapter 2 presents the state of the art across interconnected domains: biobased materials and their fabrication in architecture; material agency in nonstandard and biologically derived materials. The chapter identifies the gaps in current knowledge, synthesizes key insights, and articulates the research direction that motivates the methodological approach. Chapter 3 outlines the methodology, framed through research-by-design approach. It introduces the development of the yeast-cellulose hydrogel, the robotic fabrication strategies used to negotiate material agency, and the scaling up process from material samples to architectural prototypes. Chapter 4 presents and discusses the research outputs, drawing together findings from the included papers, design experiments, prototyping, and exhibition/testbed installations. The chapter is structured around the three research questions: material development and emergent behaviours; fabrication related insights and digital crafting knowledge; and architectural translation of the material. Chapter 5 concludes the thesis by addressing research questions, articulating the main research contributions and discussing their broader implications for sustainable architectural practice. The chapter ends with reflections on the future research directions.

2. State of the Art

This state-of-the-art builds on material classifications established in previous studies, as the reviewed literature is examined by relating mineral-based, plant-derived, and microorganism-based systems to fabrication strategies and scales of application. Through this analytical mapping, comparisons are drawn between material behaviour, component design, and architectural demonstration. Across these material families, recurring correlations emerge between material composition, fabrication logic, and architectural material qualities such as buildability, geometric resolution, surface articulation, and transformation over time. Architectural material qualities are therefore emergent properties rather than as fixed attributes. Notably, yeast remains unknown from architectural research, with existing studies confined to micro-scale applications in biotechnology and bioprinting. Key findings from this literature study indicate that bio-based materials are predominantly explored at the meso-scale through demonstrative prototypes. At the same time, the review reveals gaps in the methodological understanding of geometry as a mediator of material agency, and in the integration of emerging bio-based materials into robust architectural fabrication workflows.

2.1. Biobased Materials and Robotic Fabrication in Architecture

Architectural research at the intersection of biobased materials and additive manufacturing has intensified over the last decade, where mapping of the field revealed an increase in publications after 2015, coinciding with the environmental urgency, and parallel advancements in computational design and robotic fabrication (Gürsoy, 2018; Brasil & Martinez, 2025). Biobased materials employed in architecture fall into three families: mineral-based, plant-derived biopolymers/fibres, and microorganism-based (Carcassi & Ben-Alon, 2024), each differentiated by origin, properties, and fabrication compatibilities yet driven by the need to reduce the environmental footprint of construction. Fabrication approaches range from manual methods (moulding, layering, casting); where material control is achieved through shaping, to advanced digital processes (silk deposition, microbial 3D printing, flow-based fabrication, direct ink writing (DIW), robotic extrusion, and paste-based extrusion). These workflows determine geometric possibilities and influence curing, drying, and biological activity, making fabrication inseparable from the material's inherent behaviour. Surveying existing research and design initiatives revealed a consistent alignment between material families, fabrication method, demonstration scale, and resulting architectural application, suggesting that material systems cannot be exchanged across established workflows without significant recalibration.
This section contains a review of experimental and academic studies revealing consistent tendencies in bio-based material research. Additive (extrusion based/DIW) and manual manufacturing (molding/layering) routes appear across all material families. Architectural translations focusing on meso-scale demonstrations; around pavilions, interior installations, textile like membranes, panels, and

modular assemblies and lightweight structures, where applications remain largely demonstrative or speculative, situated in controlled exhibition contexts rather than construction. Control over the material behaviour is typically in the low to medium range, with observed properties such as porosity, patterning, optical and thermal effects achieved through geometric articulation and layering of modular constructs rather than bulk strength.

2.1.1. Mineral-based materials

Mineral-based materials, including earth, sand, clay, ceramics, and salts, demonstrate additive manufacturing applications from microscale rheological investigations to mesoscale component fabrication and finally to macroscale architectural construction as loadbearing walls, vaults, pavilions, and monolithic envelopes. At the micro scale, numerous studies examine the behaviour of pastes under extrusion, analysing how moisture content, particle grading, and ingredient ratios influence viscosity, anisotropy, and deformation during printing and drying (Perrot et al., 2018). These studies correspond with broader findings, that mineral-based mixes require careful tuning to achieve printability and structural buildup without cracking or collapse, critical when printing walls or shells without formwork. (Duque-Castro, Rafael G. et al., 2025). Ruckrich et al., 2022 demonstrated that adjusting water content, particle distribution and plasticity are necessary to achieve cohesiveness, though these modifications impact the overall material strength. At the meso-scale, these insights translate into component sized elements, including lattices, bricks, tiles, and panels, where robotic extrusion enables calibrated layering and controlled geometric variation. Multiple studies demonstrate how local soils, robotic deposition, and geometric calibration can generate architectural surfaces with minimal processing. Bajpayee et al., 2020 demonstrated extrudable, naturally sourced soil pastes for load-bearing structures, emphasizing importance of life-cycle assessment. Manikandan et al. (2020) investigated extrusion-based clay printing by systematically comparing how nozzle shape governs contour deviation, surface roughness, and mechanical behaviour of printed constructs influence filament deposition and layering. Tabakova et al., (2023) fabricated porous 3D lattice structures using algorithmically controlled travel paths to induce the controlled bending of vertical extrusions and achieve increased geometrical complexity, demonstrating how toolpath design can generate curvature and porosity without additional formwork. These prototypes establish a component-scale framework for testing buildability, interlayer adhesion, and shrinkage before scaling toward architecture (Figure 2). At the macro scale, projects such as IAAC’s Pylos, and WASP’s Gaia and Tecla houses demonstrate how mineral-based materials can be extruded into vaulted envelopes, loadbearing walls, and pavilions, emphasizing the compressive capacity while minimizing formwork and waste. Despite compressive strength and scalability, these materials display sensitive mechanical performance to humidity, particle grading, and solid content, requiring careful tuning and limiting reproducibility across contexts (Cuccurullo et al., 2021).

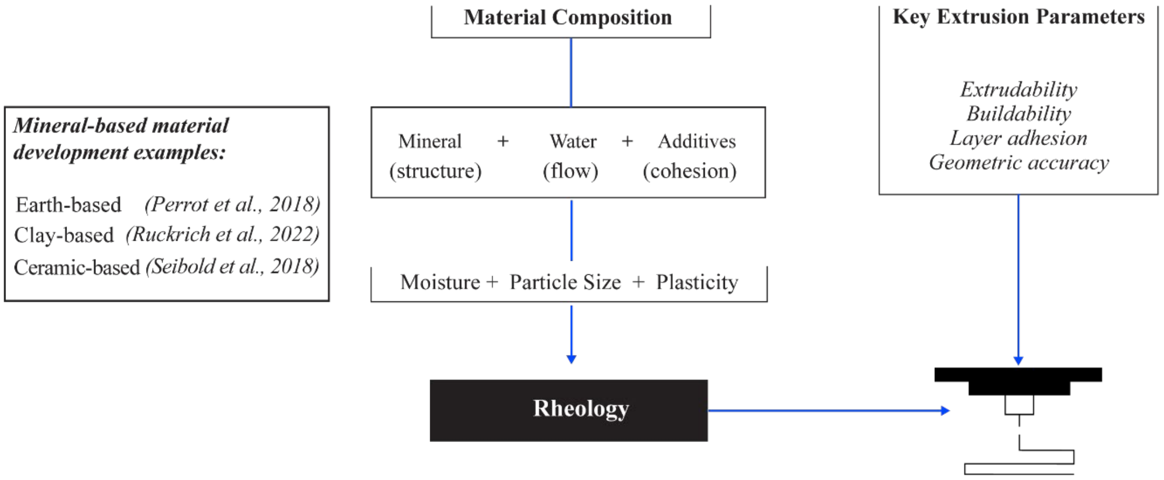


Figure 2. *Key findings synthesized from research literature on mineral-based additive manufacturing, highlighting the relationships between material composition, rheological behaviour and extrusion parameters in achieving optimized fabrication outcomes.*

2.1.2. Plant derived biomaterials

Plant derived biopolymer or fibre materials, including cellulose and its derivatives e.g., nanocellulose, microfibrillated cellulose (MFC), bacterial nanocellulose (BNC), nanocrystalline cellulose (NCC), lignocellulosic fibres, and polysaccharide-based binders such as glycerol, starch, alginate, chitin/chitosan, and xanthan gum, have been explored in architecture primarily for non-loadbearing applications such as membranes, panels, coatings, and textile-like interior elements. Nanocellulose is prominent for biocompatibility and strength, foundational to hydrogel formulations and suitable for coherent architectural surfaces (Klemm et al., 2011). At the micro scale, hydrogels are characterized by high water content and shear thinning behaviour; printability and shape retention depend on composition specific calibration of rheology (yield stress, viscosity under shear) (Choi & Yi, 2024). Markstedt et al. (2015) established that nanofibrillated cellulose combined with alginate, yields shear-thinning bioinks capable of high-fidelity 3D printing of complex forms using a bench-top system. Piras & Smith, 2020 mapped alginate-polysaccharide bioinks, linking molecular weight, concentration, crosslinking ions, and additives to rheology, printability, and biological compatibility across micro scale bioprinting tests. At the meso- and macro-scale, research shifts toward robotic extrusion systems, and these materials are prominently featured in lightweight or modular architectural elements such as membranes, panels, tiles, coatings and textile-like sheets where optical, tactile, and environmental response are prioritized. Because of this, material extrusion and direct ink writing (DIW) without thermal processing dominate fabrication approaches, with process parameters; nozzle diameter, toolpath geometry, deposition speed, and extrusion pressure play a critical role in extrudability, buildability, interlayer adhesion, and drying-induced shrinkage, all of which directly affect sagging, warping, or translucency at architectural scale. Fabrication therefore depends not only on material composition but on the logic by which the printing system places material in space. In additive manufacturing, material is extruded through a nozzle while the printing head follows a programmed path movement, referred to as a toolpath, which determines where and how material is placed, similar to how a pen traces a line while writing. Since biobased materials respond dynamically during and after extrusion, the design of the toolpath becomes central to controlling, negotiating or leveraging material behaviour. So rather than assuming toolpaths are technical instructions, research examines it as a design parameter that links material properties, fabrication constraints and the resulting physical expression.

Within this context, a multi-chamber pneumatic extrusion system mounted on a 6-axis industrial robotic arm was introduced for water-based hydrogels, enabling functional grading and material differentiation of architectural elements, e.g. transitions in stiffness, opacity, or responsiveness across a single surface. By coordinating material composition, deposition sequence, and geometry within a computational framework, this system demonstrates how humidity-responsive and performance-driven behaviours can be encoded directly through fabrication at architectural scale (Mogas-Soldevila et al., 2014; Duro-Royo et al., 2015). Extending these, Malik et al. (2020) developed a robotic, macro-scale extrusion system for algae-laden alginate hydrogels, establishing rheological knowledge for architectural-scale printing and demonstrating living, photosynthetic panels. Mogas-Soldevila et al. (2021) used custom robotic extrusion and post-curing workflows to produce silk-based composites for enabling leather-like, flexible, biodegradable textiles with tunable properties through molecular and geometric control; yet structural performance is not addressed. Relatedly, Panagiotidou et al. (2022) explored cellulose-alginate deposition geometries enabling humidity and temperature responsive behaviour. Though resulting components display low mechanical strength and long-term stability challenges. Rech et al. (2022), developed waste-based biopolymer slurries tuned for extrusion and dimensional stability, while stating that mechanical performance remains limited, print fidelity depends on inorganic additives and ionic crosslinking, shrinkage and strength are highly sensitive to drying conditions. Klemmt et al. (2022) investigated macro-scale robotic extrusion of cellulose-based composites, evaluating extrusion behaviour, drying, and buildability, that high fibre content increases rheological instability and drying induced deformation, reducing geometric precision and reproducibility. Moreover, research on nanocellulose-alginate membranes further displayed deposition density, layering logic, and drying behaviour directly condition translucency, stiffness, thickness, surface texture, and deformation; positioning toolpath geometry (spacing, intersections, curvature, overlays) as a primary design parameter. Earlier work by Zboinska et al. (2023), demonstrated the fabrication of architectural-scale membranes through robotic extrusion, using a custom-made, pressure-based system mounted on an industrial robot arm. Comparative analyses, seen in Figure 3, indicate that plant-based hydrogels excel in aesthetic tunability, functional grading, and expressive differentiation yet exhibit limited dimensional stability, low mechanical strength, and sensitivity to drying conditions unless rheology and deposition logic are tightly coupled (Campos et al., 2022).

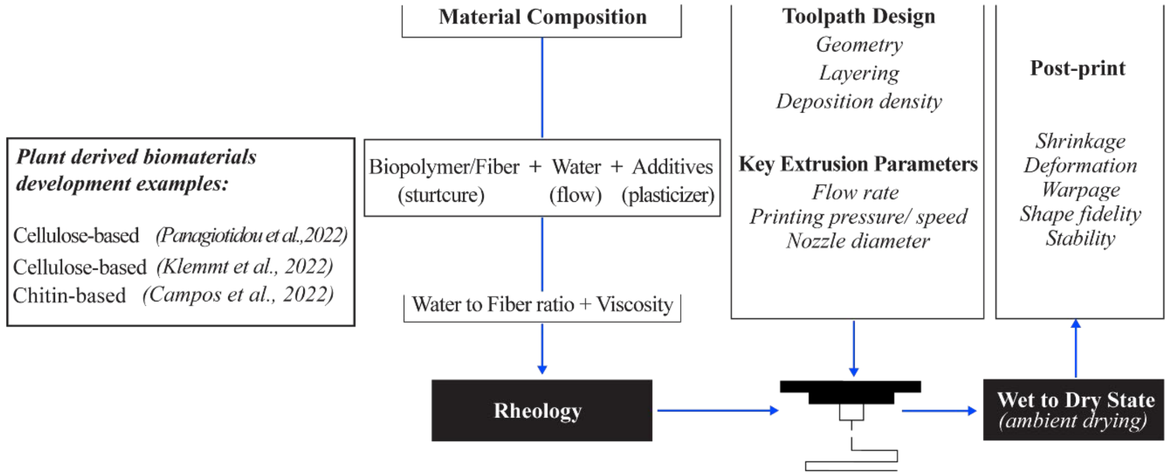


Figure 3. *Key findings synthesized from research literature on plant-derived biomaterials additive manufacturing, illustrating how material composition, rheology, printing parameters, and toolpath design impact wet-to-dry transformations, collectively shaping the behaviour of printed components.*

2.1.3. Microbial materials

Microorganism-based materials form the third family, encompassing mycelium, bacteria, silkworms, algae-based pastes, explored as pavilions, interior systems, and experimental building components, where biological processes are integrated into material formation. At the micro scale, research focuses on understanding organism behaviour, growth, substrate compatibility, and environmental dependencies which determine whether these materials can be reliably shaped, assembled, or stabilized for architectural use. Mycelium, filamentous fungal biomass, is the most extensively studied, for its ability to colonize lignocellulosic substrates, e.g. on agricultural waste fibres like straw, hemp hurds, sawdust and form lightweight composite networks (Angelova et al., 2021; Elsacker et al., 2019; Yang et al., 2021). At the meso scale, these materials are typically explored through bricks, tiles, panels, modules fabricated through mould-grown or hybrid printed-and-grown workflows, then assembled into pavilions or interior systems (Dessi-Olive, 2022), where assembly logic often compensates for material variability. Whereas Soh et al. (2020) developed an extrudable mycelium composite paste using bamboo fibres and chitosan, systematically studying workability, buildability, and growth compatibility to suggest that extrusion can replace moulding enabling greater geometric freedom for wall elements. G. Goidea et al., (2020), further utilized extrusion-based fabrication for lignocellulosic pastes followed by post mycelial growth, where fungal colonization acts as a structural biological binder to replace synthetic resins, while noting strength loss due to fibre grinding required for extrusion. Similarly, Chadha et al. (2023) explored extrusion of clay and fibre substrates combined with mycelium growth, focusing on inoculation and fabrication strategies, showing that mycelium growth can be guided by surface geometry. Although control over mycelial growth remains empirical and visually assessed. Modanloo et al. (2021), also investigated additive manufacturing of mycelium composites, producing a small-scale architectural prototype linking computational design and material behaviour, yet fabrication strategies for macro-scale construction remain unresolved. Despite ecological promise, studies document limitations of slow growth, environmental sensitivity, contamination risk, inconsistent mechanical properties, and restricted geometric resolution, when biological growth remains active during or after fabrication (Biala & Ostermann, 2022; Ghazvinian & Gürsoy, 2022; Motamedi et al., 2023; Mohseni et al., 2023; Alaneme et al., 2023). In algae-based systems, Malik et al. (2020), developed photosynthetic architectural components that demonstrate metabolic responsiveness but face challenges in scalability and long-term performance. Crawford et al. (2022) utilized clay printing to host photosynthetic microalgae, studying how geometry, thickness, and internal subdivision can enhance biological activity, remaining at experimental components. In the Silk Pavilion project (Oxman et al., 2014), silkworms were guided by a robotic scaffold to deposit fibroin filaments, demonstrating a hybrid "biofabrication" approach; despite workflows remain labour-intensive, biologically unpredictable, and limited by scale. Macro-scale assemblies such as The Living's Hy-Fi, built from mould-grown mycelium bricks, demonstrate feasibility for pavilion-scale construction, but reveal recurrent constraints: variable moisture content, limited long-term durability, and tight environmental envelopes. Consequently, manual assembly dominates at large scale, since direct robotic extrusion of living masses is not feasible due to clogging, viability loss under shear stress, and inconsistent binding. Overall, robotic extrusion for microorganism-based materials remains at meso- or experimental scale, limited by controllability, environmental dependency, and the challenge of embedding biological processes within the temporal and logistical frames of architectural fabrication (Figure 4).

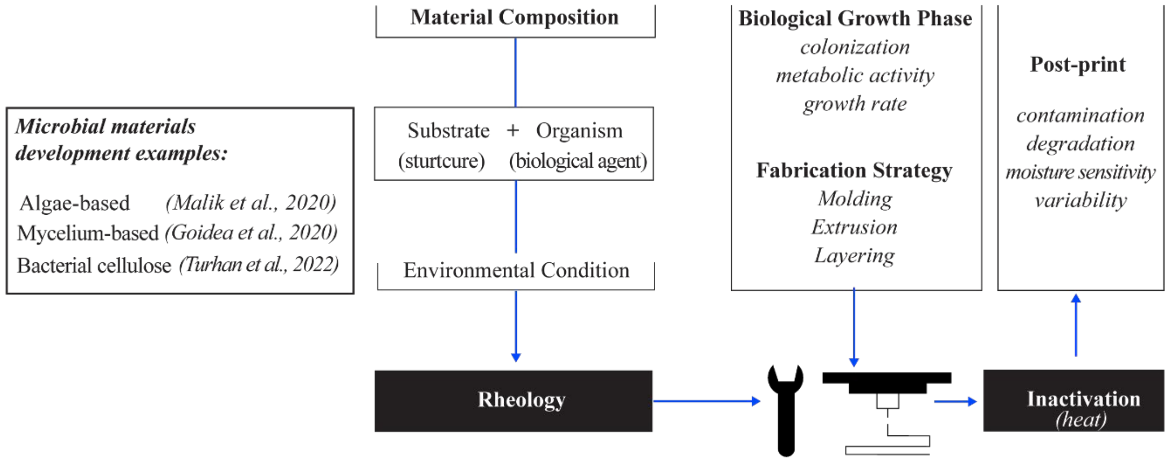


Figure 4. *Key findings synthesized from research literature on microbial materials in the literature, outlining the process from environmentally driven biological growth to fabrication methods, followed by component inactivation and post-print behaviour.*

Across all three material families, fabrication logic operates as a co-defining architectural parameter where the material qualities emerge. Manual methods are often employed to control curing conditions or biological growth, while robotic extrusion enables continuous geometries, multi-material deposition, and patterning. However, digital precision exposes material behaviour as an unavoidable and active force: slumping, shrinkage, curling, and deformation become integral to form-making rather than fabrication errors. This is particularly evident in hydrogel systems, where transformation influences final form; transformations are treated as design parameters, proposing predictive mappings that anticipate deformation. Together these studies establish that in biobased additive manufacturing, geometry, material behaviour, and time are inseparable triad: printed artifact is product of deposition logic interacting with dynamic material states. Yet multiple studies demonstrate that material composition alone cannot ensure predictable performance: deposition path geometry, line spacing, orientation, intersection angles, curvature, layering sequence, and offset distances, are key in determining deformation, porosity, surface texture, and optical behaviour.

Within this landscape, yeast represents a novel and largely unexplored direction. Yeast biomass is abundant, renewable, and can be sourced from industrial side streams, such as brewing, fermentation, and food processing, which aligns with circular-economy objectives (Parapouli et al., 2020; Buckholz et al., 1991). Unlike filamentous fungi, baker's yeast (Saccharomyces cerevisiae) is unicellular, fast growing, mass producible, and presents a lower contamination risk than mycelium whose growth depends on tightly controlled environmental conditions (Lisicar et al., 2017; Klosowski et al., 2023). Yeast is widely studied in biotechnology, food science, and biomedical engineering for 3D bioprinting, particularly for biocatalysis, drug delivery, and microreactor systems. Delgado et al. (2016) demonstrated that whole yeast biomass, processed through high-pressure homogenization and thermal treatment, can form continuous biodegradable films, while subsequent characterization studies (Delgado et al., 2018) examined their thermal and mechanical behaviour, confirming strong moisture sensitivity and limited stiffness. Peltzer et al. (2018) produced films from residual yeast cell wall using casting methods, stating constrained thermal stability and increased water vapor permeability. Studies were conducted for extrusion-based fabrication, Saha et al. (2018) demonstrated 3D printing of yeast hydrogels in lattice structures for continuous fermentation. This was further advanced by Qian et al. (2019), who introduced direct ink writing, where yeast cells can act as rheological agents to enable self-supporting, porous constructs with enhanced mass transfer and long-term metabolic activity. Despite yeast-based hydrogels can be shaped into 3D forms, their meso-macro scale behaviour, architectural performance, and compatibility with robotic extrusion remain unexplored. In this research, yeast is deactivated prior to fabrication and functioning as a bio-derived material whose microstructure and interaction with the hydrogel matrix influence rheology, drying behaviour, and post-print transformation. When combined with cellulose-based hydrogels, yeast offers scalable potential for architectural robotic fabrication. However, as with all biobased materials, yeast-cellulose inherent material-specific behaviours that cannot be concluded from other hydrogel or microbial systems.

Taken together, the state of the art highlights the fragmentation of current research; biomaterials cannot be treated like conventional engineered substances because their behaviour is dynamic, time dependent, and environmentally responsive. Fabrication, thus, becomes a negotiation rather than an imposition of form. Understanding how yeast-cellulose hydrogels participate in robotic fabrication therefore returns to the central question: why do biobased materials behave differently from conventional engineered ones, and how can fabrication accommodate their agency?

2.2. Material Agency in Non-Standard Materials

"If evolution can be engineered to occur in living, unsophisticated building blocks, then it may well be possible to evolve sophisticated materials with properties as yet inaccessible with conventional technologies." Leroy Cronin, 2011, p.38-39

Conventional architectural fabrication models are grounded in engineered materials designed for stability, homogeneity and predictability. Industrial materials such as steel, concrete, glass, and thermoplastics are optimized to minimize variability over time and to conform to predefined geometric tolerances, assuming material behaviour to be negligible. As digital design and fabrication technologies entered architectural practice, this assumption began to shift. From industrial mass production to computationally enabled geometric complexity, Kolarevic (2001) highlighted the reciprocal relationship between form and material, marking a transition toward practices in which new geometries demanded materials capable of accommodating increased curvature and performance, while emerging material systems simultaneously expanded geometric possibility.

Bio-based and non-standard materials challenge these assumptions by exhibiting material agency, actively responding to fabrication conditions, environmental exposure, and internal dynamics during and after deposition. This aligns with architectural research that reframes material behaviour not as an aftereffect but as a generative driver within design and fabrication processes (Fleischmann et al., 2012). Vazquez & Shaffer (2018) further demonstrate that when material response is integral rather than residual, fabrication can no longer be understood as a linear translation from digital model to physical component. Standard fabrication approaches therefore fail to accommodate unpredictable, heterogeneous and anisotropic nature of novel materials. Cronin (2011) extends this argument by articulating living and responsive material systems, including inorganic and hybrid materials, whose capacity to be programmed to sense, adapt, and transform requires new principles for architectural design. Within architectural research, material agency becomes a technical condition that reshapes fabrication and design methodology. Instead, deformation, instability, and variability should not be recognized as noise or failure but as information about the interaction between material composition, fabrication logic, and environment (Zboinska, 2019). Ghazvinian (2025) frames this condition as “controlling the uncontrollable,” arguing that uncertainty and instability are intrinsic characteristics of biomaterials and that architectural design must shift from control-based models toward negotiated engagement with matter.

As mentioned in Section 2.1, material agency manifests across bio-based systems through recurring yet material-specific behaviours. In mineral-based extrusion, agency appears through slumping, cracking, and shrinkage during drying, conditioned by moisture and deposition sequence. In plant-derived biopolymer systems, agency is expressed through evaporation-driven shrinkage, warping, curling, translucency, porosity, and changes in texture and colour (Campos et al., 2022; Zboinska et al., 2023).

In microorganism-based materials, agency involves biological growth or metabolic activity, extending transformation beyond fabrication timeframe. Beckett & Babu (2014) emphasize that additive manufacturing at high resolution makes such material effects negotiable across multiple scales, revealing behaviour that cannot be fully assumed at the time of design. Hydrogels further challenge the mediation of agency in extrusion-based fabrication. As water-based polymer networks existing between liquid and solid state (Tirella et al., 2009), they exhibit viscosity and flow under shear stress yet retain shape once extrusion forces are removed. As emphasized in hydrogel 3D-printing literature, the rheological properties play an important role in extrudability, shape retention, and the response to stress during printing (Herrada-Manchon et al., 2023). Consequently, extrusion depends not only on geometric parameters but on careful tuning and characterization of material composition (Huang et al., 2025). However, even when extrusion parameters are successfully calibrated, hydrogels undergo post-print transformation, as water evaporates leading to shrinkage, deformation, thickness variation and changes in mechanical and optical properties that exceed the tolerances assumed in architectural fabrication (Barrulas et al., 2023). This highlights that precision in deposition does not guarantee precision in outcome. Instead, hydrogel fabrication reveals matter as an active contributor to final form, supporting the need to treat drying behaviour and deformation as fundamental design parameters. As shown by Campos et al. (2022) and Napier (2022), such transformations can be anticipated and strategically leveraged through deposition geometry, positioning post-print deformation as a generative element. Within this body of work, fabrication workflows are calibrated to specific compositional blends to integrate material driven patterning algorithms which encoded how the material would deposit, spread, or form textures; optimized toolpaths for biological viability; designed for humidity and temperature responsive transformations; examined shrinkage, warping, and cracking, using parametric deformation maps; linked deposition strategies and layering patterns to resulting effects of texture, colour, stiffness, and translucency. Yet these strategies mainly address the macro scale of toolpath logic. What remains underexplored is the understanding of how specific geometric features of deposition paths (points, lines, curves) and their relational attributes (spacing, orientation, curvature, intersection angle) can be used to mediate between design intent, rheology, and material agency to craft specific physical and aesthetic effects.

Moreover, robotic fabrication allows continuous modulation of deposition parameters to encode behavioural tendencies directly into fabrication logic (Duro-Royo et al., 2015; Mogas-Soldevila et al., 2014). In this sense, fabrication operates as a feedback-driven process in which material agency informs decision-making (Brugnaro, 2019). Despite increasing recognition, fabrication knowledge remains highly material-specific: even within shared workflows, each material requires bespoke strategies. This gap is evident in the case of yeast-based materials. While Saccharomyces cerevisiae is well studied at micro-scale in biotechnology, food science, and biomedical engineering, typically via bioprinters, no architectural scale methodologies exist for robotic extrusion, deposition geometry, or post-print transformation. Moreover, in the context, yeast is deactivated, meaning that agency does not arise from biological growth but from its interaction with the hydrogel matrix. How yeast manifests its agency at meso- and macro scale applications remain unexplored (Figure 5). This motivates the development of a material-specific methodology for yeast-cellulose hydrogels, addressing the absence of fabrication knowledge through systematic investigation of process, geometry, and material behaviour.

Figure 5. *Yeast-cellulose samples illustrating material agency, as transformations through ambient drying reflect the material's role in form-making as matter-in-transition.*

2.3. Identified Knowledge Gaps

The review of existing biobased material research reveals several gaps that inform the focus of this thesis.

First, architectural-scale knowledge on yeast-based materials is currently absent. Although fungal materials such as mycelium are increasingly explored in architectural research, yeast has not been investigated beyond micro-scale applications in biotechnology and bioprinting. Existing studies focus on films, capsules, hydrogels and bioreactor systems, but do not consider potential architectural use, robotic extrusion or post-print behaviour at meso or macro scale. Consequently, there is no established understanding of possible material formulations, rheological behaviour or fabrication parameters for utilizing yeast biomass within architectural research.

Second, the relationship between deposition geometry and material behaviour, as well as their methodological integration, remains insufficiently understood. Across biobased additive manufacturing, research consistently demonstrated that geometry influences deformation, shrinkage, mechanical response, porosity, translucency and texture. Yet most studies concentrate on material formulation and printability calibration, fabrication strategies, or post-print behaviour modelling, while the role of geometric primitives and their relational attributes has not been systematically examined. Moreover, existing workflows continue to prioritize dimensional control and error reduction, despite consistent evidence that biobased materials behave nonlinearly and continue to transform throughout drying and curing. A methodological shift that works with these transformations is still lacking. Together, existing studies demonstrate that computational strategies for biobased materials must be material specific, and that geometry is a key mediator in the interaction between design intent, deposition logic, material performance and environmental context.

Third, the architectural integration of emerging biobased materials remains limited, particularly in relation to material agency and temporality. While architectural research increasingly engages with biomaterials, most demonstrations remain speculative instillations or experimental components situated in controlled exhibition environments. These studies successfully showcase the expressive or conceptual potential of biobased systems, but they rarely address how such materials could be scaled up, assembled, or integrated within architectural requirements. As a result, there is still limited understanding of how novel materials such as yeast-cellulose hydrogels can be meaningfully incorporated into design workflows, or how their functional and aesthetic behaviours shape the transition into architectural form.

Together, these gaps indicate the need for a material-specific and fabrication-oriented investigation of yeast-cellulose hydrogels that examines how material composition, deposition geometry, rheology and mechanical and aesthetic qualities can be integrated into robotic workflows. The following chapter presents the objectives, research questions and scope developed in response to these gaps.

3. Methodology

3.1. Research by design: Material Development and Prototyping as Inquiry

This research adopts a research-by-design methodology, in which making is positioned as a form of knowledge production and is treated as an epistemic act (Frayling, 1994; Verbeke, 2013). Knowledge is understood as situated, interpretive, and generated through active engagement with materials, tools, and processes, including sensory and perceptual encounters that arise through making and material interaction. Accordingly, design inquiry is not aimed at validating predefined hypotheses but at discovering questions, relationships, and potential. It is an experiential and interpretive process, shaped through what Schön describes as a "reflective conversation with the materials of the situation" (Schön, 1983).

Within this stance, experimentation, iteration, and failure are integral to inquiry, particularly when addressing complex and ill-defined problems typical of architectural research, where the designer/researcher responds to unexpected material behaviours and reframes the inquiry accordingly (Rittel & Webber, 1973; Pietrzyk, 2022). In this sense, the research engages architectural problems as wicked problems, where outcomes cannot be judged as true or false, but only as better or worse, and where problem formulation itself evolves through intervention. This aligns with critiques of positivist and purely analytical models of design research, that inadequately capture the complexity, uncertainty, and context dependence of architectural inquiry (Franz, 1994; Salama, 2019). As Coyne and Snodgrass argue, design is understood as an interpretive process and unfolds through "negotiation between what is expected and what is presented in the situation," rather than linear problem-solving, similar to the continuous negotiation between intention and material response. This includes the perceptual feedback emerging from material presence, scale and spatial encounter.

The study operates within an exploratory and hybrid research mode, combining architectural design methods with methods from material science and biotechnology, reflecting the inherently interdisciplinary nature of contemporary architectural research (Fraser, 2013; Zboinska, 2021). Knowledge is produced through iterative cycles of making, observing, documenting, and reflecting, allowing experiential forms of understanding to complement analytical and scientific modes of inquiry. Material formulation and fabrication trials function as generative research actions, consistent with notions of "thinking by doing" and "research through design" (Lucas, 2016; Roggema, 2017).

Building upon this, the research extends architectural design methods by integrating laboratory-based scientific protocols, positioning experimentation both as a means of form generation and as a structured mode of inquiry. This builds on the methodology taking it from intuitive material experimentation toward quantified, repeatable, and comparable procedures. Engagement with methods from material science, chemistry and biotechnology, the research systematically characterizes and controls material properties, for material development and design strategies. The adopted laboratory standards include controlled environment, calibrated measurement techniques, and reproducible experimental setups. In doing so, the research aligns with bio-design practices where architects operate beyond their disciplinary boundaries, adopting the tools, languages, and epistemologies of scientific fields to actively participate in the production of material knowledge (Stefanova, 2021). For instance, material preparation followed precise weight-based measurements, standardized mixing tools and sequences, and documentation, minimizing variability and achieving consistency across experiment rounds. This transformed material formulation into a repeatable and comparable process for variations to be systematically evaluated. This enabled the identification of cause-effect relationships between composition and wet to dry transformations. Additionally, the integration of material characterization tests further expanded the analytical assessments. Rheological testing provided insight into viscosity and flow behaviour, informing extrusion parameters and toolpath strategies for 3D printing. Tensile testing enabled the assessment of strength, elasticity, and failure modes, establishing mechanical limits and application potential. Thermogravimetric analysis revealed an understanding of the thermal stability, informing both fabrication and long-term performance of the material. Qualitative observations of flow, stability, or deformation were thus translated from descriptive evaluation to into measurable parameters. As a result, the material is treated as a dynamic system whose behaviour could be calibrated, predicted, and strategically tuned.

This approach reflects the broader shift in architectural laboratories toward sites of knowledge production, where experimental rigor and material agency redefine the practice (Uzal & Senel, 2024). Fabrication experiments were structured in a similar, iterative, scale-based progression. Initial micro-scale tests focus on isolated variables and simple geometries, allowing precise calibration of printing parameters such as speed, pressure, and nozzle diameter and optimization of material composition. Meso-scale explorations of patterned systems and layered assemblies revealed interactions between toolpath design, surface articulation, and structural behaviour forming a tunable system. Macro-scale prototypes then translated these insights into architectural components, integrating material behaviour with spatial and aesthetic considerations. Accumulated knowledge from earlier experiments informed both design and fabrication decisions. This cyclical progression establishes a feedback loop between material formulation, testing, and design iteration. Within this framework, making functions as inquiry, where knowledge emerges through the interplay of action and observation, aligning with multi-scale approaches linking material, fabrication, and form (Oghazian & Vazquez, 2021). This mode of inquiry aligns with pedagogical frameworks in bio-design, where architects develop competencies in hypothesis-driven testing, data collection, and analytical interpretation (Crawford, 2023). The architect is therefore a mediator, translating between disciplinary frameworks and establishing a shared space of inquiry for a broader operational scope of architectural research. Without such integration, material knowledge would remain external to architectural practice, limiting the capacity to uncover the relationships between material composition, processing, and performance. In contrast, the methodology developed in this research demonstrates how scientific rigor can enhance architectural inquiry to generate transferable, reproducible, and predictive knowledge while maintaining its exploratory and speculative character.

Through hands-on experimentation, the research uncovers material behaviours, constraints, and possibilities that cannot be fully anticipated through simulation or literature alone. This aligns with practice-based accounts of material research, where implied knowledge and embodied understanding play a crucial role in advancing disciplinary knowledge (Polanyi, 1966; Yasser. 2017). Prototypes and material samples operate both as research instruments and epistemic objects: as tangible artefacts they function as information carriers, enabling qualitative assessment through sensory engagement, comparative and quantitative evaluation for architectural applicability, mechanical properties and environmental response. Thus, prototyping enables inquiries difficult or impossible to address through other methods, especially when exploring new materialities and spatial effects; here, prototypes are open-ended components for discovery (Wensveen & Matthews, 2015; Zboinska, 2022).

A pedagogical framework is integrated into the methodology through a parallel architectural design studio, which functions as a testing ground for exploring the developed material's architectural expression, spatial applications, and speculative use scenarios through design explorations, toolpath design variations, and application-driven prototypes. This set-up lets architectural questions to inform material iterations and vice versa, reflecting the relationship between process-driven and output-driven design research, where outcomes remain emergent rather than predetermined (Aydemir & Jacoby, 2023; Charitonidou, 2025).

The research is inherently interdisciplinary, engaging perspectives from architecture, material science, and biotechnology. Architectural design methods contribute aesthetic and spatial reasoning, upscaling, and contextual interpretation, while material science and biotechnology provide analytical tools, experimental protocols, and biological understanding. Knowledge production is then distributed across disciplinary boundaries, requiring continuous negotiation of terminology, methods, and evaluation criteria. The research therefore operates within what has been described as a hybrid mode of inquiry, extending beyond conventional mixed-method approaches (Pietrzyk, 2020; Zboinska, 2022).

The overall research process follows an iterative and non-linear structure, characterized by repeated cycles of experimentation, evaluation, and refinement (Figure 6). Each iteration builds upon the outcomes of previous trials, allowing the research to narrow or reframe its focus as findings emerge. Iterations occur across multiple scales and dimensions, including material composition, fabrication technique, prototype resolution, and architectural application. This workflow reflects Glanville's statement that "there is no such thing as research that is not designed," emphasizing that research itself is a process of continuous adjustment, modification, and learning (Verbeke, 2013). In doing so, it balances the exploratory nature while maintaining methodological rigor.

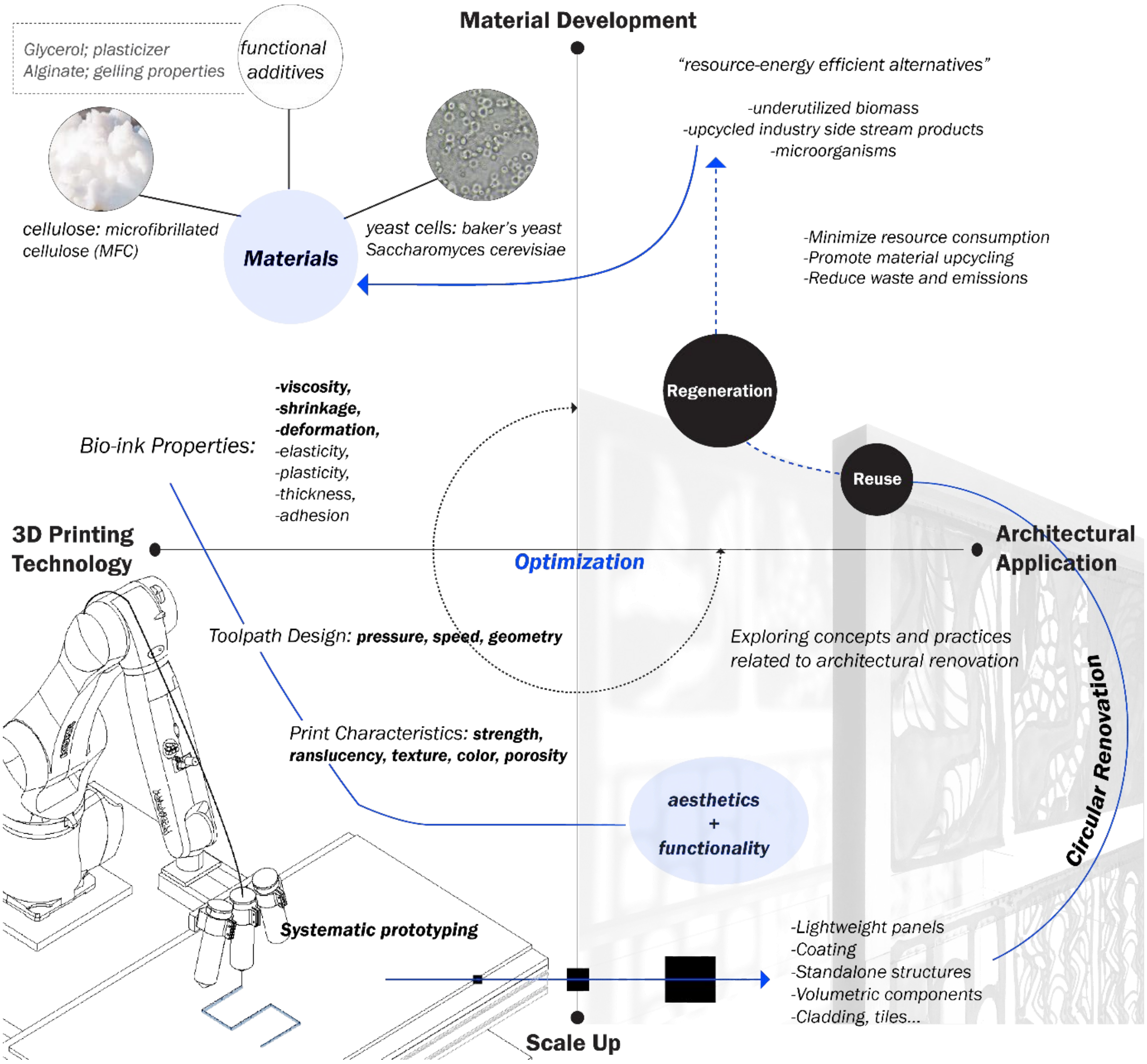


Figure 6. *Research-by-design workflow mapping the iterative relationship between material development, fabrication calibration, and design exploration, where making operates as a mode of knowledge production across scales.*

3.2. Formulating Matter: Developing the Yeast-Cellulose Hydrogel

This methodology establishes a novel, biobased hydrogel that is 3D printable and suitable for architectural applications. The focus is on material behaviour at the level of ingredients, preparation, and composition prior to any robotic or computational mediation. The objective is to define formulations that exhibit controllable flow during deposition, shape retention after deposition, low deformation and shrinkage during ambient drying. The yeast-cellulose hydrogel is not framed as a finished product, but as a negotiable matter system whose behaviour is first understood on its own terms. Understanding of the material's behaviour at a baseline level, provides groundwork, for Section 3.3, where robotic fabrication is introduced as a negotiation tool to the behaviours identified at micro-, meso-, and macro scales.

3.2.1 Material Selection

The material composition targets resource and energy efficiency by incorporating underutilized biomass, upcycled industrial side stream products, and microorganisms (Figure 7).

The primary biological ingredient is baker's yeast, Saccharomyces cerevisiae (Jästbolaget, Sweden). Commonly utilized for their role in baking and brewing, yeast is characterized by rapid multiplication, biocompatibility, and potential circular production from industrial side streams. Despite these qualities, yeast biomass remains largely underexplored for architectural scale. Here, yeast is investigated as a filler and binder within the matrix, with expected contribution to viscosity, thickness, and internal cohesion. As the material is intended for architectural applications, it was ensured that no vital biological activity remained. The yeast is therefore processed in one of two ways and to study how cellular structure influences formulation behaviour:

- YO (intact, oven deactivated), where cells are heated at 80°C degrees for 30 min. to eliminate viability, preserving overall morphology.
- YHO (homogenized, then oven deactivated), where yeast cells were first subjected to high-pressure homogenization, performed at 1500 bar for five cycles, to rupture cell wall and release intracellular proteins, carbohydrates, and lipids, producing a protein and lipids, and are then oven deactivated.

Microfibrillated cellulose (MFC) functions as the primary viscosifier of the hydrogel, provided at 2% and 10% from Borregaard, Norway. The fibrous network retains water, provides mechanical coherence, shape integrity and exhibits shear-thinning behaviour that supports flow under applied stress with recovery once stress is removed. Functional additives enhance and tune mechanical properties. Glycerol of 99.0% purity (Fisher Scientific) is used as a plasticizer to enhance elasticity and reduce drying induced cracking. Alginate, alginic acid sodium salt from (SigmaAldrich), is explored for its gel-forming polysaccharide.

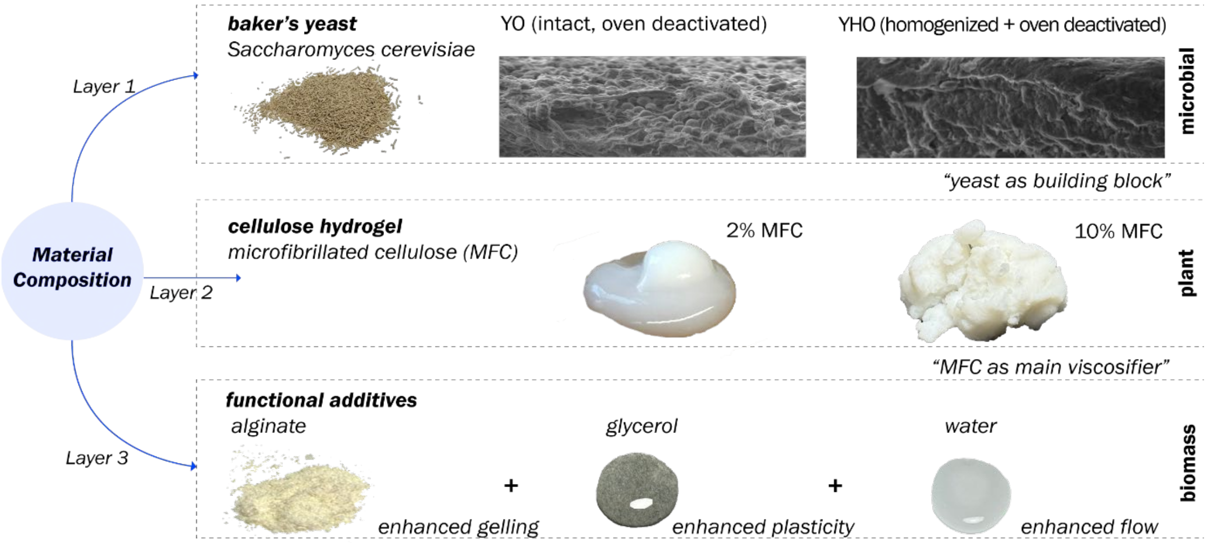


Figure 7. *Composition of the yeast-cellulose hydrogel, comprising baker's yeast, microfibrillated cellulose, glycerol, alginate, and water, highlighting their respective roles within the material matrix.*

3.2.2 Formulation Development and Experimental Procedure

Formulation development followed an iterative process designed to map relationships among ingredient ratios, composition, and material behaviour while maintaining traceability. Each iteration adjusted a limited set of parameters, specifically yeast cell state and concentration, MFC concentration, glycerol and alginate ratio. This approach enabled the discovery of 3 possible material formulations consisting of different material properties.

The preparation of yeast-cellulose hydrogel formulations followed a multi-step workflow, illustrated in Figure 8, displaying how ingredients are prepared, tools used, and extrusion logic across experiments.

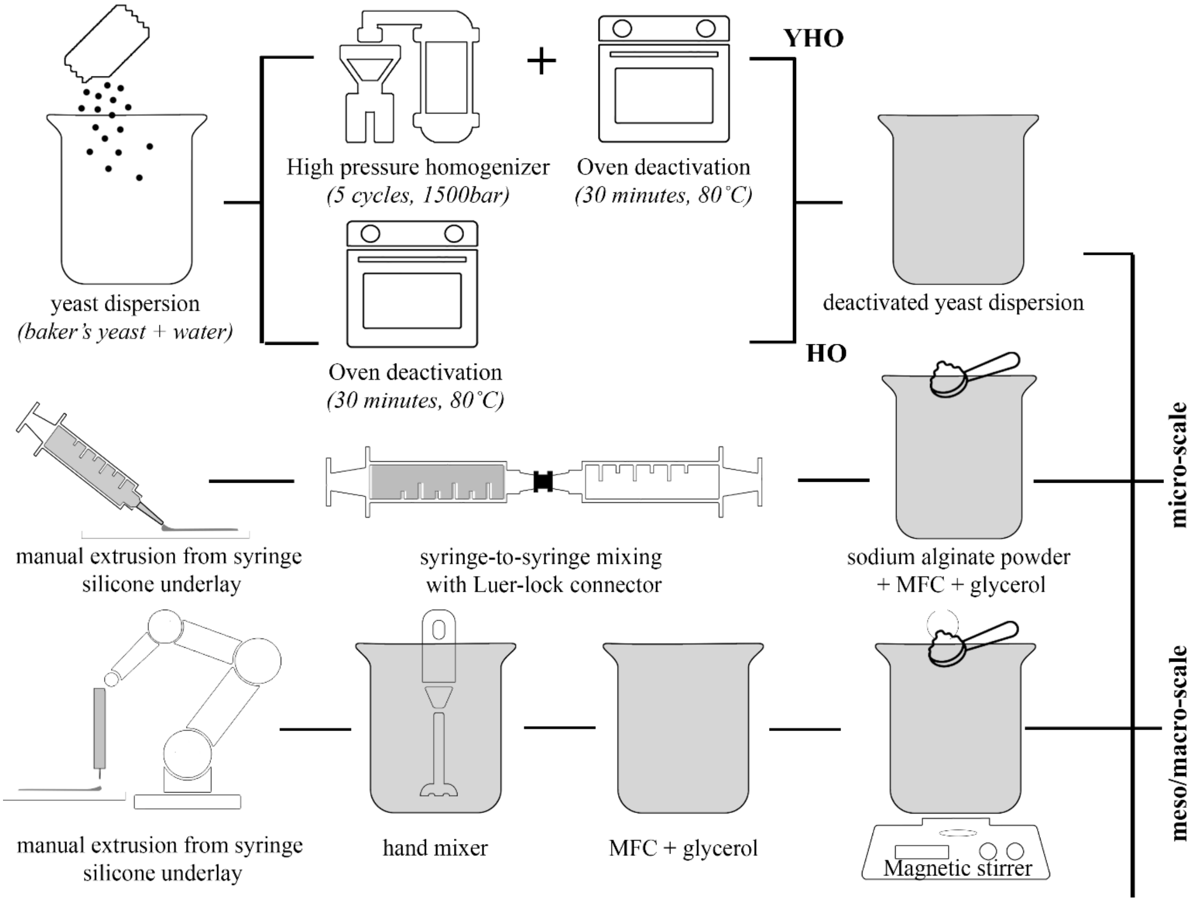


Figure 8. *Workflow of how ingredients were prepared and mixed using different tools, methods, and subsequently extruded across micro-, meso-, and macro-scale experiments.*

For each batch, yeast was first dispersed in water to the target concentration (10 or 20 percent by weight) and deactivated in the selected cell state, YO or YHO. Alginate, a dry powder, was dissolved int the yeast dispersion. MFC was then combined with yeast dispersion. Glycerol was added after. formulation For batches not exceeding 60 ml, components were blended using a syringe-to-syringe mixing method with Luer-lock connectors for ten rounds. A minimum of ten full passes were performed, providing repeatable blending without air entrapment. Microscale tests were conducted by manual extrusion from syringes onto silicone underlays to observe freeform behaviour and onto spruce or pine boards to study coating adhesion. Deposition followed simple linear and curved passes at constant, hand-controlled pressure, using consistent nozzle diameters within each round. All samples were dried under ambient room conditions. For meso- and macro-scale fabrication, batches larger than 60 ml, an adapted mixing protocol using a Bosch hand mixer, at 18,000 rpm, to ensure homogeneous blending. These formulations were then transferred into 200 ml and 300 ml polypropylene cartridges and are extruded through a robot arm following predefined toolpaths derived from prior micro-scale observations. When scaled up, the experiments shifted to evaluations between composition, rheology, toolpath geometry, and drying behaviour for architectural fabrication.

3.2.3 Evaluation Criteria

Evaluation criteria were, qualitative observations on sample behaviour or quantitative assessment on dimensional changes, fixed across rounds to enable comparison:

- Viscosity, recorded as flow control during extrusion, absence of clogging, and consistency of filament.
- Shape retention after deposition, assessed by qualitative observation of spreading and edge definition.
- Shrinkage and dimensional change during ambient drying, estimated from aligned photographs measured against a reference mark.
- Deformation and cracking, observed by comparison of wet to dry-state physical changes.
- Adhesion to substrate, evaluated through visual inspection.
- Elasticity and plasticity, assessed through presence or absence of cracks and simple bend or press tests on dried samples.
- Thickness or volume, assessed via ability to maintain section height without collapse for a given nozzle size.

For architectural 3D printing applications, low shrinkage and deformation with high viscosity, shape retention, and adhesion were identified as critical performance indicators. Other properties were assessed relative to desired property. These observations supported the identification of the material’s intrinsic logic: how it flows, where it fails, and how it stabilizes.

For each experiment, a structured lab report documented the objective, materials and preparation protocol, stepwise procedure, results and observations. Wet-state images were taken immediately after deposition and dry-state images after ambient drying. Results were then compiled into comparative sheets that group samples by composition information alongside photographs that display deformation and shrinkage effects. Documentation enabled comparison across iterations while preserving adaptability, and the identification of tendencies that inform the general formulation logic.

3.3. Negotiating with Matter Through Robotic Fabrication

The methodology follows a progressive "scaling up" framework from micro to macro, where each scale introduces increasing levels of negotiation between digital design intent, matter, and machine. Fabrication is understood as an iterative dialogue in which matter resists, informs, and reshapes computational decisions. Rather than fixing parameters, each print generates a set of guiding rules that evolve through iteration. Within this process, the robot translates toolpaths into motion and pressure while remaining responsive to material behaviour in-situ.

Experiments and findings are documented with following information, nozzle diameter, pressure, layer height, path family and sequence, and material formulation; photographs taken after deposition and after drying to record physical and aesthetic changes; evaluation focuses on include shape fidelity, dimensional consistency, adhesion at intersections, absence of deformation; prototypes progress when accuracy within digital and physical is maintained, otherwise print parameters and toolpaths are revised and reprinted so that each cycle contributes to the evolving rule set.

3.3.1 Fabrication Setup and Digital Workflow

Experiments progress across three steps and scale in a controlled manner (Figure 9).

- Manual extrusion employs a syringe with a 0.86 mm nozzle diameter that mimic 3D printing to generate baseline specimens.
- Micro scale fabrication employs a RegenHU 3D Discovery bioprinter with pressure regulated extrusion on plates of approximately 9x13 cm using 10 ml syringes. Bioprinter trials used 1.55 mm and 2 mm nozzle diameters.
- Meso- and macro scale fabrication employs a KUKA Agilus KR101100SIXX with a custom pressure-based extruder supplied by 200 ml and 300 ml syringes and a work area of about 81.3 by 97.1 cm. Adjustable regulators connected to an air compressor by air hoses provide pressure modulation. Robotic printing pressure ranges from 0.2-1.0 bar and 1.55 mm and 2.50 mm nozzle diameters.

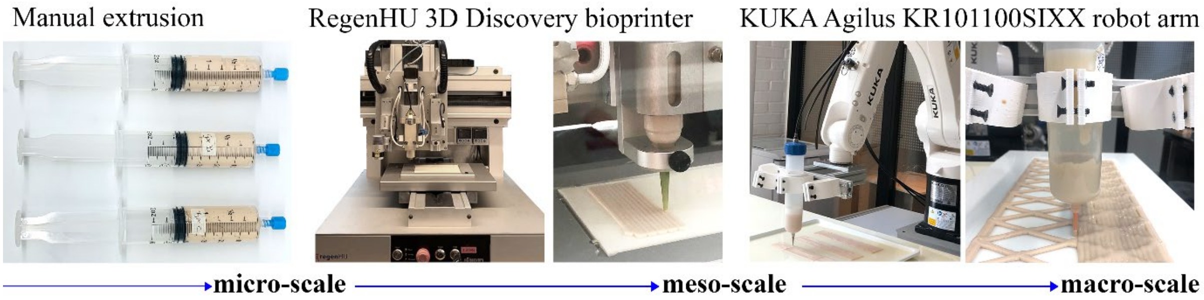
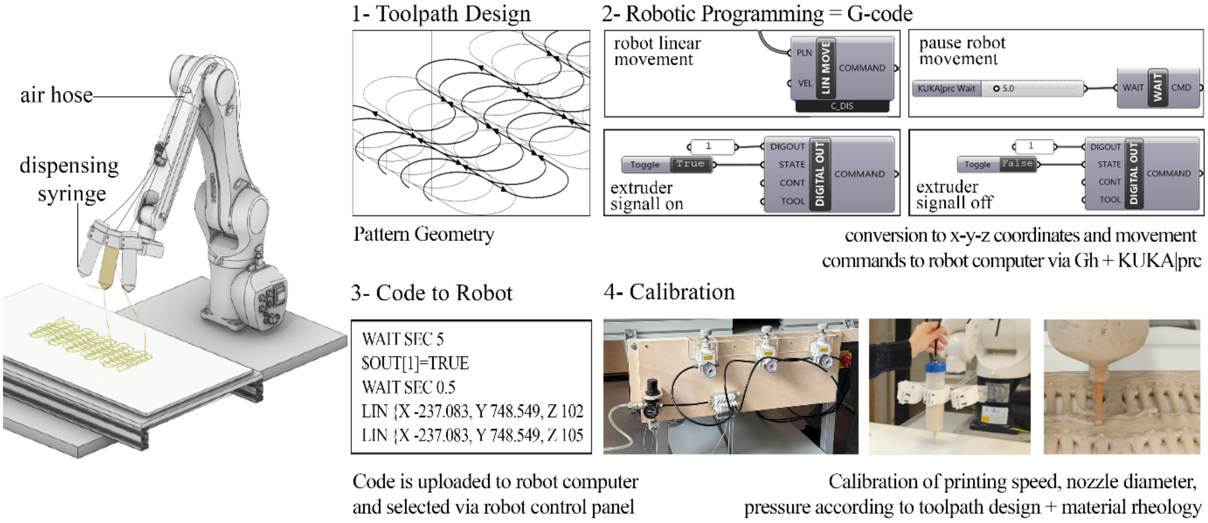


Figure 9. *Three scale fabrication setups, illustrating the progress from manual syringe-based extrusion to micro-scale bioprinting and meso-, macro-scale robotic fabrication.*

Across all scales, deposition paths are prepared in Rhinoceros 3D in Grasshopper. Robot motion is compiled with the KUKA|prc plugin to control tool-center-point speed, acceleration, start and stop pressure timing, and sequence.

The workflow operates in a cycle on responsiveness and knowledge formation, negotiation by allowing design, material, and robot to inform one another through successive refinements (Figure 10). Toolpaths are designed or updated to express design intent, a formulation is selected, deposition is executed with pressure tuning, wet and dry-state photographs and measurements are recorded, parameters and rules are defined and revised for the next iteration. This emphasis on responsiveness and knowledge formation for optimized print parameters.



```
WAIT SEC 5
$OUT[1]=TRUE
WAIT SEC 0.5
LIN {X -237.083, Y 748.549, Z 102
LIN {X -237.083, Y 748.549, Z 105
```

Figure 10. *Diagram illustrating sequence of digital workflow from toolpath design to robotic deposition; (1) toolpath generation in Rhino, (2) conversion of geometry to coordinate movements for robot, G-code, via Grasshopper and KUKA|prc, (3) transfer of the code to the robot controller, and (4) calibration of printing speed, nozzle diameter, pressure, height and extrusion timing.*

3.3.2 Toolpath Design and Scale Transition

The following phases form a structured progression for transfer across scales (Figure 11). Phase 1 maps basic properties through manual extrusion and selects several viable formulations for further study. Manual 2x2 cm square constructs were assessed in wet and dry state for extrudability, shape fidelity, pliability, shrinkage to shortlist formulations. Phase 2 utilizes the bioprinter to test deposition pattern, path spacing, layer height, continuity, adhesion, and dimensional stability to establish compatibilities between formulation and path logic via 5 x 5 cm and 7 x 7 cm constructs. Phase 3 employs robotic fabrication, linking aesthetic and mechanical properties to design by further examining patterning and layered deposition strategies. Phase 4 demonstrates full scale architectural samples, displaying possible design effects and applicability. Toolpaths embed the negotiation rules derived in prior phases with attention to pattern variation, surface articulation, and assembly.

Toolpath design functions as an instrument for inquiry. At the micro scale, spiral squares, parallel lines, orthogonal square grids, circles, and interwoven circles are explored for curvature, spacing, filament continuity and overlap. Insights from micro tests transfer to meso-scale studies that address larger areas and multi-layer sequences. Where zigzag and lattice paths examine directionality, solid surfaces test deformation and shrinkage, layered infills assess cohesion. Identified rules translate material feedback into toolpath strategies that allow design intent to be maintained.

Phase 1
Manual extrusion
2x2 cm square constructs

Phase 2
Bioprinter; 5 x 5 cm &7 x 7 cm constructs; spiral squares, parallel lines, square grids, circles, and interwoven circles

Phase 3
Robotic fabrication; 7 x 20 cm constructs
patterning + layering; zigzag and lattice patterns

Phase 4
Robotic fabrication; 50 x 20 cm tiling
solid and lattice designs

Figure 11. *Toolpath design and scale transition illustrated through four phases of the research, from manual 2×2 cm extrusion tests (Phase 1) to bioprinted 5×5 cm and 7×7 cm pattern studies (Phase 2), robotically fabricated 7×20 cm patterned and layered constructs (Phase 3), to full-scale 50×20 cm solid and lattice tile demonstrations (Phase 4). The progress highlights how material behaviour is evaluated through patterning logic and deposition strategies to inform potential architectural applications.*

3.3.3 Robotic Mediation

In the fabrication workflow, the machine mediates between digital design intent and material agency exposing multiple layers of control that can be tuned in response to material feedback (Figure 12). Negotiation is implemented through rule-based adaptation embedded directly in path generation, sequencing, and execution so that the robot balances design objectives with the capacities and limits of the material.

Material rheology directly informs printing parameters such as nozzle diameter, pressure, layer thickness as well as deposition type. Nozzle diameters are coordinated according to intended line width and layer height to ensure dimensional consistency. Pressure regulators enable adjustments during deposition accommodating changes in viscosity as material formulations evolve.

Toolpaths coordinate kinematics and timing, including start and stop, wait time, and the sequencing of pressure on/off. Simple strategies such as pressure ramps at path initiation and reductions at end improve fidelity. In injection-based deposition, toolpaths may incorporate waiting periods at specified locations, allowing the printhead to pause while maintaining pressure so that material can spread in a controlled manner before motion resumes.

The same mechanism supports short dwells at corners, entries, exits, or between adjacent segments enabling regulation of deposition rhythm and material accumulation. Sequencing and flow control are specified in the toolpath logic to organize how material is placed across the design. Layering logic further considers vertical build, accounting for first layer height and incremental increases for subsequent layers. Where enhanced bonding or specific surface formation is required, the toolpath introduces additional passes or overlays as discrete, sequential moves.

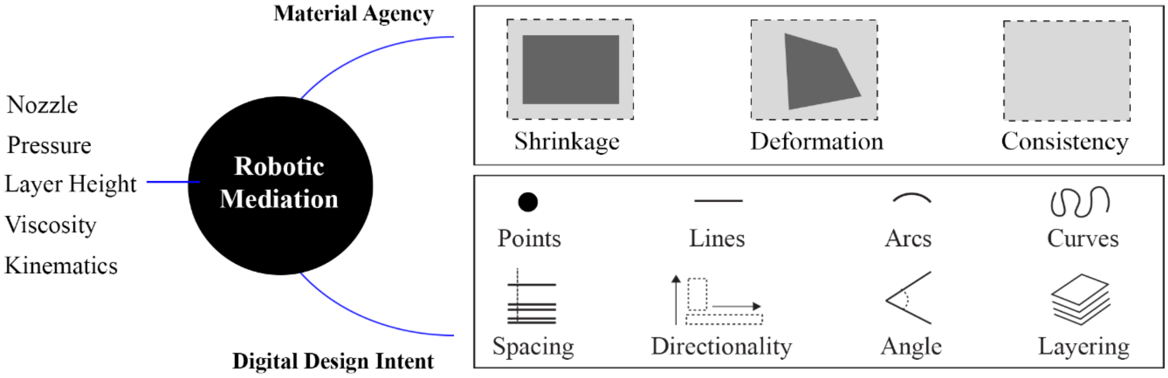


Figure 12. *Diagram illustrating robotic mediation between digital design intent and material agency, showcasing that toolpath logic, kinematic parameters, nozzle and pressure settings interact with material responses such as shrinkage, deformation, and consistency.*

3.4. Matter at Scale: From Fabrication Experiments to Architectural Prototypes

This section outlines a methodology for translating micro to macro scale material properties observed in controlled fabrication experiments into architectural scale applications through aesthetic and mechanical evaluations. Rather than extracting fixed material properties, the research records tendencies and relational behaviours, recognizing that material performance is dependent on scale, geometry, and fabrication conditions. The methodology is formulated to be transferable to different material systems and/or architectural use cases.

3.4.1 Scaling Up

Scaling up is a critical phase in which material agency becomes more pronounced and architecturally legible. As experimental samples increase in size and move towards macro-scale prototypes, factors such as gravity, weight, drying duration, geometric tolerance, and environmental exposure intensify. Without scaling up, to the full architectural potential of a material cannot be fully assessed. Questions regarding mounting, assembly, structural support, and spatial integration are addressed at larger scales, revealing constructability, spatial articulation, and perception.

Prototypes are produced at increasing dimensions to test repetition, continuity, aggregation, and modularity, while revealing thresholds of failure including deformation, shrinkage, cracking, reduced pattern fidelity or substrate interaction, and assembly tolerances. These thresholds define architectural feasibility of the material and inform design and fabrication decisions. Moreover, across scales, material behaviour is evaluated in relation to assembly logic, constructability, spatial effect, durability, and long-term performance. In this sense, the methodology operates as a validation tool where experimental findings are translated into architectural knowledge in terms of spatial, constructive, and experiential realities.

3.4.2 Translation into Architectural Application

The translation of material behaviour into architectural application is proposed as general approach through which experimental matter can enter architectural discourse, guided by evaluation of aesthetic and mechanical properties (Figure 13). These properties are examined both separately and together, and their interaction forms the basis for architectural decision making.

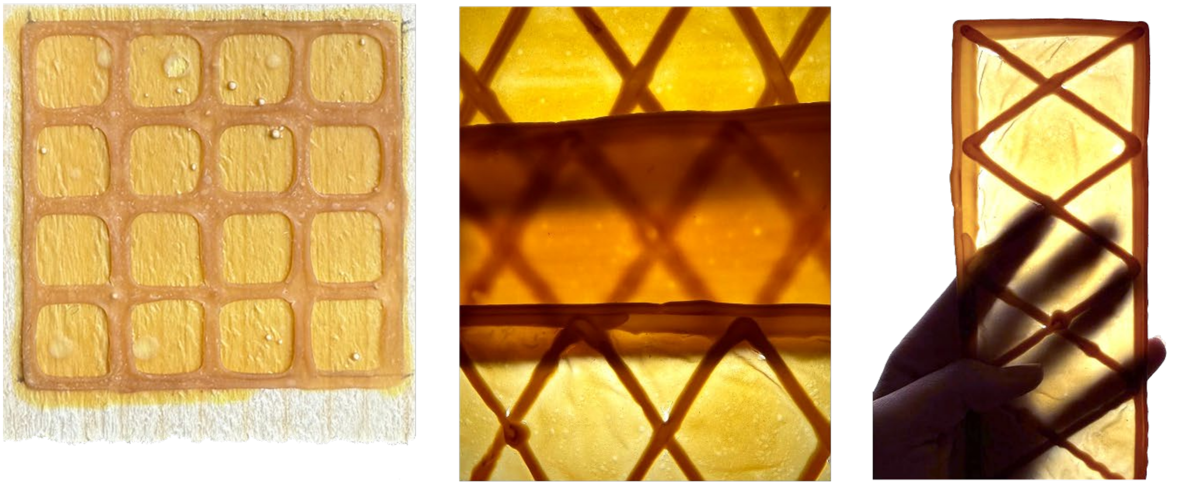
Aesthetic evaluations examine possible design effects. Visual effects such as translucency, light transmittance and colour density and tactile effects as texture and pliability are analysed as direct outcomes of material formulation, geometry, fabrication logic, and transformation over time. This analysis informs design decisions related to surface articulation, pattern legibility, and spatial expression. Mechanical evaluation is conducted for properties such as viscosity, tensile behaviour, adhesion, thermal stability and elasticity to understand how material responds to forces, deformation, and environmental change. These findings are analysed to understand both capacities and constraints which define possible architectural applications. Moreover, they inform architectural decisions related to thickness, continuity, segmentation, mounting, assembly logic. When evaluation together, mechanical behaviour conditions visual expression by producing surface relief, porosity, thickness variation, and spatial rhythm. At the same time, visual effects act as indicators of mechanical performance, revealing zones of stress, accumulation, deformation, instability, or failure. Within this methodology, the architect plays a central role, interpreting findings to define the type of architectural application that the material properties and design effects can support.

Architectural translation therefore follows a set of guiding questions:

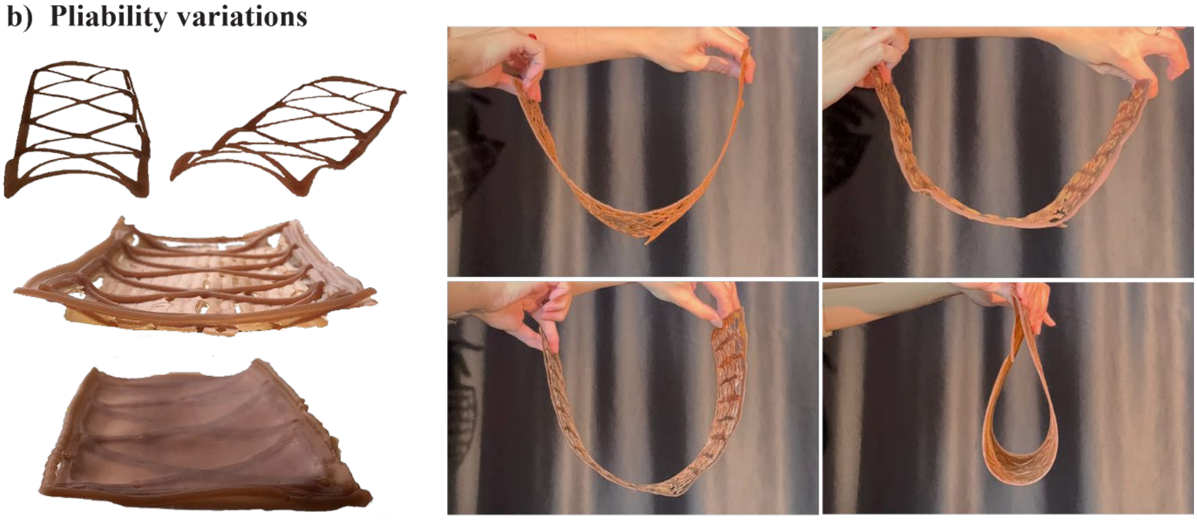
- Which visual characteristics remain coherent and expressive when the material is scaled from sample to architectural element?
- What tactile and visual properties do the material exhibit (e.g. texture, translucency, light transmission, colour saturation, pliability, softness or rigidity)?
- How does the material interact with light, shadow, and reflection, and how do these interactions influence spatial perception?
- What spatial, experiential, or atmospheric qualities emerge through the material's presence?
- Which mechanical properties are present?
- What mechanical characteristics are observable in the material's behaviour (e.g. viscosity, tensile or compressive strength, elasticity, adhesion, thermal stability, shrinkage, or deformation)?
- Is the material suited to load-bearing or non-structural applications?
- How do mechanical properties inform strategies for handling, mounting, support?
- How do mechanical capacities and limitations, degradation tendencies, and sensitivity to environmental conditions define use, scale, and lifespan

Together, these questions guide how, where, and at what scale a material can operate architecturally.

a) Color saturation & translucency variations



b) Pliability variations



c) Surface texture variations

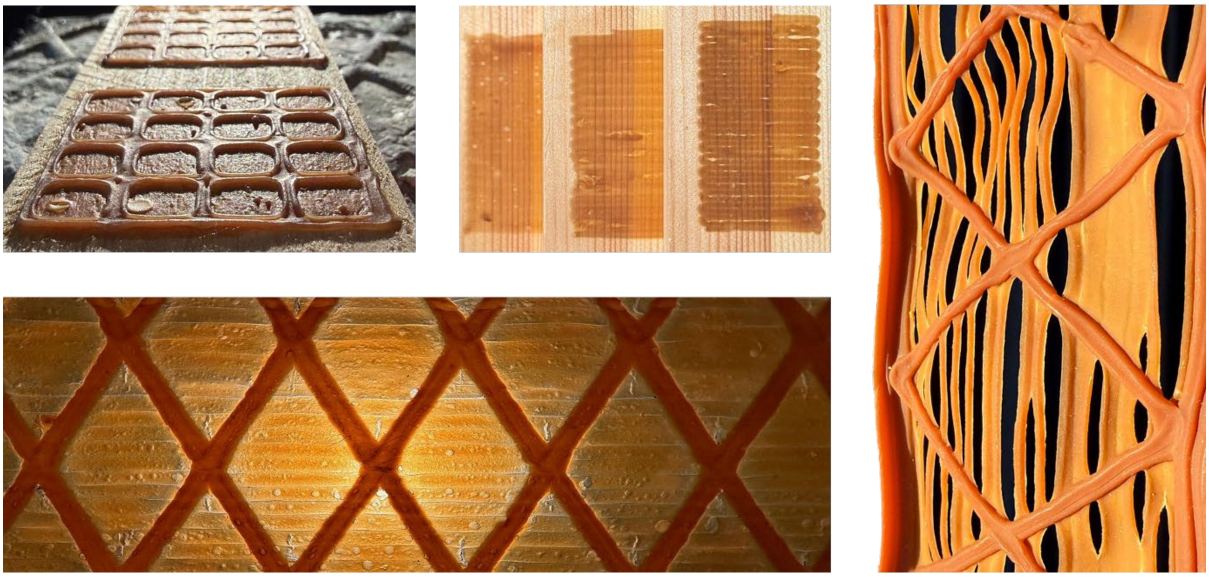


Figure 13. *Aesthetic and mechanical variations demonstrated across samples: (a) colour saturation and translucency; (b) pliability shown through bending tests; and (c) surface texture generated through changes in toolpath geometry. Together, these observations guide the identification of architectural potentials in terms of surface expression, spatial effect, and application typology.*

3.4.3 Evaluation Criteria

Across scales and application types, material performance is assessed through a combination of qualitative observation and quantitative measurement. At micro and meso scales, aesthetic and mechanical behaviour is primarily assessed through qualitative and comparative observations. Parameters in wet-state (pressure, viscosity, shape retention) are evaluated alongside dry-state (adhesion, deformation, shrinkage, thickness) through visual inspection to identify tendencies and relational behaviours.

As the research moves towards architectural scale application, quantitative evaluations are employed for validation of initial findings. Larger scale prototypes require more precise assessment of both aesthetic stability and mechanical performance to establish architectural relevance. Quantitative measurements such as shrinkage calculation, thickness variation, adhesion strength, tensile strength are evaluated. Whereas qualitative observation supports architectural assessment related to aesthetics, perception, and spatial effects. Together, they form a methodological toolkit enabling experimental material behaviour to be translated into validated architectural applications.

3.5. Matter in Context: Situated Prototyping and Material Exposure

This research adopts a methodology grounded in situated prototyping, material exposure, and in-situ engagement, not as controlled performance evaluation, to explore how emerging architectural materials may be encountered beyond laboratory conditions, positioning within public or semi-public environments, where environmental, social, and perceptual conditions can be examined. The overarching premise is that architectural materials acquire meaning and value through context and that early exposure in real-world situations can help identify questions, tendencies, and constraints relevant to further material and architectural development. The aim is to generate early insights and experiential knowledge related to environmental behaviour and user perception that can inform subsequent stages of material research and design decision-making.

Prototypes are developed at a 1:1 or near 1:1 scale, testing assumptions related to:

- Environmental durability and exposure
- Structural and surface transformation over time
- Sensory and perceptual qualities (visual, tactile, olfactory)
- Compatibility with architectural use

3.5.1. Exhibition

Exhibitions are used as a platform to transform prototypes into public material encounters. During these events, prototypes are displayed in semi-curated environments that invite direct interaction from diverse audiences, including designers, researchers, industry professionals, and the general public.

In this context, prototypes operate simultaneously as research instruments and communicative artifacts. The exhibition setting enables the study of immediate public perception and interpretation of materials, modes of interaction (touch, proximity, curiosity, avoidance) and role if scale and spatial impact. Observational data is collected through field notes, photographic documentation, and informal conversations.

3.5.2. Testbed Instillation

Testbeds operate as intermediate environments between laboratory testing and full architectural implementation. Material exposure is operationalized through the establishment of testbeds, where prototypes remain in place for extended durations. This allows for longitudinal observation of material behaviour capturing information on discolouration, deformation, biological growth, and maintenance requirements.

The IMA Testbed serves as a primary site for environmental exposure trials for the yeast-cellulose hydrogel. Here, prototypes are installed in a regulated indoor office environment, chosen to reflect realistic yet stable architectural conditions. Environmental parameters such as moisture levels, temperature fluctuations, and daylight exposure are monitored to contextualise how ambient conditions influence material deformation over time. Environmental data is recorded using Comboss wireless temperature-humidity sensors and Bright thermometer/hygrometer reader in combination with the building’s logged data. These measurements are compared with observed material stability through thermal scanning using a Hikmicro Pocket 2 thermal imaging camera, alongside photographic documentation and dimensional assessments.

3.5.3. In-Situ Engagement

To complement observational methods, semi-structured qualitative interviews, conducted at the testbed or exhibition setting, can provide information on material perception through multisensory and temporal engagement. Addressing themes such as sensory impressions, emotional responses, associations, perceived applicability and limitations. This method aims to uncover patterns that emerge through interaction with materials which can form guidelines in further development.

Overall, data from all situated prototyping are synthesized through a reflective process, referencing performative observations with perceptual feedback. The analysis emphasizes knowledge generation through material encounter, acknowledging uncertainty, transformation, and context-dependence as research outcomes.

4. Research Findings and Architectural Dissemination

This chapter presents the material findings, fabrication insights, and architectural explorations generated through the research. The results are reported across the appended papers, as well as additional dissemination through exhibition and testbed instillation communicated via physical prototypes. Detailed discussion of how the results address the research questions and objectives is provided in Chapter 6.

4.1. Yeast-Cellulose Hydrogel as Architectural Material: Development and Emergent Material Behaviour

The material investigations carried out in this study established the yeast-cellulose hydrogel as a novel biobased material for architectural use. The formulation matrix consists of baker's yeast, either intact oven deactivated cells (YO) or homogenized and oven deactivated cells (YHO), with microfibrillated cellulose (MFC), sodium alginate, glycerol, and water. The samples created throughout the study served as epistemic objects that revealed how even minor compositional adjustments resulted in distinct material outcomes. Across iterative cycles, repeatedly preparing, drying, and comparing samples, it became possible to achieve printable blends and gradually optimize the material's behaviour, including its tendency to shrink, crack, or deform during ambient drying.

The wet-to-dry transformation emerged as one of the most informative aspects of the material's behaviour. Even under controlled laboratory conditions, the hydrogel exhibited dimensional changes and localized deformation. Such transformations are not simply imperfections to be eliminated. Instead, they reflect how the biological components reorganize during drying and therefore reveal something about the material's intrinsic agency. Understanding these tendencies is essential for assessing architectural applicability because the transformation cannot be prevented entirely but can be anticipated and incorporated into design decisions.

A central finding concerned the distinction between the two states of baker's yeast. YO acted mainly as a filler, producing stiffer and more opaque samples, whereas YHO acted as a binder, creating homogeneous mixtures with lower shrinkage and smoother, more translucent results. These effects became apparent when paired with different MFC concentrations; as higher MFC content produced thicker and rigid sections, while lower MFC content resulted in thin, flexible, translucent samples. Glycerol proved important for preventing cracking and improving pliability without compromising overall stability.

Mechanical testing places the yeast hydrogel within the category of biobased thin sheets. This implies that it can tolerate handling and installation as a surface layer yet is not intended for structural loads or spanning conditions. In architectural terms, this positions the material as appropriate for lightweight applications such as mounted or suspended interior elements, textiles, and modular surface systems.

The optical and aesthetic outcomes further display that the material can be tuned to transmit varying degrees of light and can be printed with solid or perforated porosity types, offering an alternative to common thin interior finishes derived from fossil or mineral resources, such as synthetic laminates or gypsum-based products. Together, these observations indicate that the yeast-cellulose hydrogel is a lightweight, non-loadbearing, surface-oriented architectural medium that provides a range of tactile and visual effects. These findings informed the decision to pursue interior decorative tiling as the first architectural application. Tiles localize dimensional change, their modularity allows for iterative refinement and systematic comparison, and suit renovation contexts that benefit from reversible and low-impact surface transformation.

In summary, the results clarify how the yeast-cellulose hydrogel behaves as architectural matter. It is sensitive and active, requiring iterative physical testing to understand tendencies, yet capable of producing expressive surfaces from renewable biomass. The material's emergent properties and constraints naturally led to the tiling application, setting the foundation for subsequent work on fabrication strategies and design integration.

4.2. Digital Crafting and Fabrication Knowledge

The results of this extend earlier observations presented in Paper A by conducting an in-depth investigation into how variations in computational design influences the physical and aesthetic outcomes of yeast-cellulose hydrogel tiles, culminating in the development of a material-crafting framework in study B that links geometric design to the material's transformations during ambient drying. Through systematic variation of path geometry, spacing, symmetry, connection angles, intersection types, material blend combinations, deposition methods, and layer sequences, the study demonstrates how key parameters influence shape retention, interlayer cohesion, shrinkage, deformation, shape fidelity, translucency, colour, texture, and pliability. Three hydrogel blends with distinct viscosity and shrinkage profiles provided a controlled basis for comparison, allowing the effects of geometric and depositional decisions to be observed.

The primary dataset comprised architectural tile prototypes produced in a parallel teaching environment, where students were introduced to the novel yeast-cellulose material, established in Paper A, and tasked with toolpath design and robotic fabrication. This pedagogic method of inquiry produced a diverse set of protypes that functioned as epistemic objects, that allowed the research to observe how computational intent meets robotic execution and how both negotiate the material's behaviour. Although this variety expanded the number of parameters limiting validation of individual variables in the framework.

From the analysis emerged a set of design rules that can help tune 3Dprinting path geometry for improved dimensional accuracy, reduced deformation, and reliable layer bonding in yeast-cellulose hydrogel prints. Continuous paths supported dimensional stability; sharp angles, discontinuous segments, and dense intersections tend to crack; tangential and obtuse junctions improved cohesion while acute intersections weakened it; balanced material distribution across the tile reduced anisotropic shrinkage and preserved planarity; tight spacing or excessive intersection created local material accumulation that influenced warping and surface thickening. These effects were amplified or reduced depending on the blend: high viscosity supported sharp edges and lattice articulation, medium viscosity material sustained curved or radial paths, and low viscosity performed best as infill to produce smooth translucent areas. These behaviours were not incidental failures; rather, they show that toolpaths are more than geometric instructions, since the material interprets the computational script and toolpath decisions shape its deformation, bonding, and change over time. These rules of geometry, viscosity, and deposition also enabled craft-like tuning of visual and tactile properties of the hydrogel. Strand-based deposition with higher viscosity created rippled textures; droplet-based deposition formed pixelated nodes; and injection-based depositions with lower viscosity generate smooth surfaces with high translucency. Collectively defining a spectrum of possible design outcomes, supporting designers to make intentional and informed decisions where it best serves the architectural intent.

Altogether, the study shows that fabrication with yeast cellulose hydrogel operates through an ongoing negotiation between computational intent, robotic control, and material agency; this negotiation is central to reframing the act of fabrication as a craft practice conducted through digital and robotic means. The diverse prototypes generated in the pedagogical environment made it possible to observe these interactions across many design strategies, allowing multi scalar relationships, from path to tile, to be traced across many instances, strengthening the framework's robustness. The resulting material crafting framework highlights these insights by mapping toolpath design, blend selection, and deposition parameters to the resulting physical and aesthetic transformations. As a design method, it enables designers to work with the hydrogel's emergent effects rather than treat them as failures, offering a structured basis for selecting toolpaths and blends for applications such as claddings, screens, partitions, and decorative elements where lightweight, translucency, and textural modulation are valued. It also establishes a foundation for future development, including predictive simulation, multi material strategies, and environmental response studies, which will further strengthen the architectural potential and reliability of this renewable biomaterial.

4.3. Material Evaluation Beyond the Lab: Exhibition and Testbed Installations

An important aspect of this study was the placement of the yeast-cellulose hydrogel prototypes beyond the laboratory as exploratory trials, to gather insights that emerge through prototypes situated within public contexts. Rather than delivering conclusive assessments, this study functions as an initial inquiry into how environmental exposure and user perception might be studied more rigorously in later phases of the research. To this end, two situated setups were employed: a public exhibition using Study A tiles and an indoor testbed using Study B tiles, each designed to foreground different aspects of material encounter. Together, these setups extended the research beyond academic boundaries and enabled observations of user perception, spatial presence, and environmental exposure.

Exhibited under the title "Mycotecture: Sustainable architecture from yeast materials," the public installation centred around aesthetic expression, material novelty, and the sustainability narrative of the work. The exhibition served as an early probe into how spatial presentation and scale shape first impressions of unfamiliar materials, highlighting the sensitivity of perception to modes of encounter and informing the design of future user perception studies. The instillation centred on macro-scale tile assemblies suspended from the ceiling, allowing light to pass through, producing dynamic visual effects such as shadow play, translucency gradients, and varying pattern depth as visitors moved through the exhibition space (Figure 14). The suspended placement enables interpretation of the material through atmosphere, light, and movement rather than sole tectonic reading. Alongside these macro assemblies, micro- and meso-scale samples were displayed to invite tactile engagement, enabling visitors to explore surface texture, softness, and weight, complementing the visual experience of the suspended tiles. Through this multi-scalar setup, the exhibition staged the material as a sensory encounter, in which seeing and touching operated together, though at different spatial distances. While the precise cause could not be isolated, three suspended tiles deformed by tearing, potentially due to a combination of prolonged exposure to artificial lighting, elevated local temperatures, or intensive mechanical handling, indicating further studies on stability.

Figure 14. *Photographs from the Helsinki Design Week exhibition showing the display setup of yeast-cellulose hydrogel sample.*

Observations during the exhibition were informal, primarily of visual inspection on visitor interaction and modes of engagement. No structured user surveys were conducted; instead, the exhibition served to surface questions and sensitivities relevant for the design of future studies on material perception and user interaction. During the exhibition period, three of the suspended tile elements exhibited noticeable deformation via tearing, due to a combination of prolonged exposure to artificial lighting and increases in indoor temperature. These point to the need for further systematic investigation of long-term environmental stability. Moreover, tactile engagement suggest that accessibility plays a key role in shaping user interaction, highlighting the need to consider handling and durability in future research.

Alongside, the investigation shifted from curated encounters to prolonged everyday exposure through an indoor office space testbed installation. In this setting, the tiles were assembled along a timber frame and arranged in horizontal rows, forming a configuration that resembles an interior cladding system (Figure 15). This arrangement emphasized continuity, repetition, and surface behaviour over time, allowing the material to be read in relation to familiar architectural elements while revealing potential sensitivities arising through exposure. The installation was placed in a monitored office environment managed by Sankt Kors/IMA, where indoor temperature remained relatively stable (21-25 °C), fluctuations were seen in humidity, and dynamic illuminance (300-4.700 lux). The setup was not intended to simulate extreme conditions, but rather to establish a baseline context representative of everyday interior environments, against which initial material responses could be observed.The testbed was examined over a seven-week period, where temperature, humidity, and illuminance data were collected hourly to capture daily and weekly variations and their impact on the assembled tiling system. Thermal imaging of sample geometries captured how the material responds to fluctuating light and heat within an indoor setting. Variations in illuminance were found to be the primary driver of surface temperature changes, producing localized heating on days with direct sunlight, while the interior of the tiles remained comparatively stable.

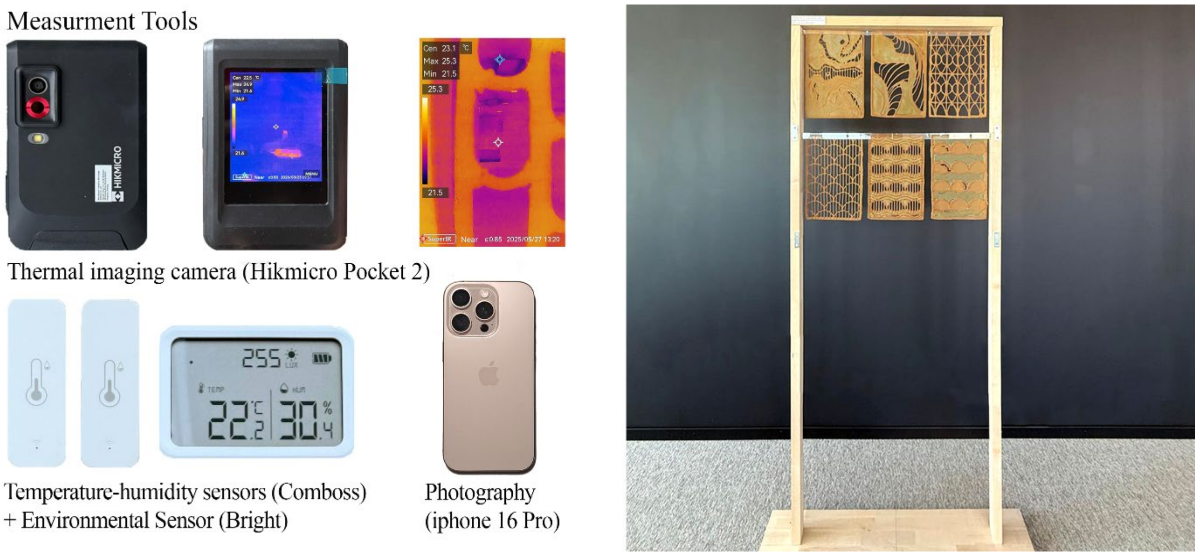


Figure 15. *IMA Testbed setup showing yeast-cellulose hydrogel prototypes and the measurement tools used for environmental monitoring, thermal imaging and documentation.*

Maximum surface temperatures frequently reached 27-32 °C range on brighter days, while the interior remained stable at 22-23 °C. Tile geometry influenced this behaviour, with more porous configurations exhibiting lower peak temperatures and denser patterns exhibiting localized heat accumulation due to light trapping and reduced airflow across the surface. No visible deformation occurred during the observation period; however, the data suggests that persistent localized heating in thicker regions impacts long-term behaviour, forming concavity or other form changes over extended duration. When considered alongside the exhibition samples that deformed, these findings underscore that situated contexts impose environmental conditions that shape material performance in ways not captured by laboratory testing alone. The testbed functioned primarily as a scoping exercise, revealing the need for conducting future studies focused on environmental exposure, long-term stability, and durability across varying architectural contexts.

During the testbed, exploratory semi-structured interviews were conducted with three office workers who experienced the material throughout their daily routines. These interviews were not intended as a comprehensive perception study, but rather as a methodological pilot to capture how individuals perceive the material through multisensory engagement. Participants reflected on visual impressions, tactile qualities, emotional associations, perceived limitations, and imagined application scenarios, while demographic and professional backgrounds were noted to contextualize perceptual differences, particularly for industry professionals who may bring predispositions regarding durability, maintenance, or architectural norms. Across interviews, several commonalities emerged. Initial visual impressions evoked associations with soft, organic, and edible materials, generating curiosity to touch the samples. Handling the material changed perceptions, as participants found it more flexible and durable than expected, moderating initial assumptions of fragility. Prolonged proximity revealed a shared concern regarding how the material's smell might increase in larger interior applications. Participants commonly associated the material with warmth, playfulness, and softness, and imagined its use primarily in interior, nonloadbearing contexts, while expressing uncertainty regarding durability, maintenance, and long-term performance. Although limited in number, the interviews indicate that perception of the material is dynamic and shaped by embodied and temporal engagement, supporting the relevance of in-situ, multisensory methods for future user perception research.

Taken together, these insights underscore that evaluating emerging architectural materials requires situated prototyping, where material behaviour, user interpretation, and spatial context intersect. The exhibition demonstrated how framing, scale, and presentation can increase sensory and aesthetic qualities, while testbed installation revealed how the material responds to environmental exposure over time, and the interviews indicated that perception evolves through sensory engagement. Situated exposure, both environmental and experiential, therefore emerges as a crucial instrument for guiding future iterations of the biobased material and its integration into architectural practice, confirming the importance of conducting a more systematic user perception study in subsequent phases of the research.

4.4. Exploratory Potential of Yeast-Cellulose Hydrogels in Architectural Restoration: Timber Coating Applications (Work in Progress)

These results present a state-of-the-art of the potential use of yeast-cellulose hydrogel materials as decorative and restorative coatings for interior timber surfaces in architectural renovation and heritage preservation contexts. Findings discussed are based on early-stage inquiries from micro-scale experiments (Figure 16) and from pedagogical explorations, therefore represent a conceptual approach to restoration that identify material agencies, design and application hypotheses, rather than validated data. This positioning aligns with research-by-design methodologies, in which architectural application of novel biomaterials is first identified through speculative and situated practices. The pedagogical setup comprised of a deteriorated timber facade as a design prompt, development of toolpaths according to design intent, implementation of the yeast-cellulose hydrogel material, and fabrication of physical prototypes aimed at explorations for restorative strategies for aesthetic surface transformation.

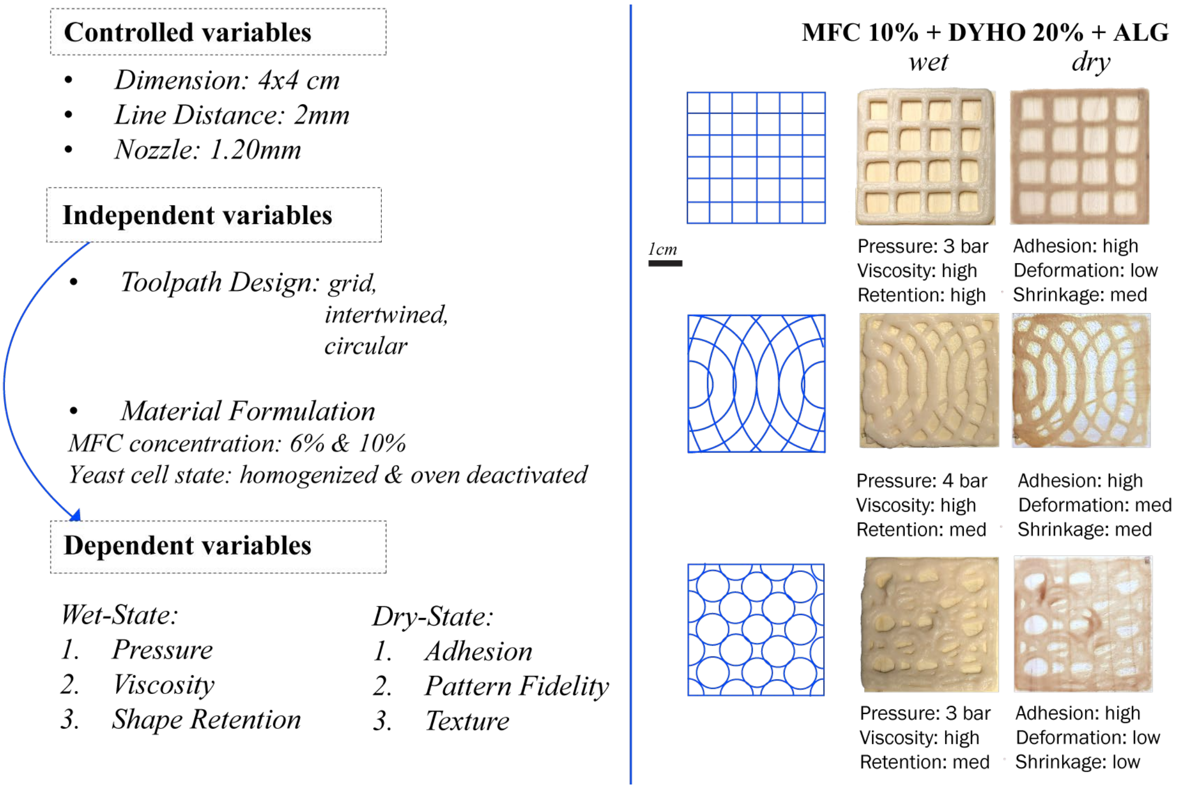


Figure 16. *Overview of early-stage, micro-scale, extrusion tests exploring how toolpath design and formulation matrix influence coating behaviour in both wet and dry state samples.*

Architectural timber; exterior, interior and restorative, often requires surface treatment through performative (protective to UV-radiation, insulative, antimicrobial) and/or aesthetic (visual or tactile) coating applications. Shape fidelity ensures that coatings maintain their intended geometry post-application, critical for structural integrity, aesthetic precision, and functional efficiency. In both artistic restoration and modern architecture, high-fidelity coatings prevent misalignment, warping, and surface degradation, ensuring seamless integration with existing materials. The ability to precisely control texture and form enhances transition from design accurately into physical structures. Beyond decorative purposes, shape fidelity is crucial for material performance, e.g. in acoustic applications geometry and surface texture must be maintained to ensure the intended performance, enabling the material to be adapted to specific functional requirements. 3D printing transforms coating applications by ensuring precise material deposition, bridges traditional restoration with digital craftsmanship, expanding material selection, design possibilities, tunable properties, scalability and repeatability while minimizing human error. This enhances durability and adaptability of biobased materials, requiring new levels of knowledge and customization, to become a viable alternative to traditional synthetic materials. The yeast-cellulose hydrogel here is perceived as visually and materially compatible with timber, particularly aged, worn, or deteriorated surfaces. In studied designs, rather than replacing existing material, the hydrogel was primarily used to augment, infill, or overlay existing timber. Prototypes demonstrated their capacity to function simultaneously as a reparative and decorative layer. Embedded in digitally mediated material additions, layered deposition and differentiated surface articulation allowed the historic timber fabric to remain visible, supporting conservation approaches that highlight the dialogue between historical authenticity and contemporary interpretations. In parallel, the articulation of toolpaths proved to be a critical design driver where application strategies such as layered deposition, patterning, and controlled variations in thickness shaped surface expression (Figure 17). Consequently, displaying the potential of computationally informed restoration strategies in which digital fabrication logic (geometry, sequencing, spacing, layering) is co-tuned with material behaviour (viscosity, shrinkage, deformation) to achieve targeted responses at the scale of detail. In other words, the intervention is not just material placement; but becomes the mediator in which design intent, diagnosis of decay, and hydrogel behaviour inform one another.

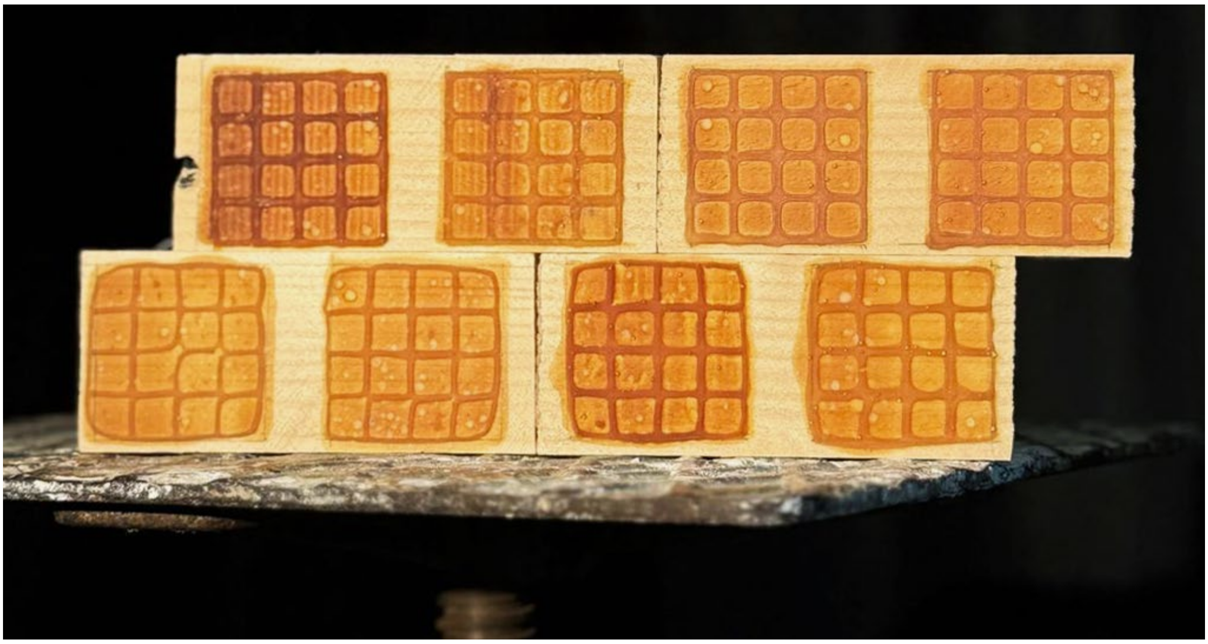


Figure 17. *Timber elements coated with yeast-cellulose hydrogel through grid-based toolpath deposition over a continuous base layer. The patterned infill and layered extrusion illustrate how variations in toolpath density and thickness influence surface articulation and material expression.*

Three restoration logics were identified, outlining a preliminary application space for yeast-cellulose hydrogels in architectural restoration of timber. First, decay induced losses such as rot cavities and edge erosion was approached through infill or void negotiation, where negative geometries are addressed using latticelike infills, bridging and stitching paths. Second, surface modulation and layering were utilized to treat thinning paint and discolouration as gradients, controlling variations in deposition thickness, density, and directionality. This forms coating layers that are both reparative and decorative, incorporating material behaviours as shrinkage and deformation into the design logic for surface expression in dialogue with existing decay. Third, patterning as a translation of decay, where mapped deterioration; cracks, moisture marks, and localized surface inconsistencies, informed generation of toolpaths. Seen in Figure 18, then suggesting computationally informed workflows in which diagnosis, toolpath generation, and fabrication are linked through measured decay data.

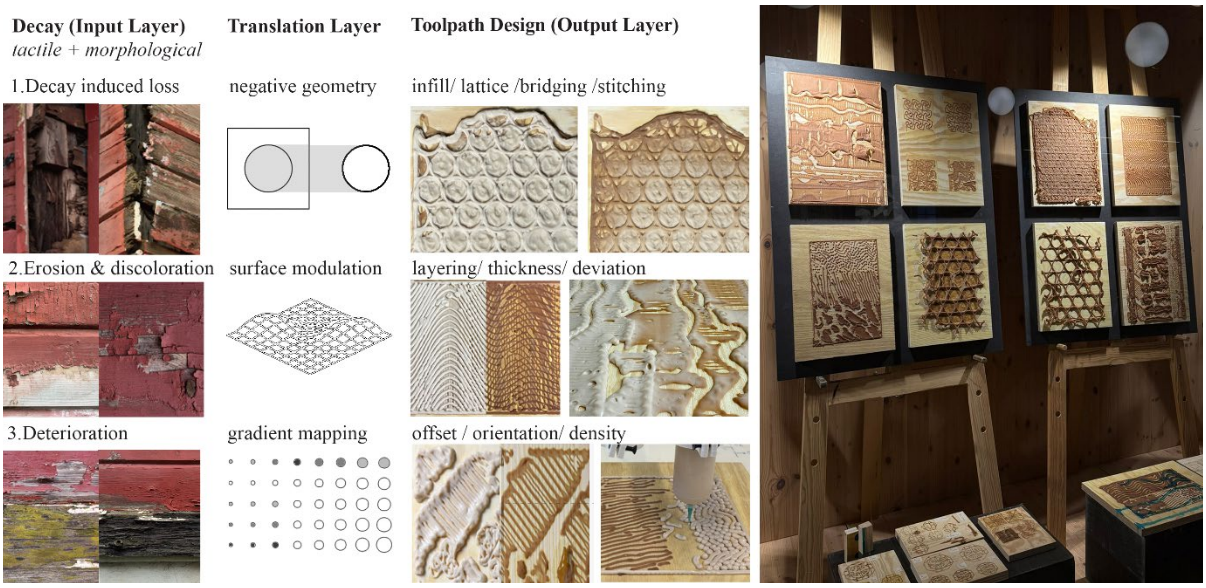


Figure 18. *Example of pedagogical explorations illustrating the decay-to-toolpath framework using yeast-cellulose hydrogel coatings on timber blocks. The figure maps observed decay conditions and their corresponding digital translation strategies to the toolpath design logics in robotic fabrication. The prototypes demonstrate how digitally mediated additions can act as both reparative and decorative overlays, supporting computationally informed restoration strategies. Photos, designs and protypes created by students Junjia Liang, Tereza Táborská, Chengrui Yan, Shixu Ye, Sebastian Johansson, Kuan Ting Kuo in master's studio ACE510- Mediated Material Interfaces at Chalmers University of Technology. Further details and permissions for reproducing the work are available upon request.*

The prototypes overall demonstrate that architectural surfaces treated with such novel materials can operate as interactive interfaces, engaging visually, tactically, and culturally within the built environment. From a research perspective, the findings position yeast-cellulose hydrogels as a sustainable alternative to conventional synthetic coating materials. Taking together, these results indicate that the restoration of timber surfaces emerge as a promising application pathway and a clear research trajectory towards systematic testing and optimization of material formulation, robotic fabrication strategies, shape fidelity, adhesion, environmental durability.

5. Discussion and Conclusion

This chapter compiles the key findings of the research in relation to the overarching research objectives (RO) and research questions (RQ). It highlights the main contributions made through the development of the yeast-cellulose material, exploration of robotic fabrication methods, and the demonstration of possible architectural applications. Discusses the broader implications of working with biobased materials for sustainable architectural renovation and the aesthetic transformation of built environments. Finally, the chapter outlines directions for future research.

5.1. Addressing Research Questions

RQ1: Materiality

How can underutilized biomass be transformed into a novel yeast-cellulose biomaterial whose emergent behaviours and properties inform its architectural applicability?

RQ1 is primarily addressed through the first objective, which aimed to develop robotically 3d printable novel yeast-cellulose hydrogel formulations from underutilized biomass, and is supported by the fourth objective, which aimed to systematically investigate emergent material properties relevant for architectural use. This was addressed in Paper A, which employs methods including consecutive formulation optimization, multi-scalar 3D printing, characterization of microscopic, rheological, tensile, and thermal degradation properties to establish key architectural attributes.

Through iterative preparation and comparative testing, variations and selection of the yeast cell state (YO vs. YHO), tuning MFC content, and additives were shown to shape rheological properties governing print stability and drying transformation (shrinkage, deformation, warpage). These insights form the basis for fabrication and design decisions by clarifying how the material responds and transforms during ambient drying. Mechanical test results further show that the hydrogel exhibits gel-like viscoelastic behaviour that supports shape retention after printing, with tensile strength up to 2.7 MPa and elongation at break of 25.2%. Architectural qualities such as shrinkage (2-10%), light transmittance (5.6-31.6%), colour variation, and porosity configurations are quantified to evaluate the expressive and functional potential.

Paper A further displays the material's suitability as a lightweight, non-loadbearing, 3D-printable interior tiling system, providing an initial demonstration of how the rheological, mechanical, and aesthetic characteristics can be translated to architectural design. While aesthetic analysis indicates its potential for light modulation, porosity, translucency, colour and tactile expression. Together these qualities motivated interior decorative tiling as the first architectural application; as tiles localize dimensional change, enable iterative refinement, and align with reversible, low impact renovation contexts.

Ongoing investigations presented in the work in progress for timber coating applications further extends RQ1 by probing questions of adhesion, environmental response, and compatibility with existing building components. Although preliminary, these observations suggest opportunities for restoration-oriented applications.

RQ2: Robotic Fabrication

Which material properties and toolpath parameters need to be optimized to develop a robotically 3D-printable yeast-cellulose hydrogel that negotiates material agency across micro through meso to macro scales for architectural design?

RQ2 is addressed primarily through the second objective, which focused on establishing and optimizing robotic 3D printing strategies for the yeast-cellulose hydrogel. This was initially explored in Paper A and further developed in Paper B. Additional insights emerge from work aligned with the third objective, evaluating printed components across scales, and the fourth objective, by integrating these fabrication findings into an early-stage design framework.

Early experiments in Paper A examined the fabrication implications of material's rheology, initiating an exploration of toolpath patterns as well as the optimization of extrusion pressure and nozzle dimensions. These established the groundwork for identifying post deposition deformations as fabrication dependent material constraints. Experiments revealed how the hydrogel's viscosity and drying transformation affected deposition stability and geometric retention. Collectively, highlighting the need for systematic analysis of parameters and toolpath strategies.

Paper B delivers an in-depth investigation of RQ2. It analyses computational design parameters, toolpath logic (continuity, junction angles, spacing, symmetry), deposition techniques (strand, droplet, injection), and blend selection, and relating them to outcomes such as dimensional accuracy, inter layer cohesion, deformation, shape fidelity, translucency, texture, and pliability. The study develops a material-crafting framework that maps geometric intent to physical and aesthetic outcome, establishing practical design rules for the yeast hydrogel. These rules define a printability envelope where fabrication is aligned with the material's intrinsic tendencies. Work related to the third objective further clarifies how these strategies behave at different scales. Multi-scalar prototyping demonstrated that toolpaths performing well at the micro scale sometimes fail at the macro scale. This finding shows that the relationship between geometry and material changes with scale and requires careful calibration when transitioning to architectural components.

Through the fourth objective, these fabrication insights are synthesized into an emerging framework that supports material-informed and fabrication-aware decision making. This framework helps designers anticipate how geometric, robotic, and material variables interact throughout the printing process and during drying. It positions yeast-cellulose hydrogel as a craft-like and design-responsive medium in which robotic printing becomes a dialogue between computational shaping and biological material behaviour.

Together, Papers A and B provide a comprehensive fabrication knowledge that positions yeast-cellulose as a printable, craft-like, and design-responsive architectural medium. The combined findings demonstrate that robotic fabrication is shaped by a negotiation between computational intent, robotic execution, and material agency, and that this negotiation can be strategically designed for.

RQ3: Architectural Potential and Integration

How can novel biobased materials be translated into possible architectural applications through robotic 3D printing, and how do their functional and aesthetic qualities shape this translation?

RQ3 is addressed through work aligned with the third objective, which explored architectural application potential through multi-scalar prototyping, and the fourth objective, which aimed to integrate material and fabrication insights into architectural design logic. These investigations are presented across multiple dissemination formats; Papers A and B, public exhibition and the test bed installation, reflecting the design-led and practice-oriented aspects of the research.

In Paper A, architectural potential is first articulated through the tiling system, where modularity and surface articulation align with the material's emergent behaviours. Paper B expands this potential by demonstrating how specific toolpaths, geometries, and blends combinations produce distinct expressive and functional effects, proposing potential application for customizable cladding, screens, partitions, and other interior finishes. Beyond publications, the exhibition of material prototypes allowed public audience to experience the aesthetic and tactile qualities of the yeast-cellulose material, highlighting aesthetic value, material novelty, and the role of multi-scalar prototyping in communicating architectural potential. Whereas, in the test bed installation situated prototypes within an occupied office environment provided evaluations of opportunities and practical concerns relevant to architectural integration. This setting enables exploratory observations of environmental responsiveness (heat/light dynamics, geometry specific thermal behaviour), early user perception, and indications of long-term performance. Although work in progress, timber coating study further extends RQ3 by showing into how the hydrogel might engage with architectural restoration, suggesting alternative strategies for surface repair, layering, and decorative implementation on timber substrates. Taken together, these contributions demonstrate that yeast-cellulose hydrogels can be integrated into architectural applications when their material agency and fabrication strategies are incorporated into the design logic.

Collectively, the research answers the three research questions by showing how a novel biomaterial can move from biomass to formulation, micro to printable medium, transformed into architectural expression, and finally to situated contexts. The work not only establishes technical feasibility but also articulates a conceptual and methodological foundation for integrating emergent biobased materials into architectural practice.

5.2. Research Contributions

This licentiate contributes new knowledge at three interlinked levels: (i) Matter (establishing a novel yeast-cellulose hydrogel), (ii) Negotiation (robotic fabrication strategies that work with the material's agency), and (iii) Translation (demonstrating architectural applications through surface-based systems) (Figure 19).

At the level of Matter, the work contributes with a novel 3D printable hydrogel derived from underutilized biomass and demonstrates its viability at architectural scale. Therefore, the research expands the architectural material palette with a renewable alternative and clarifies how formulation choices drive behaviours relevant architectural design. A central finding is the binder/filler role yeast cell state provides: YHO functions as a binder that reduces shrinkage and increases pliability, whereas YO acts as a filler that increases stiffness and opacity. In combination with microfibrillated cellulose (main viscosifier) and additives such as glycerol and alginate (enhance mechanical properties), these variables form a set of ingredients from which multiple optimized compositions can be derived can be created. The contribution lies both in the documentation of these formulations but also in the articulation of how specific ingredients and their ratios influence the material behaviour. This positions the hydrogel as a designable material system rather than a fixed recipe, offering a foundation for future investigations. Overall, the work shows that the material functions simultaneously as substance and agent, contributing to emerging architectural discourse on material agency and biologically informed design.

At the level of Negotiation, the research positions robotic fabrication as a form of material craft, where computational intent and fabrication constraints are mediated by the hydrogel's behaviour. This is expressed through the contributed material crafting framework which links computational geometry, deposition parameters, and blend selection to the resulting form and surface qualities. Rather than offering universal rules, the framework provides a reproducible workflow which enables designers to work with emerging biomaterials whose behaviours cannot be fully predetermined but must instead be shaped through iterative interaction between digital and physical processes. More broadly, this contribution addresses a persistent fragmentation in bio-based research, where material knowledge often remains specific and difficult to transfer. Articulating the relationships between rheology, deposition logic, and design effects, the research supports fabrication as negotiation tool in which designers, robots, and materials co produce outcomes.

At the level of Translation, the research demonstrates how material and fabrication knowledge can be applied to architectural contexts, developing first macro-scale applications, tiling system and timber coating explorations. Full-scale prototypes translate biological matter from laboratory formulation into macro-scale architectural elements, validating both material performance and fabrication feasibility at architectural scale. They operate as interfaces between building, environment, and occupant, revealing how biological matter can contribute to architectural experience through its visual, tactile, and performative qualities. These applications show that yeast-cellulose materials can move beyond speculative experiments to real-world applications, contributing forms, scales, and contexts.

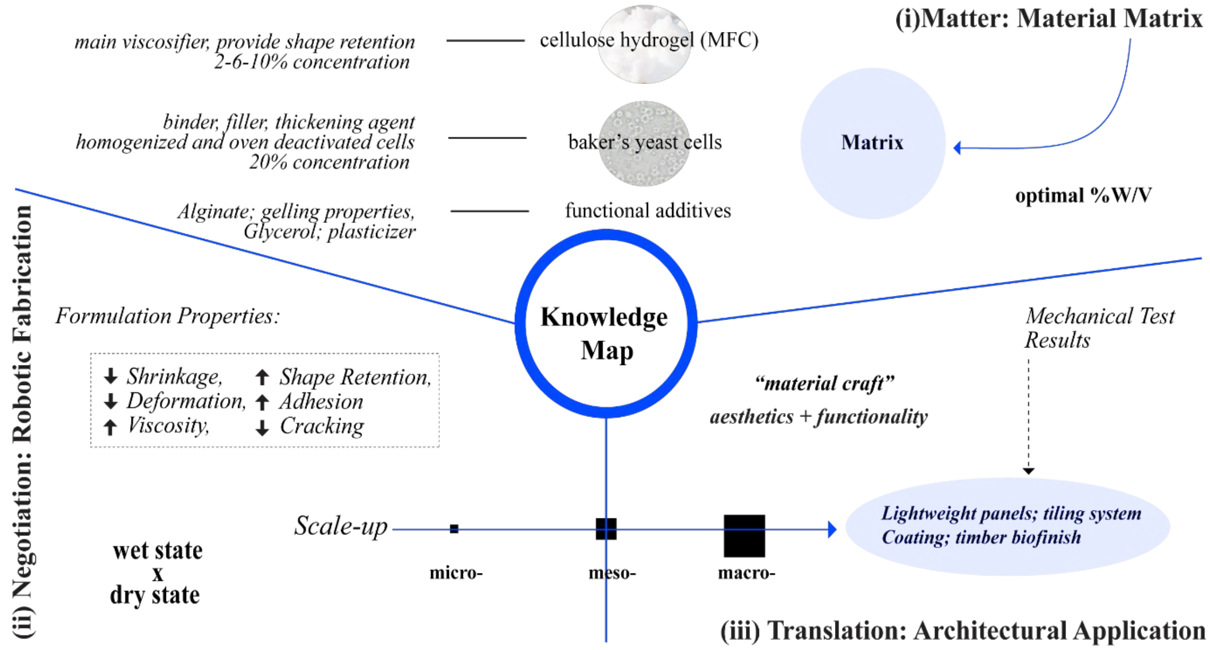


Figure 19. *Diagram synthesizing the licentiate's three interlinked contributions, mapping key contributions; development of a yeast-cellulose hydrogel (Matter), it's robotic fabrication strategies (Negotiation), and prototyping that demonstrates architectural application potential (Translation), collectively addressing the knowledge gaps identified in the field.*

Collectively, the work reframes material instability as a design resource, repositioning how temporality and heterogeneity can be encoded into computational logics and fabrication strategies. Beyond singular prototypes, the research develops transferable rule sets that enable results to be transferable across different studies and design contexts. By integrating yeast into architectural fabrication and translating its behaviour into spatial systems, the research contributes to a broader transition toward resource-efficient and circular architectural practices.

The thesis also expands the architect's role within biomaterial research. Here, the architect acts as a translational integrator who:

i. transforms formulation behaviours into design rules and application typologies
ii. coordinates feedback between material science, computational design, and robotic fabrication
iii. curates public encounters that generate perceptual and environmental evidence necessary for real-world adoption

In this way, the licentiate advances from artefacts toward shared method, providing a foundation for future development of the novel material, its standardization and scaling.

5.3. Future Research

The applications presented in this thesis suggest a promising direction for sustainable renovation practices and decorative material interfaces although they remain in an exploratory state as a foundation which future explorations may be built upon. Next steps to further advance the yeast-cellulose hydrogel include material performance, environmental aging, user perception studies, forming a comprehensive understanding in the realization of this biomaterial.

One important concern within this research is how the mechanical properties and environmental responsiveness of the biomaterial influence its architectural applicability. Stability and durability must be considered in relation to how the material performs, transforms, and is experienced within a spatial context. The response of the yeast-cellulose hydrogel to environmental conditions such as UV exposure, temperature variation, and humidity cycles affects both its visual qualities and physical form, raising questions about how these changes can be incorporated into design. From this perspective, discolouration, deformation, surface softening, swelling, or shrinkage can inform design decisions, indicating where and how the material can be applied. Further revealing how the material evolves over time and how this temporality can be aligned with architectural intent. Integrating the material response into decision-making allows architectural elements to be conceived as systems that evolve in relation to their environmental context.

The hydrogel's potential for restorative applications as coating material on timber surfaces represents an opportunity within renovation and heritage conservation, providing tactile and visual improvement without demolition or replacement of existing elements. Future work should then investigate adhesion performance, moisture-temperature cycles, and wettability of surfaces between the hydrogel and different wood species. Such investigations would open pathways for embedding hydrogel into practical renovation workflows. Moreover, robotic crafting strategies, similar to those developed in Paper B, can be adapted to surface interventions that respond directly to the conditions of decayed timber. Crafted geometries then become both a technical and artistic tool: variations in toolpath density, directionality, and thickness can mediate drying behaviour, modulate surface relief, and generate expressive interventions that merge renovation, care, and architectural expression.

Another direction is the study of user perception, particularly in relation to perception driven material development that considers for the sensory and experiential impact of biomaterials. Through interviews, qualitative analysis can be conducted to identify recurring themes related to touch, texture, smell, and colour, along with associated emotions, impressions, and expectations. These findings can guide the refinement of material and fabrication strategies by connecting material performance and design strategies with perceptual, experiential, and cultural dimensions of use. This approach could help clarify how such materials are interpreted and evaluated, revealing perceptual factors that influence their acceptance and integration into architectural applications.

5.4. Conclusion

The findings of this research position the yeast-cellulose hydrogel within a broader transformation of architectural thinking, where materials are active agents in the formation of architectural expression. The research shows that architectural form continues to develop after fabrication through drying, shrinkage, deformation, and environmental response, challenging the assumption that form is completed at the moment of robotic deposition. Instead, design becomes a co-authored process in which material tendencies participate in shaping the outcome.

(1) The transformative behaviour of the hydrogel demonstrates the temporal dimension of architectural matter, underlining how material properties unfold, deform, stabilize, or shift over time. This shift contributes to ongoing disciplinary discussions surrounding material agency and computation, where architectural form emerges through interactions among biological behaviour, environmental conditions, and fabrication parameters. Variability in matter, is often treated as a technical problem, here it becomes a source of aesthetic and spatial differentiation, revealing alternative modes of architectural authorship guiding material expression. The resulting architectural authorship is defined by guided material expression, where pattern, thickness, moisture content, and drying conditions generate subtle yet meaningful variations in surface relief, texture, and form. Care in this context is not limited to technical maintenance; it aligns with architectural discourses on care and reflects on the role of the architect who should attend to material needs, design choices, ecological implications and material lifecycles.

(2) The experimental nature of the material and fabrication process introduced limitations that define both the current scope of applicability and the challenges ahead. While the hydrogel demonstrated suitable performance for interior applications, its long-term behaviour under fluctuating humidity, temperature variation, UV exposure, and microbial colonization remains uncertain. These unresolved questions restrict its suitability for exterior contexts. Such limitations challenge architectural expectations of permanence, invariance, and material stability. Where projects demand temporal expressiveness, reversibility, or biodegradability, these traits may be desirable rather than problematic. Where durability is required, they represent constraints to be addressed. Moreover, environmentally responsive transformations in form of bio-based materials challenge the expectation that architectural materials must remain dimensionally and materially fixed over time. Instead, they introduce the possibility that change, aging, and decay may become intentional aspects of architectural design. The inherent variability of biological materials further complicates replication and standardization. This highlights a conceptual shift: rather than seeking absolute control over material outcomes, architectural research should recognize that complete standardization may never be fully attainable, focusing on advancing strategies to work with uncertainty and transformation over time as design resources. Which challenges should be solved, and which can be embraced?

(3) The findings indicate potential for applying the yeast-cellulose hydrogel in renovation, adaptive reuse, and cultural heritage restoration; where lightweight, non-invasive, and reversible materials are prioritized. In these contexts, the hydrogel can function as a surface intervention that enhance spatial character, modulates performance, or introduces new textures and patterns, without affecting structural integrity. This aligns with circular strategies that prioritize renewable, reversible, and replaceable building components. Robotic fabrication further allows for precise adaptation to irregular or aging surfaces, enabling applications for repair and aesthetic transformation, allowing in-situ deployment. The hydrogel's biodegradable nature makes it promising for temporary additions that can be applied and removed without damaging underlying layers. Such applications support conservation practices that view buildings as temporal composites, assembled layers and transformed over time. Furthermore, the low environmental impact offers an alternative to synthetic coating and cladding systems, which often rely on fossil-based resources.

(4) A fundamental aspect of this research is its multidisciplinary character. The development of a novel biomaterial requires expertise from architecture (digital fabrication, aesthetic properties, application typology), material science (mechanical behaviour), and microbiology (yeast characteristic, biomass transformation). The work demonstrates that no single discipline can fully advance the research on its own, instead, innovation emerges through collaborative, iterative exchanges where experiments, prototypes, and computational models are co-developed across fields. This multidisciplinary integration is not simply a method; it is crucial to the emergence of materially aware, ecologically embedded architectural practice. Bringing together scientific knowledge, computational methods, and design sensibilities, the research exemplifies how architecture can operate as a mediating discipline that translates biological processes into architectural materiality.

Overall, this licentiate thesis contributes to the broader disciplinary transition toward resource efficient and circular architecture practices, particularly within renovation and transformation of the existing built environment, where material behaviour, environmental impact, and architectural expression are interconnected (Figure 20). The yeast-cellulose hydrogel challenges assumptions of permanence and precision, present an architectural materiality grounded in temporality.

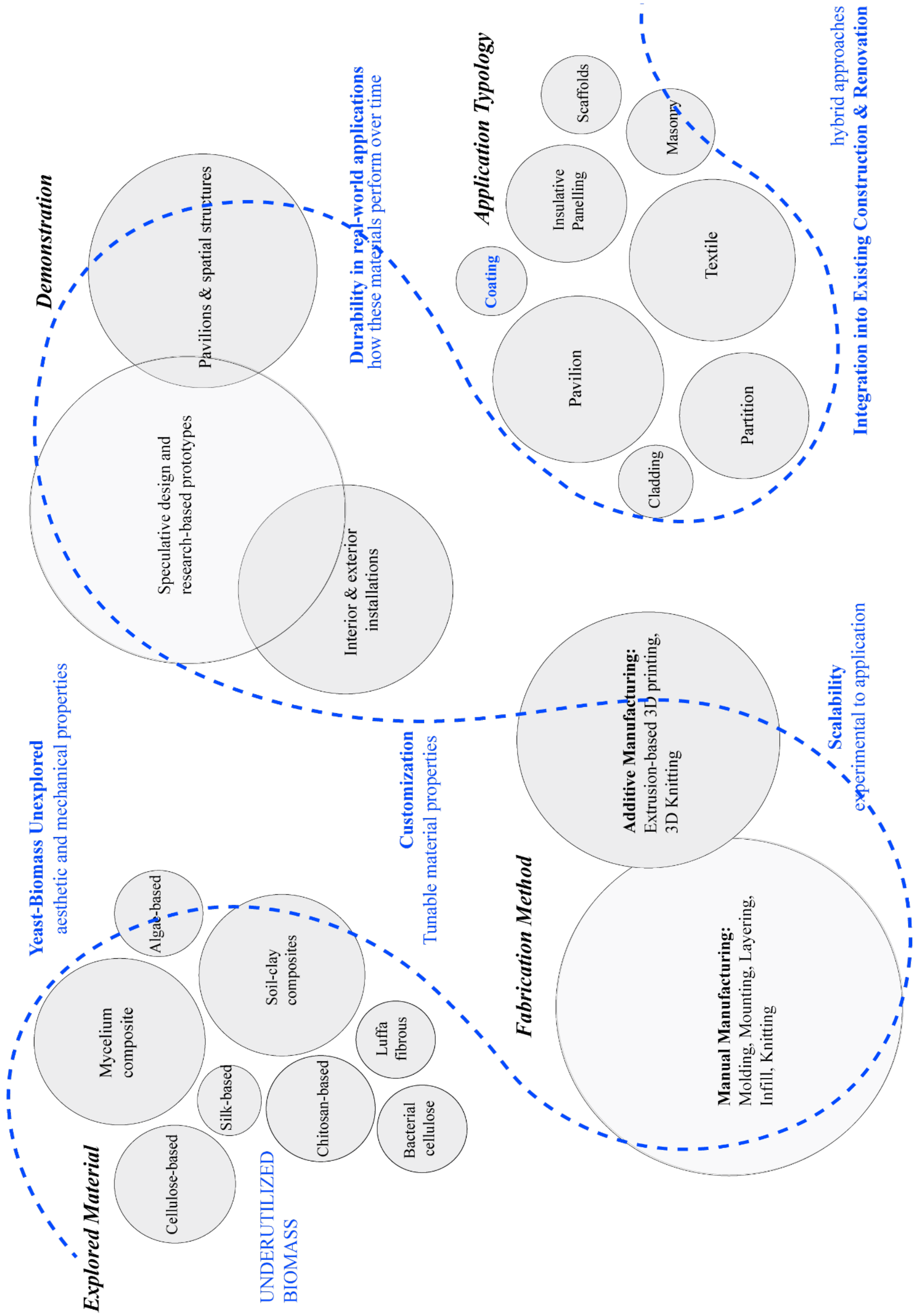


Figure 20. *Diagram visualizing thematic clusters within the literature mapping of experimental and academic biobased material studies, categorizing explored material types, fabrication methods, demonstration scales, and application typologies into an overview of the current state of knowledge and remaining gaps in the field. Elements highlighted in blue represent the research contributions of this thesis.*

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Preliminary User Perception Study

Semi-Structured Interview: Multi-Sensory Perception of a Biobased Architectural Material

Method: Semi structured interviews were conducted to gather qualitative data on participants' subjective impressions, expectations, and multi-sensory perceptions of a novel biobased material.

Aim: To investigate how participants perceive and interpret the material visually and physically, and to document their sensory, descriptive, and associative responses.

Display: Large scale 3D printed yeast-cellulose hydrogel based tiling system was presented as the primary interaction artefact

Participant Focus Group: Industry professionals

Objectives:

- Participants verbally described selected prototypes using free descriptions, keywords, and associations.
- Participants compared the biobased prototypes with conventional materials, products, or systems.
- Participant descriptions were coded using verbal prompts to sensory, emotional, associative, and perceptual observations (e.g., physical properties; visual and tactile qualities; olfactory impressions; perceptive meanings such as "modern" or "safe"; associations such as "reminds me of…"; emotional reactions).
- Semantic differential scales (e.g., "Beautiful vs Ugly," scored from −2 to +2) were used to capture evaluative perceptions.
- Demographic information was collected (age, education, environmental concern, etc.).
- Participants reflected on both experience-based and technical attributes, including texture, origin, warmth, and other descriptive qualities.

Participant Information Sheet

Below is the information related to the interviews.

Purpose of the Research: We are interested in learning how people perceive a new material through sensory experiences. To ensure the objectivity of answers, detailed information regarding the research and material itself are minimized.

Research Organization: Chalmers University of Technology, Department of Architecture and Civil Engineering

Interviewer: Yagmur Bektas, PhD

What to Expect: You will be provided with researched material samples. First, we will ask for your visual impressions. Then, for you to handle the material and tell us about the physical experience.

Interview Structure: Questions are semi-structured, to bring out your personal impressions, feelings, and associations towards the material. There are no right or wrong answers.

Interview Time: The interview will take approximately 30 minutes

Demographic Information: The interview required information on demographics of interviewees, as age, gender, nationality, educational background, professional expertise and current field of work. The demographic information is important to analyze differences in participants answers and how they experience a material as human perception relates to socio-cultural-economic background.

Recording and Anonymity: The interviews will be recorded solely for research purposes, to analyze and transcribe the conversation, not to be used or shared with a third party. The research data will only be accessible to the research team. Personal information as name of participant or the names of any related companies, will be anonymized for any publication, data-analysis or data-sharing of this research.

Interview Template:

Section 1: Introduction & Ethics (Consent and Recording)
Informative opening

Section 2: Background (Demographics)
Name? (will be anonymized) Age? Gender? Nationality? Educational background? Professional expertise? Current role?

Section 3: First Impressions-Visual Response
Material will be provided during the interview; participant will first take visual look before engaging in other sensory experiences

What is your first reaction upon seeing this material?
Can you describe its appearance using 3 keywords?
What does it remind you of, if anything? From objects, places, or even maybe other materials that you have seen before?

Section 4: Multi-Sensory Perception (tactile, visual, smell, encourage or discourage interaction, positive or negative quality)
Participants will be asked to physical encounter; touch, hold, bend, or interact with the material

How does the material feel in your hands? Can you describe its texture, weight, temperature?
What sensations do you associate with this touch?
Has your descriptive keywords differed after interacting physically with the material?
Would you say the material is pleasant or unpleasant to touch and why?
What other characteristics have you recognized in this material?

Section 5: Emotional Response
What kind of emotions does this material evoke for you? kind of mood or atmosphere?
Can you imagine how your body might respond if you were surrounded by this material?
Can you recall any associations it brings up?

Section 6: Concerns and Barriers (Concerns? Bias? Discomfort? Visual, mechanical, cultural?)
Would you feel comfortable using or being close to this material on a daily basis?
Is there anything about the visual or physical experience you had off-putting or cause hesitation?
Section 7: Application Scenarios (imagination on how to integrate it?)

What kind of qualities do you relate the material to?

Can you imagine using or being surrounded by this material in daily life? Why or why not?

What kinds of products or environments do you think this material is (or isn't) suitable for?

Does it feel high-tech, organic, luxurious, cheap, innovative? Why?

Section 8: Reflection and Closing

Overall, how would you summarize your experience of this material in one or two words?

Is there anything surprising or unexpected about your interaction with the material?

Do you have any final thoughts or suggestions for designers considering using this material?

Can you define from below spectrums where you situate your sensory experience towards the material.

Ugly ——medium—— Beautiful
Cold —— medium —— Warm
Safe —— medium —— Unsafe
Natural —— medium —— Artificial

Table 1. *Summary of semi-structured interview responses organized by section, presenting participant demographics, visual, tactile and olfactory impressions, emotional reactions, perceived application scenarios, concerns, and ratings to provide an overview of user perceptions of the biobased material.*

	Participant #1	***Participant #2***	***Participant #3***
Background	Age: 37 Profession: Sales	Age: 29 Profession: Communications, Media	Age: 51 Profession: Mechanical engineering
Visual Impressions	association to candy	association to candy association to clay association to acoustic panels	association to bakery association to paste
Tactile Impressions	hard flexible	organic flexible	fragile less elastic than assumed
Olfactory Impressions	food-like concern in architecture	food-like concern in architecture	food-like concern in architecture
Emotional Response	curious, playful	calm, acoustic-like	neutral
Concerns	smell, imperfections	aesthetic precision, fragility	strength, durability, smell
Application Scenarios	feature walls, playful surfaces	acoustic panels, ceilings	decorative only
Semantic Scales	Beautiful; Warm; Safe; Natural	Beautiful; Warm; Medium; Natural	Medium; Warm; Medium; Natural

Papers A

Novel 3D Printable Yeast-Based Materials for Architectural Applications

Bektas, Y., Zboinska, M. A., Geijer, C., Nypelö, T., & Hefny, Z.

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RESEARCH ARTICLE

Novel 3D printable yeast-based materials for architectural applications

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Bio-based materials;
Biofabricated yeast hydrogels;
Cellulose composites;
Architectural design;
Sustainable building materials;
Robotic 3D printing

Abstract Conventional building materials rely on non-renewable ingredients, contributing to global resource depletion. To address this challenge, bio-based alternatives from renewable nature-based biomasses are under development. This study presents one such alternative—a novel 3D-printable biomaterial from baker's yeast. Optimized formulations contain 3% (w/v) yeast solution (intact or homogenized cells), 13% (w/v) aqueous microfibrillated cellulose solution (10% microfibril concentration), 1% (w/v) sodium alginate, 5% (w/v) glycerol, and water. Research methods included sequential formulation optimization, 3D printing, characterization of microscopic, rheological, tensile, and thermal degradation properties, and establishment of architectural attributes, encompassing shrinkage, deformation, light transmittance, color, and porosity. The material exhibited gel-like viscoelastic solid behavior ($G' > G''$) supporting shape retention post-printing. Mechanical tests showed a maximum average tensile strength of 2.7 MPa and elongation at break of 25.2%. Large 3D-printed tile prototypes (20 cm × 50 cm) demonstrated low linear shrinkage along edges (2%—10%), tunable light transmittance (5.6%—31.6%), a four-color palette (NCS 4040-Y30R, NCS 5030-Y40R, NCS 3030-Y20R, NCS 3040-Y30R), and configurable porosity (solid, perforated, hybrid). These characteristics indicate the material's application potential as 3D-printable lightweight architectural sheets for interior applications, which in the future could replace fossil-based products.

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1. Introduction

Conventional construction materials, such as bricks, steel, glass, gypsum, concrete and plastics, contribute to 30% of planetary raw material depletion and account for 33% of solid waste generation (Al-Numan, 2024). These materials are derived from non-renewable, depleting resources, such as clay, sand, minerals, metal ore, and petroleum, and are made to last for millennia (Jackson et al., 2014). However, because they are usually placed in large volumes at the landfill after demolition, they contribute to excessive volumes of global waste and may have a negative long-term effect on the natural environment, releasing harmful volatile compounds and breaking down into microplastics (Issac and Kandasubramanian, 2021).

To tackle these challenges, the circular economy model has been proposed that cycles resources within regeneration and renewal loops, supports the making of materials from waste and side stream products, and explores more sustainable ways of manufacturing materials and products (Norouzi et al., 2021). In construction, recent advances in advanced manufacturing positioned 3D printing (3DP) as one of the technologies that can support the implementation of the circular economy model by optimizing material use, minimizing waste, and promoting resource efficient production (Teixeira et al., 2023). In this trajectory, conventional cementitious materials such as Ordinary Portland Cement (OPC) and concrete (İlerisoy et al., 2025), as well as plastic-based materials, including PET and other synthetic polymers (Jaivignesh and Sofi, 2017; Yousaf et al., 2024), have been widely explored due to their strength, durability, and ease of processing. However, these materials rely on non-renewable resources (Yousaf et al., 2024) and generate solid waste streams and pollution (Ziani et al., 2023).

To overcome these limitations, 3D printable construction materials from renewable bio-based ingredients, such as abundant biomasses from side stream products of major global sectors including agriculture, forestry, and timber processing (Manrique, 2021), emerge as promising solutions. They offer independence from non-renewable resources and can safely biodegrade without harming the natural environment (Kumar and Singh, 2025). Latest research in architectural biomaterials for 3DP applications explored solutions based on natural fibers derived from bananas, coconuts, date palm, hemp, kenaf and straw, as well as earth and cob (Carcassi et al., 2024; Gomaa et al., 2021; Yousaf et al., 2025a,b). However, this prior work targeted bulky materials for structural applications while lightweight material solutions remain unexplored.

The novelty of this study is the proposal of a novel bio-based material from yeast and cellulose biomass, intended for future applications as 3D printed lightweight sheets for interior claddings. The focus on yeast and cellulose biomass arises from their exquisite abundance and scalability, which are crucial for applications in construction. Cellulose can be sustainably sourced from plant-based products and biogenic industrial by-products. The pulp industry alone produces approximately 150 million tons of cellulose pulp annually (Alén, 2018), and large volumes of cellulose microfibrils are also derived from wood waste (Li et al., 2024), which has spurred extensive research on cellulose-based building materials (Bierach et al., 2023; Bourbia et al., 2023; Choi and Yi, 2024; Mogas-Soldevila and Oxman, 2015; Panagiotidou et al., 2022; Rech et al., 2022; Wei et al., 2022; Zboinska et al., 2023). Microbial biomass comprised by yeast is also highly abundant and scalable because these microorganisms grow rapidly and can be produced on demand in large volumes. Furthermore, yeast biomass has notable environmental benefits, including a low carbon footprint, renewability, biodegradability, and ability to be grown on organic waste (Alaneme et al., 2023; Babenko et al., 2025; Dessi-Olive, 2022).

Despite these benefits of yeast biomass, it has not yet been studied for applications in building materials. Instead, the main research front on fungal materials in architecture concerns mushroom-based mycelium (Gavriilidis et al., 2024; McGaw et al., 2022; Saeidi et al., 2024). While promising, its use is limited by high proneness to contamination and molding (Ghazvinian and Gürsoy, 2022; Motamedi et al., 2023), inconsistent mechanical properties (Jones et al., 2020), slow production process (Obodaiet al., 2003), and not being directly 3D-printable, which constrains shape variability and product size (Dessi-Olive, 2022; Özlü and Nicholas, 2021).

These limitations form as strong incentive to investigate other fungal organisms, in our case baker's yeast *Saccharomyces cerevisiae*, to achieve enhanced material properties and higher design flexibility. In contrast to mycelium, baker's yeast is less prone to contamination by other microorganisms (Kłosowski et al., 2023). Yeast materials in the form of films prove to be much more homogeneous, exhibiting uniform mechanical properties (Delgado et al., 2016, 2018; Peltzer et al., 2018) due to yeast being unicellular and not filamentous. Yeasts are also much faster than mycelium in forming large volumes of biomass, displaying exponential growth and a doubling time of 90 min. Just a few milligrams of starter culture can yield several tons of biomass within a week in a yeast factory setting (Bergman, 2001; de Oliveira and de Oliveira Junior, 2022). Additionally, yeast can be cultivated on carbohydrate-rich feedstocks found in low-grade side streams of agriculture, forestry, and papermaking (Lisičar et al., 2017). Finally, large volumes of yeast biomass arise as underutilized by-product of alcoholic beverage brewing (de Oliveira and de Oliveira Junior, 2022). Leveraging these properties of yeast in new building materials offers a promising pathway toward circular microbial material solutions that can complement the current portfolio of bio-based architectural products.

So far, the use of yeast as component in materials has only been explored at the miniature scale of 3D-printed engineered living materials (ELMs) for applications in biocatalysis, bioremediation, and drug delivery (Etter et al., 2023; Rivera-Tarazona et al., 2022; Sandak, 2023; Qian et al., 2019). Because these applications remain confined to biomedical and pharmaceutical contexts and are verified only at miniature scales, the key novelty of the presented work is to establish the suitability of yeast as a building block in 3D printable materials for future architectural applications, displayed on a larger scale.

The research objectives were as follows:

- Material development: To formulate and optimize yeast-based composite materials for extrusion-based 3D printing, systematically varying yeast cell state (intact vs. homogenized) and ratios of yeast, microfibrillated cellulose (MFC), alginate, and glycerol.
- Multi-scale material property characterization: To characterize the developed material formulations' microstructural features, rheological behavior, mechanical performance, and macro-scale architectural attributes encompassing shape fidelity, light transmittance, color, surface patterning and texturing.
- Architectural potential demonstration: To display the material's aesthetic qualities and future potential for application on an architectural scale using robotic 3D printing.

2. Materials and methods

2.1. Research process

The experimental workflow designed to address the research objectives comprised four sequential phases (Fig. 1), featuring gradual refinement of yeast material formulations and their 3D printing strategies. The following subsections will highlight in detail the materials and methods applied in each phase. Section 3 presents the results of each phase.

2.2. Materials

The yeast material formulation comprised anhydrous granular baker's yeast (*Saccharomyces cerevisiae*) from Jästbolaget, Sweden, glycerol ($C_3H_8O_3$, $\geq$99.0%) from Fisher Scientific, alginic acid sodium salt from Sigma-Aldrich, and microfibrillated cellulose (MFC, 2% and 10%) from Borregaard, Norway (Fig. 2). This component selection builds on authors' prior research on 3D-printable hydrogels formulations from nanocellulose, MFC and sodium alginate for architectural applications (Rudin et al., 2022; Zboinska et al., 2023), demonstrating that these hydrogels, when ambient dried, exhibit substantial deformation and shrinkage (up to 31%). The present study hypothesized that the inclusion of yeast and glycerol would enhance the physical properties of the MFC-alginate material matrix upon drying, based on promising prior work reporting favorable physical and mechanical properties of yeast-glycerol films (Delgado et al., 2018). We hypothesized that the yeast cells could introduce binding and filling functions within the material, while glycerol would enhance flexion and form stability.

2.3. Formulation preparation, drying and characterization

The material formulations were prepared in ambient room conditions (temperature 21.8 ± 0.5 °C and humidity 30.5% ± 4.4%). Baker's yeast preparation treatments followed procedures reported by Delgado et al. (2016) and Delgado et al. (2018), with some modifications. Yeast was prepared in two forms, oven deactivated (YO), and homogenized and oven deactivated (YHO). Each was mixed with water to rehydrate the yeast and form dispersions in two concentrations, 10 and 20 wt percentage (wt%), ensuring a consistent concentration of yeast cells in the formulations. The aim of oven deactivation at 80 °C for 30 min was to kill the microorganisms. Homogenization aimed to break open the yeast cells, releasing their internal contents, including proteins, nucleic acids, carbohydrates, and lipids. Homogenization was carried out using the GEA PandaPLUS Lab Homogenizer 2000, under a pressure of 150 MPa, following protocols described in Marín-Sánchez et al. (2024).

The remaining material components, i.e., MFC, glycerol, and alginate, were mixed following an adjusted combination of procedures published in Delgado et al. (2016, 2018), and Zboinska et al. (2023). The components were weighed using a precision balance and added to the yeast dispersions in ratios established for specific material formulations. pH was not controlled in the different formulations. For material batches not exceeding 60 mL, component mixing was done manually for at least 10 rounds using two syringes connected with a Luer fitting. For batches larger than 60 mL, the components were mixed mechanically at 18,000 rpm using a Bosch Ergo Mixx stirrer in three rounds, 30 s each, to assure homogeneity of the mixes.

Homogenization effects were initially examined using a Zeiss Primostar 3 microscope at 100× magnification. To further validate the efficiency of homogenization and oven deactivation, cell viability assay, biochemical analyses of DNA and protein release were additionally performed, following the protocols specified in Appendix A, based on procedures established in literature (Alperovich et al., 2023; Feddersen et al., 2012; Kwolek-Mirek and Zadrag-Tecza, 2014).

To characterize the microstructure of homogenized and oven-deactivated yeast formulations and determine how each interacts with the matrix in terms of cellular integration, bond formation, and structural differences, a JEOL JSM-7800F Prime Field Emission Scanning Electron Microscope (FE-SEM) was used. Films measuring 1 cm × 1 cm were cut, coated with a thin layer of gold and mounted on aluminum stubs. Imaging was performed in standard observation mode with a probe current of 6, an accelerating voltage of 5.0 kV, a working distance (WD) of 10 mm and a magnification of 900×. The LED detector was used to capture secondary electron signals, and images were acquired at a scale of 10 μm. Fine scan settings were applied

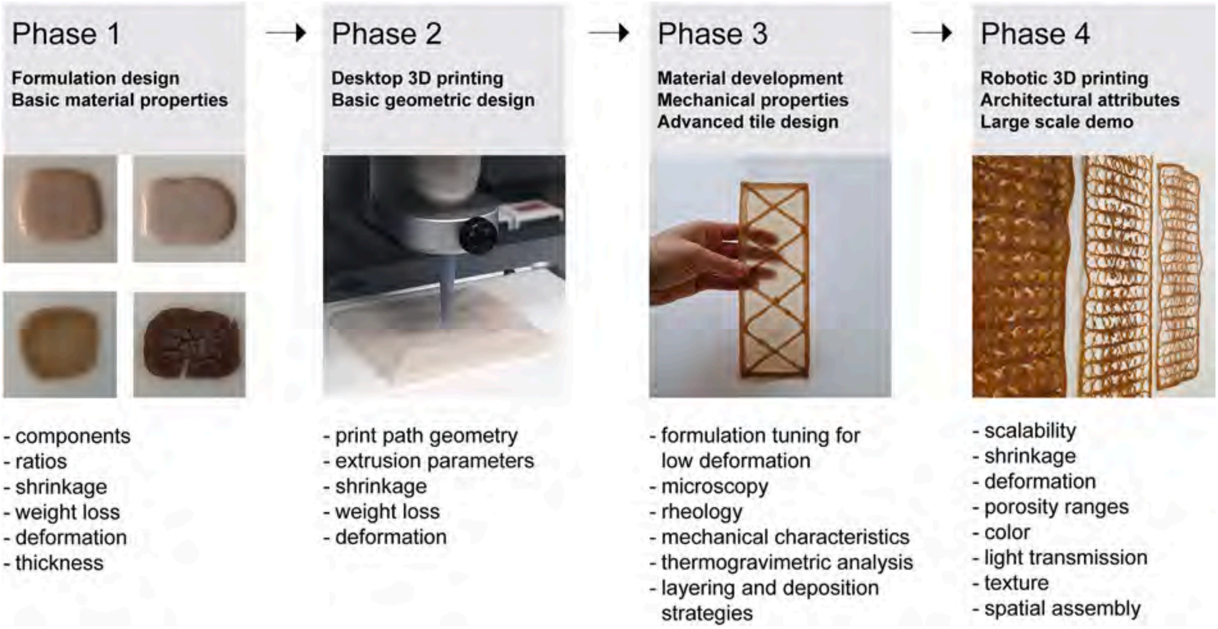


Fig. 1 Development workflow for yeast-based materials applied in robotic 3D printing of architectural wall tiles.

to ensure high-resolution imaging of the microstructural features.

2.4. Extrusion and 3D printing

The materials in phase 1 were manually extruded into square constructs measuring 2 cm × 2 cm using a syringe with a tapered 0.86 mm dispensing tip. For extrusion by hand, layer height and pressure were not controlled. The constructs in phase 2, measuring 5 cm × 5 cm and 7 cm × 7 cm, were 3D printed using the RegenHU 3D Discovery bioprinter using 1.55 mm and 2 mm dispensing tips, at air pressures ranging 0.3–0.6 bar. The height for the first layer was set to 2 mm, with an incremental increase of 1 mm for subsequent layers in multi-layered constructs to ensure the merging of respective layers and achieve enhanced bonding. The constructs in phases 3 and 4 were manufactured using a custom, in-house built pressure-based 3D printing system, commissioned on an industrial robot KUKA Agilus KR10. The mechanical assembly of this system, as well as the 3D print toolpath generation procedures for the RegenHU bioprinter and the robotic 3D printer, are described elsewhere (Zboinska et al., 2023). The pressure ranges applied in robotic 3D printing were 0.2–1.0 bar, the dispensing tip diameters used were 1.55 mm and 2.50 mm. The height for the first layer was set to 3 mm, with an incremental increase of 1 mm for subsequent layers for enhanced merging of layers.

2.5. Shrinkage and deformation measurements

For surface shrinkage estimation, photographs of each specimen were taken in wet and dry state using an iPhone 8 Plus with 12 MP, f/1.5–2.4, 26 mm, 1/2.55 in, 1.4 μm pixel

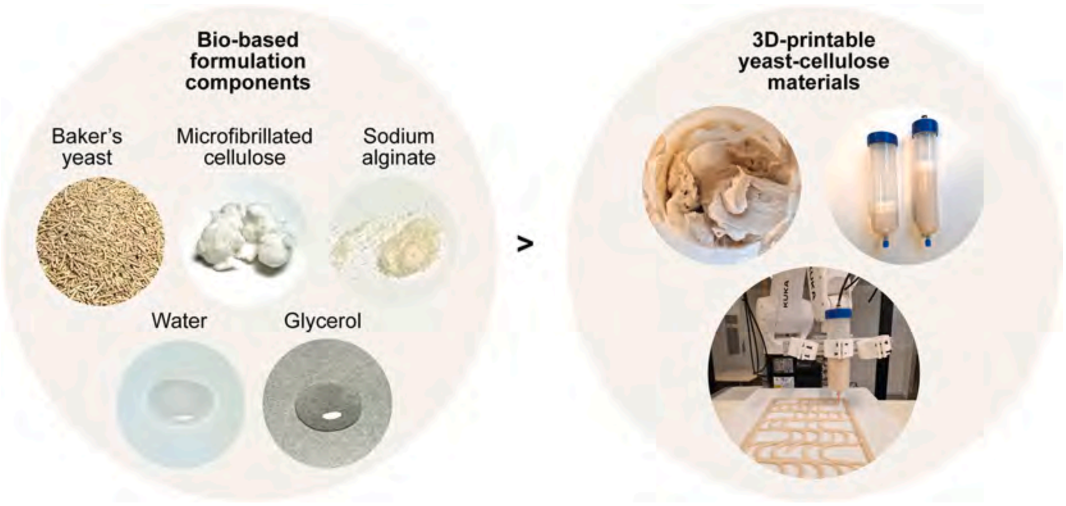


Fig. 2 Yeast material composition.

size camera. The photographs were imported to Adobe Illustrator software v. 29.7.1 for rescaling. Using the image trace function, boundaries of the specimens were extracted from the photographs and converted into vector paths. The vector paths were then imported to Rhinoceros 3D software, version 8, for surface area calculation. Based on this data, surface area shrinkage percentage (S_a) was calculated to estimate the reduction in surface area of the constructs after drying in ambient room conditions at a temperature 21.8 ± 0.5 °C and humidity 30.5% ± 4.4%, for 2–3 days (for constructs measuring 2 cm × 2 cm, 5 cm × 5 cm and 7 cm × 7 cm), 3–5 days (for 7 cm × 20 cm constructs), and 7–10.5 days (for 20 cm × 50 cm constructs).

The shrinkage calculation was based on the initial and final surface areas, using Eq. (1):

$$S_a\,(\%) = \frac{(A_i - A_f)}{A_i} \times 100, \tag{1}$$

where A_i is the initial surface area of the wet construct and A_f is the final surface area of the dry construct.

For linear shrinkage (S_l) calculations, the same method of digital measurement of the specimens' total length and width was applied. The calculation was based on the initial and final length/width dimensions, using Eq. (2):

$$S_l\,(\%) = \frac{(D_i - D_f)}{D_i} \times 100, \tag{2}$$

where D_i is the initial length/width of the wet construct and D_f is the final length/width of the dry construct.

To further characterize material changes after ambient drying, weight loss between the wet and dry state was estimated for each construct. The weight in wet state was calculated as a product of the deposition path length calculated based on the parametric model of path geometry generated in Rhinoceros 3D and its visual programming environment Grasshopper (version 1.0.0007), nozzle diameter, layer height and material density, which was assumed to be equal to the density of water (1.0 g/cm^3) due to the aqueous nature of the extruded hydrogel. The dry material weight was determined by weighing each construct on a high-precision balance. The weight loss percentage (WL) was calculated using Eq. (3):

$$WL\,(\%) = \frac{(W_w - W_d)}{W_w} \times 100, \tag{3}$$

where W_w is the weight of the wet construct and W_d is the weight of the dry construct.

For 3D deformation assessment, local height differences between the physical construct and a flat planar surface were calculated following a procedure in a digital modeling environment Rhinoceros 3D. Each construct was digitally captured as a 3D mesh using the photogrammetry software RealityScan (version 2.0.1, Epic Games, Inc.) and imported into Rhinoceros 3D for geometric evaluation. Mesh vertices were extracted using the *ExtractPt* command, and a best-fit reference plane was generated using the *PlaneThroughPt* command. Perpendicular distance from each mesh vertex to the reference plane was computed using the *PointDeviation* command, yielding values for mean and median distance, standard deviation distance, and minimum and maximum distance from the closest and farthest point. This allowed for a quantified characterization of construct planarity and distortion.

Outer edge deviation and linear consistency were assessed using the same procedure performed for outline curves of the dry-state mesh. The curves were sampled into discrete points using the *ExtractPt* command and their displacement in relation to a reference plane's outline was calculated using the *PointDeviation* command and reported as median, mean, standard deviation, minimum and maximum distances. These metrics provided a measure of edge linearity and deformation magnitude.

2.6. Sample thickness measurements

The thickness of dried 20 cm × 50 cm architectural tiles was measured using a digital micrometer (Limit MDA 25, Sweden) with a measurement range of 0–25 mm, resolution of 0.001 mm and accuracy of ±0.002 mm. For each tile, ten measurements were taken at different locations to account for variations in surface thickness.

2.7. Mechanical testing

Tensile tests were conducted with an Instron Universal Testing Machine, model 5565A (Instron, Norwood, MA, USA) following the ASTM standard D882–02 for testing thin plastic sheeting. The tests were performed on ISO 527–2/5A dumbbell specimens, ten per each of the two tested material formulations, prepared using a manual cutting press (EP-08, Elastocon AB, Sweden) with standardized dies to ensure parallel edges and uniform geometry. The dry specimens were elongated at a speed of 25 mm/min. Thereafter, the load applied to the specimens and the corresponding extension until failure were registered to calculate the resultant stress and strain values.

2.8. Rheology testing

Rheological tests were conducted using the Discovery DHR3 rheometer (TA Instruments, UK) with 40 mm stainless steel Peltier plate at 25 °C. An oscillatory time sweep test was performed at a fixed strain amplitude of 0.3% and frequency of 1 Hz for 150 s, to assess time-dependent viscoelastic behavior. Following, a flow sweep test was carried out to evaluate shear-dependent viscosity with the shear rate ranging from 0.01 to 100 s^{-1}.

2.9. Thermogravimetric analysis (TGA)

Thermogravimetric analysis was performed using a Mettler Toledo TGA/DSC 3+ instrument to characterize thermal degradation behavior and assess thermal stability of the yeast-based materials, recording mass loss as the temperature increased. The formulations were tested in triplicate, with 8 mg samples placed in a platinum crucible and heated in a temperature range 20–800 °C, with an increase of 10 °C/min, under a nitrogen atmosphere.

2.10. Color and translucency evaluation

To determine the color of the different formulations, the Natural Color System (NCS) based on human perception of colors was used as a reference. 3D printed constructs were examined one by one in a light room illuminated with consistent artificial light. Each construct was placed on a white background to avoid color interference. Then, the NCS color sampler was placed next to the construct to select a matching color.

To determine the translucency of the 3D printed constructs made from different material formulations, light transmittance percentage was calculated based on measurements with an Uni-T UT383 digital light meter. 3D printed constructs were examined one by one in a light room illuminated with a consistent artificial light source to minimize ambient light interference. The baseline light intensity from the source without the construct was first registered, followed by registration of transmitted light intensity measured when the construct was placed between the light source and the light meter device. The final light transmittance was calculated using Eq. (4):

$$T = \left(\frac{I_t}{I_0}\right) \times 100, \tag{4}$$

where T is the light transmittance percentage (%), I_0 is the baseline light intensity (lux) and I_t is the transmitted light intensity (lux).

3. Results and discussions

3.1. Formulation design and basic property evaluation

Baker's yeast in two states was included in the material formulations: intact oven deactivated cells (YO) and ruptured (homogenized) oven deactivated cells (YHO). Intact cells were evaluated for their ability to act as a filler in the material matrix, while ruptured cells were assessed toward a binder functionality. To determine the minimum number of homogenization rounds required to achieve sufficient cell disruption and visibly alter the ratio of intact to ruptured cells, the state of yeast cells was analyzed following homogenization. Comparative evaluations were conducted after two, five, and eight rounds of homogenization, relying on both qualitative visual observations of microscopy images and quantitative measurements, including cell viability assays and DNA and protein release measurements, providing information on the molecular interactions within the material matrix. The results are presented in Appendix A. Together with microscope images (Fig. 3), they led to the conclusion that five homogenization rounds are sufficient to ensure effective cell disruption.

Next, three groups of material formulations were assembled and assessed (Table 1). The formulations in Group 1 were created to investigate the impact of MFC concentration on the material properties in relation to yeast cell state (YO and YHO). The MFC concentrations were based on original material formulations supplied by the manufacturer, i.e., aqueous 2% and 10% microfibril dispersions. From our prior research (Zboinska, 2025), we know that 2% MFC yields flexible constructs and 10% results in stiff ones. Therefore, these default concentrations were selected as representative low and high endpoints for the subsequent experiments. The microfibril concentrations were altered in the formulations by varying the percentage of these two aqueous dispersions in the tested material formulations.

The formulations in Group 2 were made to investigate the impact of yeast concentration (10% and 20%) and cell state (YO and YHO) on the material properties with alginate also added to the formulations. Group 3 was created to determine the ratios and impact of additives, i.e., glycerol and alginate, in relation to yeast cell state (YO and YHO). The amount of sodium alginate in Group 3 was kept constant and within ranges suggested in prior literature (Malik et al., 2020; Markstedt et al., 2015; Piras and Smith, 2020; Stolz and Mülhaupt, 2020; Zboinska et al., 2023). For glycerol, the quantity in this formulation group was varied to evaluate its impact in more detail because its recommended dosages in the literature vary greatly and depend on the material composition. For instance, in chitosan bioinks, the recommended range was 0.5–0.7 wt% (Cui et al., 2024), whereas in gelatin bioinks, the value was set at 10% v/v (Shin and Kang, 2018). For hydrogels featuring silk proteins, the ranges were 20–35 wt% (Mogas-Soldevila et al., 2021), whereas for architectural slurries featuring large cellulose fibers, the dosage was 8 wt% (Rech et al., 2022). For biomaterials containing yeast, a glycerol concentration ranging from 0 to 30 wt% was established, with 15 wt% identified as optimal for enhancing mechanical properties (Delgado et al., 2018; Peltzer et al., 2018). However, these studies were limited to formulations for cast films and did not address 3D-printable materials. Therefore, we investigated dosages between 3% and 5% w/v, which are close yet below the lowest dosages reported for yeast films. The reason for lowering the quantity was to achieve similar properties of pliability as reported for non-printed films while ensuring shape fidelity during 3D printing, which would be compromised if higher doses of glycerol were used.

To compare the properties of material formulations from all groups, each formulation was manually extruded into a 2 cm × 2 cm square construct and left to dry under ambient room conditions. Each construct was registered in digital photographs in wet and dry states. The constructs were compared using five metrics: surface area shrinkage, weight loss, deformation, and thickness (Table 2).

Group 1 formulations with higher MFC (YO20-MFC10 and YHO20-MFC10) showed lower weight loss and deformation, and larger thicknesses in dry state compared with those having less MFC (YO20-MFC2 and YHO20-MFC2). This is consistent with previous findings on bioinks containing cellulose nanofibrils, which demonstrated that these fibrils play a crucial role in enhancing the shape fidelity of 3D printed structures. They contribute to high viscosity and shear thinning behavior, ensuring that the ink solidifies after extrusion and does not flow (Piras and Smith, 2020; Stolz and Mülhaupt, 2020; Zboinska et al., 2023).

For Group 2 formulations, the higher yeast concentration (20%) in formulations YO20-MFC10-ALG and YHO20-MFC10-ALG led to thicker constructs and lower weight loss. However, for surface area shrinkage and deformation, it was difficult to establish clear differences between the formulations featuring higher and lower yeast concentrations. Regarding the yeast cell state effects, it was observed that formulations based on homogenized and oven deactivated yeast (YHO20-MFC10-ALG and YHO10-

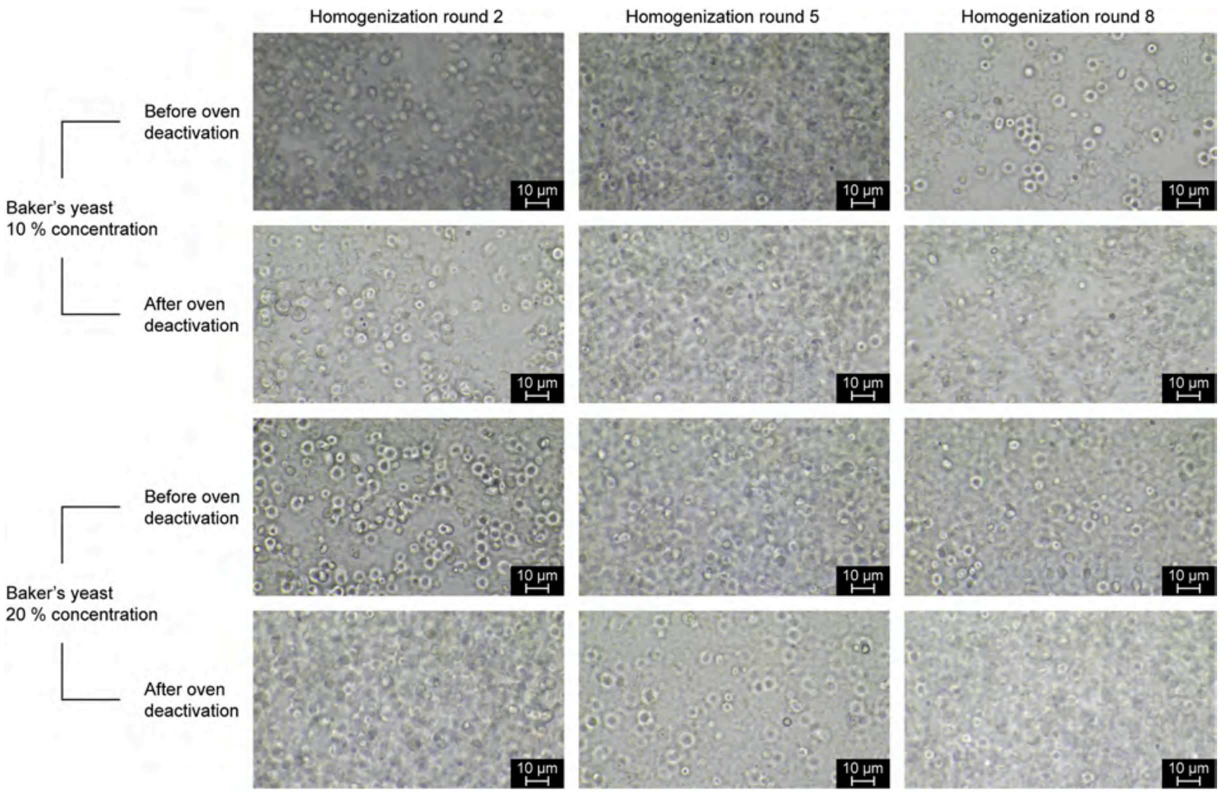


Fig. 3 Microscope images showing baker's yeast cell disruption after two, five and eight homogenization rounds at 10% and 20% concentrations.

MFC10-ALG) tended to yield lower surface area shrinkage and deformation compared with the oven deactivated yeast formulations (YO20-MFC10-ALG and YO10-MFC10-ALG). This is likely caused by the presence of intracellular components of yeast, including proteins, carbohydrates, and lipids (Delgado et al., 2016, 2018), in the material matrix of YHO formulations (Figure A.2, Appendix A). These components likely enter molecular interactions with other ingredients,

Table 1 Yeast-based material formulations from research phase 1.

Material formulation		Material formulation ingredients				
		Yeast solution (% w/v)	MFC solution[a] (% w/v)	Sodium alginate (% w/v)	Glycerol (% w/v)	Water (% w/v)
Group 1	YO20-MFC10	20	10	—	—	61
	YHO20-MFC10	20	10	—	—	61
	YO20-MFC2	20	2	—	—	69
	YHO20-MFC2	20	2	—	—	69
Group 2	YO20-MFC10-ALG	20	10	6	—	64
	YO10-MFC10-ALG	10	10	6	—	74
	YHO20-MFC10-ALG	20	10	6	—	64
	YHO10-MFC10-ALG	10	10	6	—	74
Group 3	YO20-MFC10-ALG-GLY↓	20	10	6	3	61
	YO20-MFC10-ALG-GLY↑	20	10	6	5	59
	YHO20-MFC10-ALG-GLY↓	20	10	6	3	61
	YHO20-MFC10-ALG-GLY↑	20	10	6	5	59

[a] Note that 2% of MFC2 brings 0.04% of active cellulose fibrils into the formulation and 10% of MFC10 brings 1% of active cellulose fibrils into the formulation.

Table 2 Basic material property characterization for yeast material formulations in research phase 1.

Material formulation		Surface area shrinkage (%)	Weight loss (%)	Deformation (%)	Thickness (mm)
Group 1	YO20-MFC10	15–20	78–82	<1.0	0.25–0.30
	YHO20-MFC10	≤15	82–86	1.0–1.5	0.25–0.30
	YO20-MFC2	15–20	>86	1.5–2.5	≤0.20
	YHO20-MFC2	≤15	>86	1.5–2.5	≤0.20
Group 2	YO20-MFC10-ALG	>25	82–86	1.5–2.5	>0.30
	YO10-MFC10-ALG	>25	>86	1.5–2.5	0.20–0.25
	YHO20-MFC10-ALG	20–25	82–86	>2.5	>0.30
	YHO10-MFC10-ALG	20–25	>86	>2.5	0.25–0.30
Group 3	YO20-MFC10-ALG-GLY↓	20–25	82–86	1.5–2.5	>0.30
	YO20-MFC10-ALG-GLY↑	20–25	78–82	1.5–2.5	>0.30
	YHO20-MFC10-ALG-GLY↓	15–20	78–82	1.5–2.5	>0.30
	YHO20-MFC10-ALG-GLY↑	15–20	≤78	1.5–2.5	>0.30

enhancing the bonding between the nano and micro components in the formulation and improving the overall structural integrity and homogeneity of the material. This, in turn, leads to maintained construct integrity even after water evaporation upon ambient drying. Through these observations, we established that in a 3D printable hydrogel material matrix, homogenized and oven deactivated yeast (YHO) solutions act as a binder, whereas oven deactivated yeast (YO) solutions featuring intact cells act as a filler.

For Group 3 formulations, the results confirm the previously reported effects of both alginate and glycerol on the properties of the biomaterial formulations, as well as the physical constructs derived from them. In bioinks formulated for 3D printing, alginate is typically added as a gel forming agent to reduce shrinkage (Piras and Smith, 2020). Glycerol on the other hand is an established plasticizer, promoting moisture retainment, material texture improvement, and crack prevention (Cottet et al., 2020; Delgado et al., 2016, 2018; Peltzer et al., 2018). In our physical constructs, alginate contributed to an increased viscosity of the formulation, although it was not possible to clearly determine its positive effect on shape retention and shrinkage mitigation. The inclusion of glycerol noticeably improved the pliability of the constructs and reduced their shrinkage, and to some extent also led to lower deformation when compared with constructs from Groups 1 and 2, which did not contain glycerol. Overall, however, increasing the quantity of glycerol from 3% w/v to 5% w/v did not largely affect the four evaluated properties of constructs in Group 3.

The conclusion from this research phase was that the formulations comprising 20% yeast of both types, MFC in 10% concentration, and 3%–5% glycerol resulted in the most favorable material characteristics, i.e., moderate surface area shrinkage, weight loss, and deformation, and greater thickness. However, the formulations containing 2% MFC, despite exhibiting higher weight loss and lower thickness, were still potentially suitable for application in architectural tiles because they yielded texturally uniform, continuous, pliable, highly translucent surfaces. Thus, these formulations were selected for further development and evaluation in the next research phases.

3.2. Desktop 3D printing and basic geometric design evaluation

Table 3 specifies two material formulations prepared based on the results from the previous phase. Here, the yeast type (YO and YHO) was varied whereas the yeast concentration (20%), MFC and glycerol ratios were kept constant. No alginate was added in this phase to compare the deformation and continuity of the 3D printed constructs with the results from the previous phase.

Analytical comparisons of 3D printed material specimens, shown in Fig. 4, indicated that solid constructs made from the homogenized and oven deactivated yeast formulation (YHO20-MFC10-GLY) displayed lower shrinkage and deformation that constructs from the oven deactivated formulation (YO20-MFC10-GLY). For the perforated constructs made from both formulations, the deformation and shrinkage values did not vary as much as for the solid ones. Nevertheless, the occurrence of deformations and high area shrinkage (17%–52%) led to the conclusion that alginate should be added back to the formulations in the next material development stages, to improve these aspects.

3.3. Material formulations, multi-scalar characterization, and design strategies

3.3.1. Formulation tuning

Based on the results of the desktop 3D printing evaluation, two material formulation groups were created as specified in Table 4. The first group (Group 5) comprised two formulations, featuring two yeast types, YO and YHO, both in 20% concentration. To reduce shrinkage and deformation, alginate was added back to both formulations and glycerol quantity was increased. This formulation group was assumed to be suitable for 3D printing of the structural patterns in the new constructs due to the greatest thickness and rigidity of the material observed in the first and second research phases.

To introduce more variability in the texture, light transmission, and color of the constructs produced in this and the next stage, a second formulation group was created (Table 4, Group 6), with the formulation design based on

Table 3 Yeast-based material formulations from research phase 2.

Material formulation		Material formulation ingredients				
		Yeast solution (% w/v)	MFC solution[a] (% w/v)	Sodium alginate (% w/v)	Glycerol (% w/v)	Water (% w/v)
Group 4	YHO20-MFC10-GLY	13	3	0	3	81
	YO20-MFC10-GLY	13	3	0	3	81

[a] Note that 10% of MFC10 brings 1% of active cellulose fibrils into the formulation.

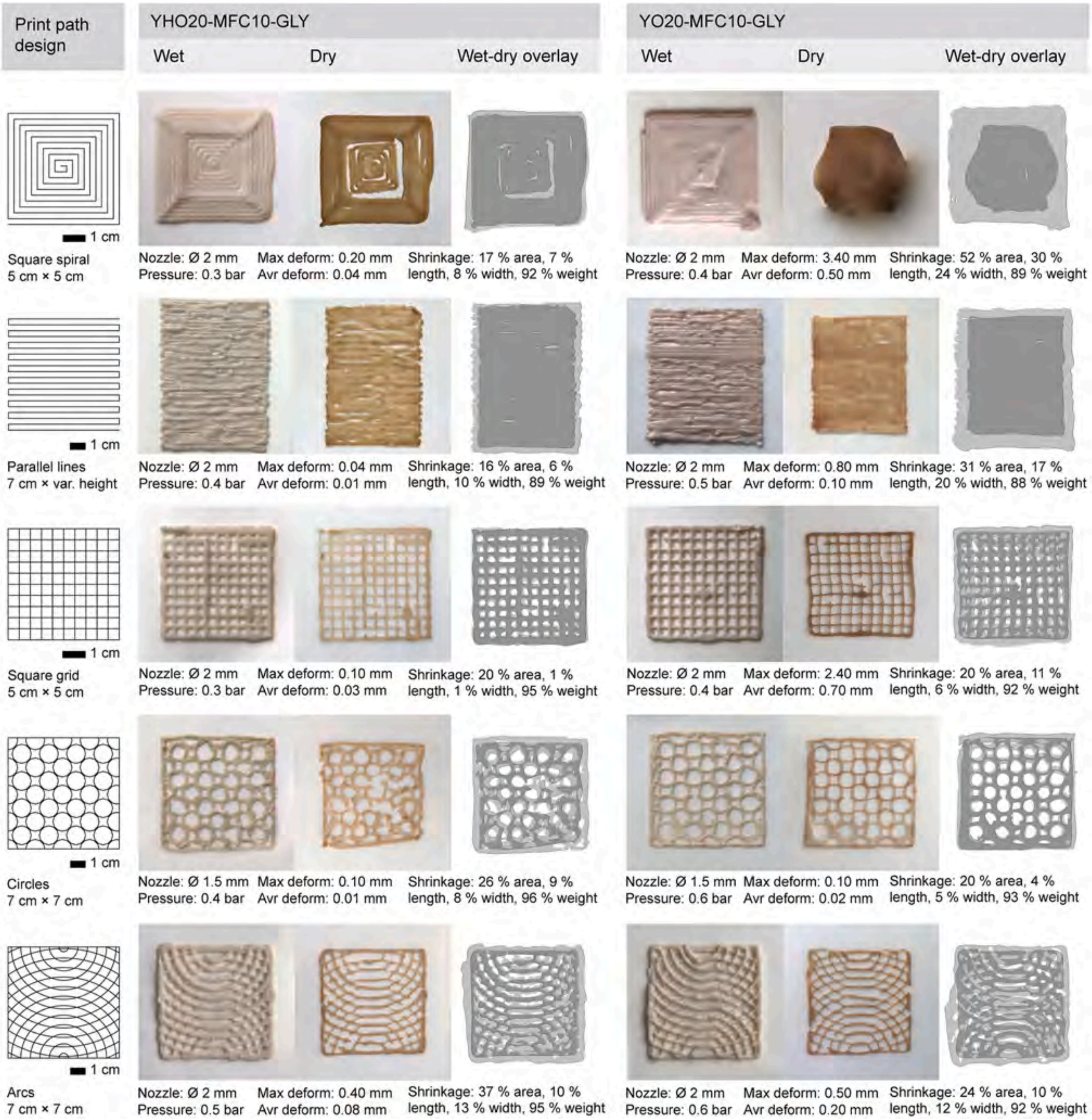


Fig. 4 Comparison between different geometric path designs for 3D printing and resulting deformations and shrinkage for constructs from homogenized (YHO20-MFC10-GLY) and oven deactivated (YO20-MFC10-GLY) yeast formulations.

Table 4 Optimized yeast formulations for architectural tile production.

Material formulation		Material formulation ingredients				
		MFC solution[a] (% w/v)	Yeast solution (% w/v)	Sodium alginate (% w/v)	Glycerol (% w/v)	Water (% w/v)
Group 5	YHO20-MFC10-ALG-GLY	13	3	1	5	78
	YO20-MFC10-ALG-GLY	13	3	1	5	78
Group 6	YHO20-MFC2-ALG-GLY	1	13	1	2	83
	YO20-MFC2-ALG-GLY	1	13	1	2	83

[a] Note that 2% of MFC2 brings 0.04% of active cellulose fibrils into the formulation and 10% of MFC10 brings 1% of active cellulose fibrils into the formulation.

findings from the first research phase (Table 1, Group 1, formulations YO20-MFC2 and YHO20-MFC2). It was made in two variants, each with a different yeast type, YO and YHO, both featuring MFC in 2% concentration, and glycerol and alginate to reduce shrinkage and deformation. The materials from this group were assigned to act primarily as infill, based on their low shrinkage and low thickness established in the first research phase.

3.3.2. Microstructural, rheological, mechanical, and thermal properties

As formulations from Group 5 were assigned to act as structural pattern parts in the 3D printed constructs due to their thickness and rigidity established in the first and second research phase, this material group was subjected to multi-scalar property analyses through Scanning Electron Microscopy (SEM), rheology characterization, tensile testing, and thermogravimetric analysis (TGA) (Fig. 5).

The SEM investigation revealed that the YO formulation yielded a more heterogeneous material matrix with visible intact yeast cells, whereas the YHO formulation displayed more homogeneity due to yeast cell disruption, seen as the lack of visible intact cells and a spill of internal cell contents into the matrix (Fig. 5(a)).

The rheological analysis confirmed the shear-thinning behaviors of the yeast material. Shear thinning occurred continuously throughout the test (Fig. 5(b)), yielding sloped curves congruent in terms of shape with the typical shear-thinning profiles of nanocellulose hydrogels (Markstedt et al., 2015). This confirms the importance of MFC in the yeast material formulation as an extrusion-enhancing and form-stabilizing agent. In the linear viscoelastic (LVE) region (Fig. 5(c)), both formulations exhibited gel-like behavior, with storage modulus (G') exceeding loss modulus (G''). The YO formulation demonstrated a higher G' (1.5×10^4 Pa), G'' (3×10^3 Pa), and viscosity (20,258 Pa•s at 0.01 s^{-1}), indicating that it behaves like a rigid and structured gel resisting deformation. The YHO formulation showed lower moduli ($G' = 1.0 \times 10^4$ Pa, $G'' = 2 \times 10^3$ Pa) and viscosity (13,144 Pa·s), suggesting it is less stiff, and indicating a softer and more flexible structure.

Specimens containing oven-deactivated yeast (YO) exhibited higher maximum tensile stress and strain than those with homogenized and oven-deactivated yeast (YHO) (Fig. 5(d)), indicating that intact yeast cells enhance the material's resistance to tearing. The average tensile strength was 2.7 ± 0.8 MPa for YO and 1.3 ± 0.4 MPa for YHO, while maximum strain reached 25.2% ± 2.9% and 19.1% ± 3.1%, respectively (Table 5). These values fall within ranges reported for comparable bio-based films with similar components, for which tensile stress spans 1.5–3.1 MPa and strain varies between 7.0% and 48.5% (Table 6). Overall, the moderate tear resistance and ductile behavior of yeast-based materials suggest potential for applications in lightweight, wallpaper-like building skins and decorative tapestries.

Thermogravimetric analysis (TGA) of both yeast material formulations, YO and YHO, showed nearly identical thermal degradation profiles, indicating that yeast cell state has minimal influence on thermal behavior (Fig. 5(e)). Below 180 °C, in the water evaporation stage, both formulations showed a stable weight loss reaching 10%. Between 180 and 330 °C, a rapid mass decrease of around 70% occurred, which can be linked to the breakdown of cellulose chains and organic compounds in the material (Lichtenstein and Lavoine, 2017). Beyond 330 °C, mass loss was less abrupt and slower, stabilizing around 85%. Unlike pure cellulose films, which fully degrade above 300 °C, the incorporation of yeast and glycerol prevented complete thermal decomposition, consistent with observations by Atta et al. (2021). This enhanced high-temperature stability suggests that the material might have improved fire safety potential relevant for indoor applications.

3.3.3. Material deposition strategies and robotic 3D printing trials

To verify the scalability of the material and establish deposition strategies for multi-material 3D printing of the demonstrators, tile fragments measuring 7 cm × 20 cm were 3D printed using a custom pressure-based extrusion system deployed on an industrial robot, using four formulations (Table 4) deposed in sequences shown in Fig. 6. Each design comprised a rectangular frame with a zigzag (triangular inlay) pattern inside, with or without infill. The zigzag geometry was chosen to assess material deposition quality, including corner continuity and overlapping layer bonding at characteristic intersection angles (60°, 90°, 120°). This approach follows the protocols from prior architectural research on 3DP with bio-based material composites, in which zigzag, triangular, and lattice patterns are typically used to evaluate printability and material deposition quality (for example, see Carcassi et al.,

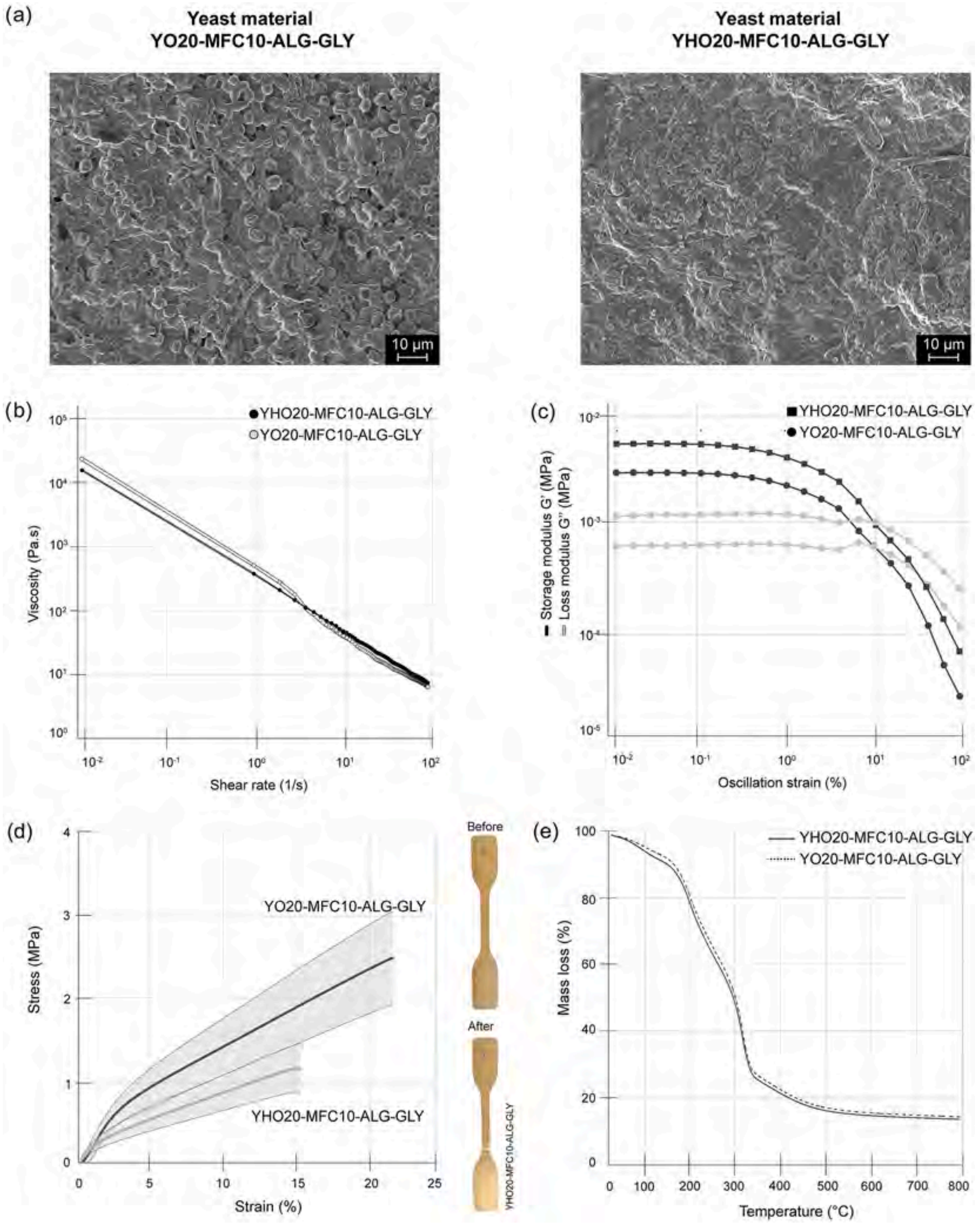


Fig. 5 Multi-scalar property characterizations for yeast-based formulations YHO20-MFC10-ALG-GLY and YO20-MFC10-ALG-GLY: (a) scanning electron microscopy (SEM) images, (b) viscosity versus shear rate profiles, (c) oscillatory strain sweeps comparing storage (G') and loss (G'') modulus, (d) stress—strain curves from tensile testing, and (e) thermogravimetric analysis (TGA).

2024; Gomaa et al., 2021; Mogas-Soldevila et al., 2021; Zboinska et al., 2023).

For the infill, two deposition methods were examined; linear infill 3D printed between the zigzag lines and linear infill with full coverage of the zigzag lines. These were analyzed visually to determine infill surface continuity and deformation, and the effectiveness of infill bonding with the zigzag pattern.

First, lattice structures with no infill were 3D printed to compare the deformation and shrinkage effects for two material formulations from Group 5. The second round was focused on evaluating the aesthetic design and deposition effects for the different material formulations combined within solid tile constructs. In this round, formulations from Group 5 featuring 10% MFC were investigated as the main pattern expression material. The first formulation of Group 5 (Table 4), which was less viscous, and both formulations from Group 6 (Table 4), featuring 2% MFC, were verified as translucency-modulating infill materials.

The results are shown in Fig. 6 and compiled in Table 7. The lattice construct printed with the formulation based on homogenized and oven deactivated yeast (YHO20-MFC10-

Table 5 Mechanical properties of yeast-based materials.

Material	Specimen	Maximum stress (MPa)	Maximum stress average (MPa)	Maximum strain (%)	Maximum strain average (%)
Yeast YHO20-MFC10-ALG-GLY	1	1.9	1.3 ± 0.4	21.3	19.1 ± 3.1
	2	1.7		23.9	
	3	1.3		18.5	
	4	1.5		21.9	
	5	1.8		23.1	
	6	1.1		15.4	
	7	1.2		17.7	
	8	1.1		17.4	
	9	0.8		15.5	
	10	0.7		17.0	
Yeast YO20-MFC10-ALG-GLY	1	4.9	2.7 ± 0.8	32.9	25.2 ± 2.9
	2	3.1		26.1	
	3	2.6		21.9	
	4	2.4		23.4	
	5	2.3		24.2	
	6	2.1		23.1	
	7	2.7		25.7	
	8	2.6		24.1	
	9	2.1		25.4	
	10	1.9		25.4	

ALG-GLY) exhibited 28% shrinkage in surface area, 6% shrinkage in length, and 4% shrinkage in width (Fig. 6(b)). Its outline did not deviate much from the shape in the wet state, and it remained planar after drying. The material was continuous at corners, along the linear edges and at most of the angled material crossings. In comparison, the construct from the formulation featuring intact oven deactivated yeast cells (Fig. 6(c), YO20-MFC10-ALG-GLY) shrunk by 24% more in surface area and 6% more in length and width, its outline deformed more (Fig. 6(c)), and splitting occurred along one of the edges. These findings confirmed the observations from the earlier research phases, in which we established that homogenized yeast formulations, due to higher material matrix uniformity, are less prone to shrinkage and distortion. Thus, the YHO material formulation is suitable for tiles requiring pliability and lower deformation, whereas the YO formulation could be applied in rigid tiles.

The second 3D printing round of constructs shown in Fig. 6(e), 6(f), 6(h), and 6(i), demonstrated how material combinations and their deposition strategies influence dimensional accuracy and surface continuity in lattice-

Table 6 Mechanical properties of comparable bio-based film materials.

Material	Maximum stress average (MPa)	Maximum strain average (%)
Bio-based protein film (commercial soy protein isolate, glycerol) (Denavi et al., 2009)	2.4 ± 0.2	48.5 ± 7.7
Microbial film (homogenized yeast *Saccharomyces cerevisiae*, glycerol) (Delgado et al., 2018)	3.1 ± 0.3	7.0 ± 1.8
Reinforced microbial film (homogenized yeast *Saccharomyces cerevisiae*, glycerol, rice husk cellulose nanofibers) (Delgado et al., 2021)	1.5 ± 0.2	11.0 ± 2.0
Reinforced microbial film (homogenized yeast *Saccharomyces cerevisiae*, glycerol, bacterial nanocellulose) (Delgado et al., 2021)	2.3 ± 0.4	18.0 ± 3.0
Bio-based composite microbial film (intact yeast *Meyerozyma guilliermondii*, bacterial cellulose, carboxymethyl cellulose, glycerol) (Atta et al., 2021)	2.2 ± 0.3	15.5 ± 0.8

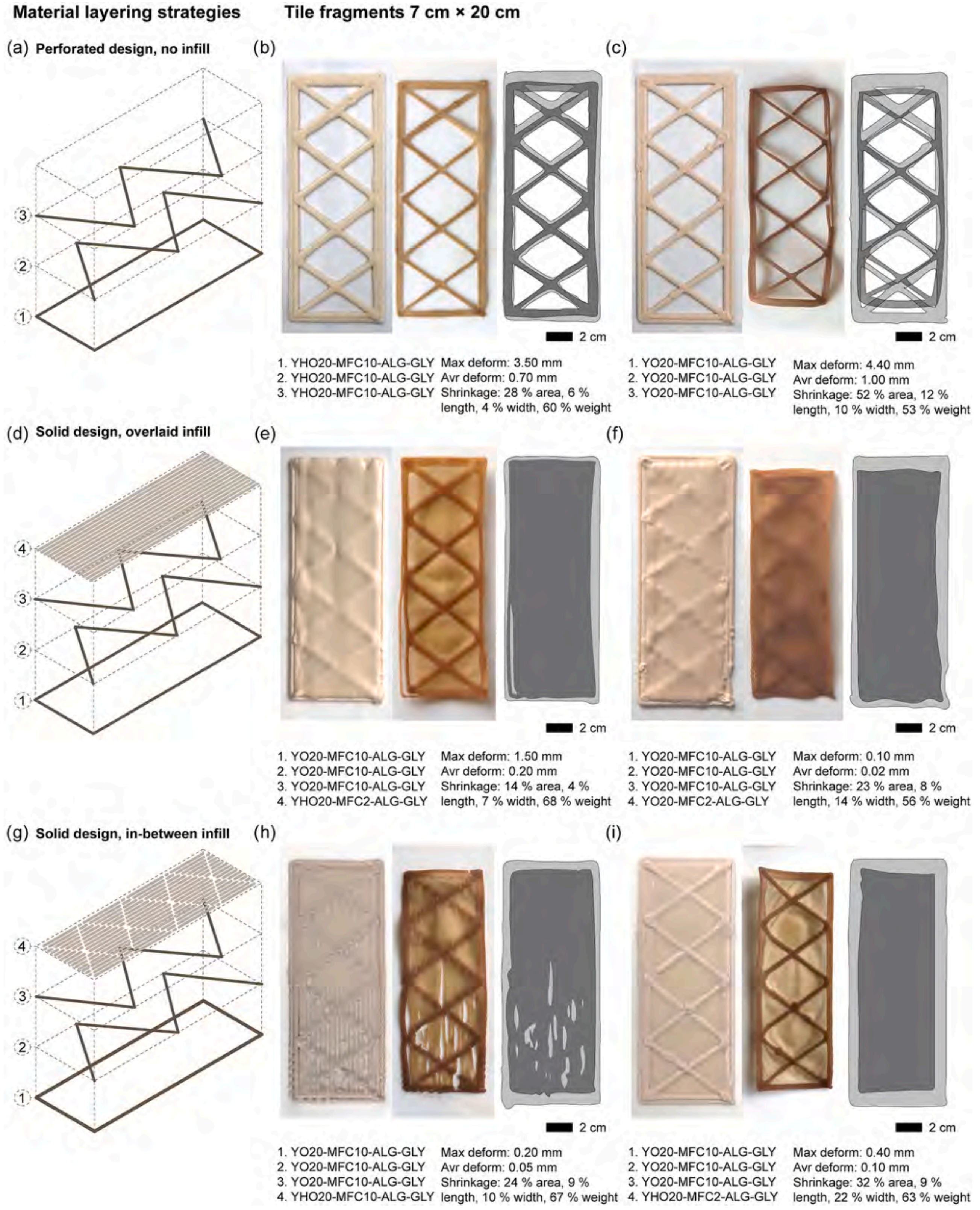


Fig. 6 Deformation and shrinkage analyses for 7 cm × 20 cm architectural tile fragments representing (a)–(c) perforated lattice and (d)–(i) solid designs, for four yeast material formulations (YO20-MFC10-ALG-GLY, YHO20-MFC10-ALG-GLY, YO20-MFC2-ALG-GLY and YHO20-MFC2-ALG-GLY) and three material layering strategies for 3D printing, (a), (d), (g).

Table 7 Design properties of yeast material formulations for architectural tiling applications.

Properties	Material formulations			
	Group 5		Group 6	
	YHO20-MFC10-ALG-GLY	YO20-MFC10-ALG-GLY	YHO20-MFC2-ALG-GLY	YO20-MFC2-ALG-GLY
Shrinkage	Low	High to moderate	Low	Moderate to low
Continuity	High	Moderate to low	High	High to moderate
Shape fidelity	High	Moderate	Low	Low
Texture	Moderately rough	Rough	Smooth	Moderately smooth
Light transmission (%)	16.8	5.6	31.6	20.4
Color (NCS)	4040-Y30R	5030-Y40R	3030-Y20R	3040-Y30R

patterned solid prints. All four constructs used the same pattern material (YO20-MFC10-ALG-GLY) but differed in infill formulations (YO20-MFC2-ALG-GLY, YHO20-MFC2-ALG-GLY, and YHO20-MFC10-ALG-GLY), each extruded either as a full overlay (Fig. 6(d)) or as in-between infill (Fig. 6(g)).

Among these, the most effective combination in terms of shrinkage was the YHO20-MFC2-ALG-GLY formulation extruded as a full overlay over the YO20-MFC10-ALG-GLY lattice (Fig. 6(e)). This variant exhibited the lowest shrinkage among the solid samples, i.e., 14% in surface area, 4% in length, and 7% in width. It showed only one surface rupture along an edge and maintained a nearly planar surface in its dry state, with average 3D deformation of 0.2 mm and maximum deformation reaching 1.5 mm. Compared to the lattice construct from the first printing round (Fig. 6(c)), which used the same zigzag pattern material, the addition of a solid overlay featuring the homogenized yeast formulation led to the reduction of area shrinkage by 38%, maximum 3D deformation by 34%, and average deformation by 20%.

Surface continuity was influenced by both the infill formulation and its extrusion method. The construct using YHO20-MFC10-ALG-GLY as in-between infill (Fig. 6(h)) displayed the worst continuity, with 16 surface ruptures measuring 2–5 cm in length. Conversely, the remaining three constructs, each using infill with a lower MFC concentration of 2%, exhibited no visible discontinuities (Fig. 6(e), 6(f), 6(i)).

Light transmission measurements further clarified the suitability of each formulation for translucent versus opaque tile applications. The YO20-MFC10-ALG-GLY formulation, containing intact yeast cells and 10% MFC, exhibited the lowest transmission at 5.6%, making it ideal for opaque tiles. In contrast, the other three formulations showed higher transmission values ranging from 16.8% to 31.6%, indicating their potential for daylight-permeable tile systems.

To conclude, for lattice tiles, YHO20-MFC10-ALG-GLY is a good choice for flexible, form-stable and nearly planar lattices whereas YO20-MFC10-ALG-GLY applies for rigid lattices, in which higher deformation is acceptable. Both can be used to produce smooth, soft-patterned solid tiles when the pattern is printed before the infill. To achieve pronounced 3D texture effects, the infill should be printed in-between or beneath the structural features. Additionally, YHO20-MFC2-ALG-GLY is well-suited for translucent surfaces, whereas YO20-MFC10-ALG-GLY is preferable for opaque ones.

3.4. Evaluation and demonstration of the architectural potential of yeast materials

For the architectural application evaluation and demonstration, 17 rectangular tiles, each with outer dimensions 20 cm × 50 cm in wet state, were robotically 3D printed using three material formulations from Table 4, where YHO20-MFC10-ALG-GLY and YO20-MFC10-ALG-GLY were used as pattern material and YHO20-MFC2-ALG-GLY was used as infill. The designs followed three porosity archetypes: solid, hybrid, and perforated (Fig. 7).

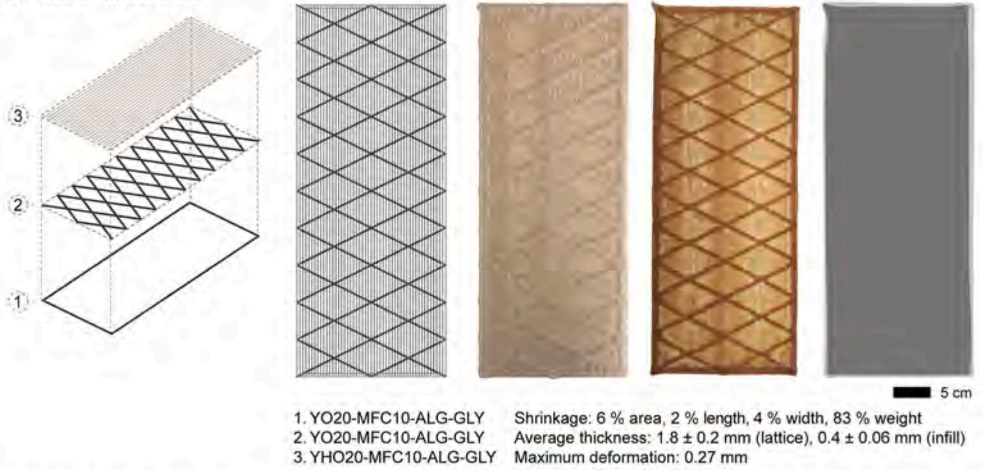
To evaluate suitability for future architectural tiling applications, three tiles representing the porous, solid and hybrid design archetypes were analyzed in detail to determine thickness, shrinkage, and deformation. Thickness measurements taken across multiple sections of the dry-state tiles revealed uniform profiles for the pattern and infill. Layers comprising the zigzag patterns composed of YO20-MFC10-ALG-GLY (Fig. 7(a), layer 2; Fig. 7(b), layers 2–4; Fig. 7(c), layers 2–4) had thicknesses of 1.7/1.8 ± 0.2/0.3 mm. The infill layers composed of YHO20-MFC10-ALG-GLY (Fig. 7(a), layer 3; Fig. 7(b), layer 5) measured 0.2/0.4 ± 0.06/0.07 mm.

Area shrinkage comparisons revealed that the solid design (Fig. 7(a)) displayed the lowest surface area shrinkage of 6%, the hybrid one (Fig. 7(b)) showed moderate area shrinkage of 20%, and the perforated one (Fig. 7(c)) displayed the highest value of 40%. In contrast, linear shrinkage measurements along tile width and length showed only minor reductions with low values ($\geq$5%) for the solid and perforated designs and slightly higher values for the hybrid one (max 10%), confirming that outer dimensions in the dry state remained close to the original wet state. Together, these findings suggest that shrinkage in the hybrid and perforated designs occurred primarily within the tile body rather than along its perimeter. Thus, the high area shrinkages observed for these designs did not correlate strongly with their overall dimensional stability, and global dimensions remained largely unaffected.

The three-dimensional surface deformation analyses revealed characteristic differences among the three designs (Table 8). The solid construct showed minimal deviation from the best-fit plane, with an average distance of

Material layering strategies **Architectural tiles 20 cm × 50 cm**

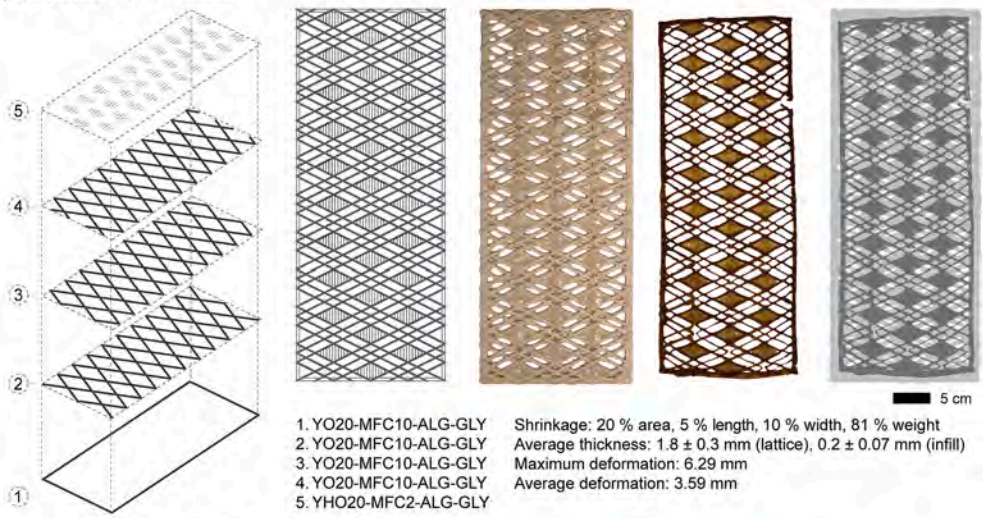
(a) **Solid design, full infill**



1. YO20-MFC10-ALG-GLY
2. YO20-MFC10-ALG-GLY
3. YHO20-MFC10-ALG-GLY

Shrinkage: 6 % area, 2 % length, 4 % width, 83 % weight
Average thickness: 1.8 ± 0.2 mm (lattice), 0.4 ± 0.06 mm (infill)
Maximum deformation: 0.27 mm
Average deformation: 0.17 mm

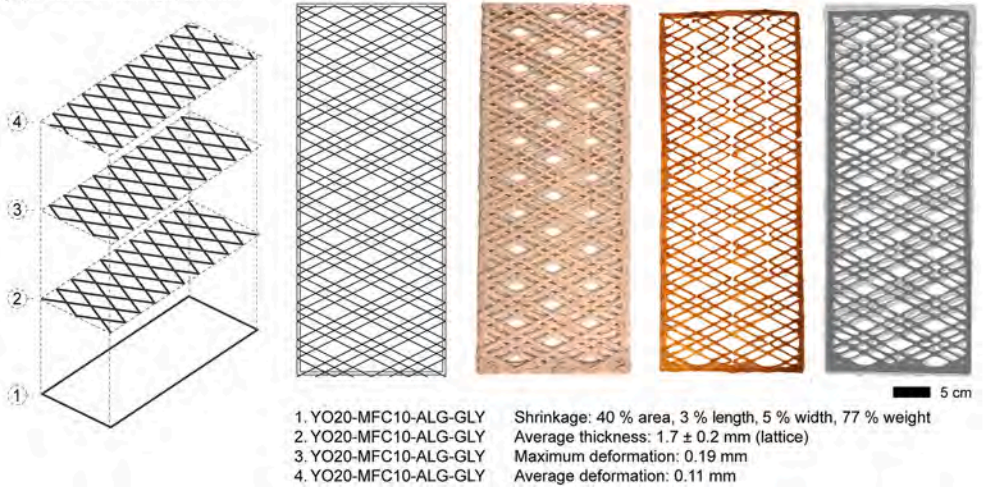
(b) **Hybrid design, partial infill**



1. YO20-MFC10-ALG-GLY
2. YO20-MFC10-ALG-GLY
3. YO20-MFC10-ALG-GLY
4. YO20-MFC10-ALG-GLY
5. YHO20-MFC2-ALG-GLY

Shrinkage: 20 % area, 5 % length, 10 % width, 81 % weight
Average thickness: 1.8 ± 0.3 mm (lattice), 0.2 ± 0.07 mm (infill)
Maximum deformation: 6.29 mm
Average deformation: 3.59 mm

(c) **Perforated design, no infill**



1. YO20-MFC10-ALG-GLY
2. YO20-MFC10-ALG-GLY
3. YO20-MFC10-ALG-GLY
4. YO20-MFC10-ALG-GLY

Shrinkage: 40 % area, 3 % length, 5 % width, 77 % weight
Average thickness: 1.7 ± 0.2 mm (lattice)
Maximum deformation: 0.19 mm
Average deformation: 0.11 mm

Fig. 7 Thickness and shrinkage analyses for (a) solid, (b) hybrid, and (c) perforated tiles 3D printed using different yeast material combinations.

0.02 mm and a maximum deviation of 0.12 mm, indicating a high degree of planarity and negligible spatial deformation. The perforated construct displayed slightly higher variability, with an average deviation of 0.03 mm and a maximum of 0.23 mm, which can still be considered as acceptable and indicative of its flatness. In contrast, the hybrid construct demonstrated substantial spatial deformation, with an average deviation of 0.28 mm and a maximum of 1.87 mm, accompanied by a high standard deviation of 0.22 mm.

The outer edge deformation analysis (Table 9) revealed similar trends. The solid and perforated construct maintained consistent outlines, with average deviations of 0.17 mm and 0.11 mm, respectively, and maximum deviations at and below 0.27 mm. These values indicate that edge geometry remained largely stable, suggesting potential for accurate alignment in tiling configurations. Conversely, the hybrid design exhibited pronounced edge distortion, with an average deviation of 3.59 mm and a maximum of 6.29 mm, coupled with a large standard deviation of 1.58 mm. This suggests that the hybrid tile design would not allow for perfectly seamless assembly and would necessitate corrective measures.

Taken together, these variations remain within acceptable dimensional tolerances for non-loadbearing architectural components. In facade and cladding systems, installation tolerances of ±2 mm for panel thickness and up to ±15 mm for structural interfaces are commonly accommodated without compromising performance or aesthetics. Given that the deviation values observed in this study fall well below these tolerances, they can be assumed feasible for future architectural application. Nevertheless, it is important to highlight that further work is needed to optimize the material formulations, develop tools for the prediction of material deformations based on specific tile designs and 3D printing approaches, and establish methods for accurate tile assembly.

To further demonstrate the architectural potential of the yeast-based 3D-printed material, the tiles were assembled into a demonstrator representing a vertical screen structure (Fig. 8(a)). The different tile designs included in this demonstrator were aimed to highlight the aesthetic versatility of the yeast material, expressed in variable translucency (Fig. 8(b)), colors, patterns, textures (Fig. 8(c)), and tile overlays (Fig. 8(d)). The successful gradual increase in constructs size, reaching the final dimensions of 20 cm × 50 cm, indicates the scalability potential of the material.

Compared to conventional cladding materials, the 3D printable yeast material solution offers unique mass customization opportunities. Through strategic selection of specific material formulations, custom parametric design methods and tailored 3D printing strategies, the constructs can be varied aesthetically at the component level. This points to the potential for cost-efficient customization, desired not only in new products but also in context-sensitive architectural applications such as renovation or transformation that require careful stylistic product adaptation to existing architectural features. The demonstrator indicates future application potential in lightweight, thin-sheet bio-based claddings for interiors, in products such as tapestries, wallpapers, drapes and room partition screens. However, further research is required to tackle the current material limitations and optimize its performance for specific application cases.

While bio-based materials are typically susceptible to environmental factors such as humidity-induced shape alteration and dimensional transformations, the presented results show that the final yeast material formulations exhibit reduced shrinkage and deformation upon ambient drying compared to the initial ones. Although not all the derived constructs are perfectly flat and with ideally straight edges, they could still be suitable for applications where moderate variations in shape and minor dimensional inconsistencies are acceptable, for example, in standalone room partitions, decorative wall coverings, and free-form daylight-modulating screens. Nevertheless, further research is needed to fully assess these properties and enhance dimensional and geometric accuracy.

Although the study of material connection details was beyond the scope of this work, the material's successful clamp-based, adhesive-free mounting in the demonstrator indicates compatibility with traditional assembly techniques for architectural wallpapers, fabrics, and lightweight sheets. One potential mounting option encompasses direct wall installation using bio-based adhesives. Another alternative is mechanical fastening with non-invasive clamps to secure the material sheets without puncturing

Table 8 Surface deformation metrics for three tile designs (solid, hybrid, perforated), calculated in Rhinoceros 3D using *PointDeviation* between a best-fit plane and photogrammetry-derived mesh points.

Metric	Solid design	Hybrid design	Perforated design
Average distance [mm]	0.02	0.28	0.03
Median distance [mm]	0.02	0.24	0.02
Standard deviation [mm]	0.01	0.22	0.02
Maximum distance [mm]	0.12	1.87	0.23
Minimum distance [mm]	1.54×10^{-8}	7.63×10^{-7}	5.16×10^{-8}

Table 9 Edge deformation metrics for three tile designs (solid, hybrid, perforated), calculated in Rhinoceros 3D using *PointDeviation* between a best-fit plane boundary and photogrammetry-derived mesh boundary points.

Metric	Solid design	Hybrid design	Perforated design
Average distance [mm]	0.17	3.59	0.11
Median distance [mm]	0.16	3.22	0.11
Standard deviation [mm]	0.03	1.49	0.03
Maximum distance [mm]	0.27	6.29	0.19
Minimum distance [mm]	0.10	1.58	0.05

them. For perforated or hybrid tile designs, concealed fasteners could be positioned at corners or along edges, allowing for a flush finish and easy removal or replacement. Finally, direct 3D printing onto wall sheathing as a decorative coating and finishing layer could enable seamless integration with underlying substrates and creation of continuous, customized surface patterns on existing surfaces. Further research is required to determine the mounting strategies suitable for specific application cases.

Despite current limitations, this study establishes a knowledge foundation for continued research and development of scalable, customizable, bio-based architectural

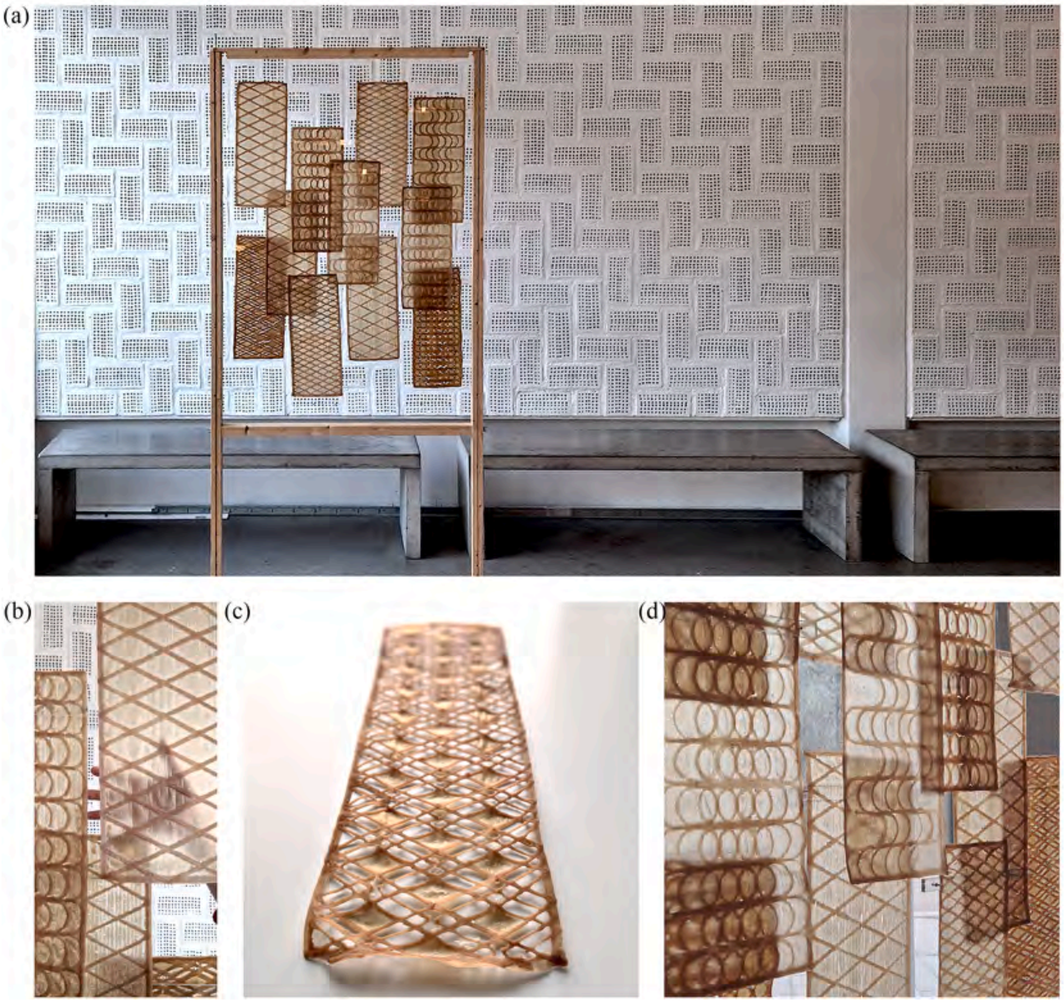


Fig. 8 (a) Architectural demonstrator featuring diverse yeast tile designs displaying aesthetic versatility of the yeast material through variable (b) translucency, (c) color and texture, and (d) layering effects.

products from yeast and cellulose biomass. With further research addressing long-term durability and optimization of manufacturing precision toward high dimensional accuracy, these solutions could be a valuable addition to the current repertoire of mass-customizable bio-based materials and products for architecture.

4. Conclusion

This study demonstrated the feasibility of using unicellular baker's yeast in 3D printable, bio-based architectural materials. Optimized formulations containing 3% (w/v) yeast solution (intact or homogenized cells), 13% (w/v) aqueous microfibrillated cellulose solution (10% microfibril concentration), 1% (w/v) sodium alginate, 5% (w/v) glycerol, and water exhibited shear-thinning, gel-like behaviors favorable for extrusion-based 3D printing ($G' > G''$). The mechanical properties of the material align with typical properties of bio-based film materials with similar components, showing a maximum average tensile strength of 2.7 MPa and elongation at break of 25.2%. The largest solid tile constructs measuring 20 cm × 50 cm exhibited a low surface area shrinkage of 6% and low three-dimensional deformation averaging 0.02 mm, which indicates future potential for lightweight interior cladding applications. Collectively, the 3D printed tiles assembled into a demonstrator displayed a wide range of tunable design attributes of the material relevant for its architectural use, including variable light transmittance, color palette, surface texture, and porosity.

The presented yeast material should be considered in future architectural research and applications due to its unique sustainable composition, customizable aesthetic attributes, and compatibility with a mass-customizable, resource-efficient fabrication method of 3D printing at room temperature, with no heat and scaffolds. As such, this yeast material offers a valuable renewable and biodegradable alternative to conventional synthetic claddings. Its ability to be produced as lightweight surfaces and sheets with adjustable translucency, color, and texture points at application potential in interior design.

In future research, several limitations must be addressed. Firstly, the presented mechanical characterization encompassed tensile strength and elongation at break while other application-specific properties, such as flexural performance and impact resistance were not evaluated and should be investigated further. Secondly, the presented material formulations do not allow for form-stable stacking of multiple material layers, restricting the current application scope to material sheets and thin surfaces. Architectural application potential was shown for tiles measuring 20 cm × 50 cm, and further scaling up for larger components and more complex geometric designs remains to be established. Finally, the biodegradability, aging and resistance of the material to indoor climate fluctuations in temperature and humidity were not verified. Future work should evaluate these durability aspects, as well as fire resistance, acoustic and thermal properties, biodegradability, and user acceptance. Together, these investigations will help derive fully optimized material formulations that align with construction industry standards and yield architecturally compelling solutions for sustainable buildings.

Data availability

Data will be made available upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foar.2026.01.003.

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Papers B

Digital Crafting of Architectural Biomaterials: Computational Geometric Design and Robotic 3D Printing of Yeast-Cellulose Hydrogels

Bektas, Y., Zboinska, M., Skånberg Dahlstedt, T., Geijer, C., Nypelö, T

Digital Crafting Of Architectural Biomaterials

Computational Geometric Design and Robotic 3D Printing of Yeast-Cellulose Hydrogels

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Abstract. Sustainable materials from microbial and plant biomass sourced from industrial side streams offer a promising solution for resource-efficient architectural design. Prior research has demonstrated how computational design can tailor the visual and mechanical properties of such materials. However, each new material blend requires a material-spec1ific design and fabrication approach. Adopting an architectural research-by-design method, this study investigated how geometric design parameters in robotic 3D printing can help tune the physical and aesthetic properties of architectural tiles made from a new yeast-cellulose hydrogel. Three material blends with distinct viscosity and shrinkage profiles were evaluated post-print to define a proof-of-concept framework for yeast-cellulose material crafting via 3D printing. The framework specifies key parameters influencing design features of 3D printed biobased architectural tiles, namely, path geometry, spacing, symmetry, connection angles, intersection types, material blend combinations, deposition methods, and layer sequences. By offering a framework linking geometric design to material transitions from wet to dry state, this work contributes an early understanding of how computational design strategies can respond to dynamic material behaviour, providing an essential knowledge foundation for continued architectural research and applications.

Keywords. Biobased Building Materials, Yeast-Cellulose Hydrogels, Microbial and Fungal Biomass, Robotic Deposition, Biomaterial Extrusion, Parametric Fabrication, Material-Driven Computational Design, Biofabricated Architectural Components

HUMANISTIC COMPUTATION AND INTELLIGENCE, Proceedings of the 31st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2026, Volume 2, 205-214.

1. Introduction

Human activity has reshaped the Earth's resource balance, with anthropogenic mass now exceeding natural biomass (Elhacham et al., 2020). The construction sector contributes to this imbalance through resource extraction and carbon dioxide emissions (UNEP, 2025). In response, circular design approaches promote renewable materials from industrial side streams, including novel research into architectural materials from biomass. Organic hydrogels based on mixtures of water with algal, bacterial, fungal, and plant biomasses are particularly promising due to their renewability and suitability for 3D printing via pneumatic extrusion, without heat and at ambient conditions (Aljohani et al., 2018; Carcassi and Ben-Alon, 2024; Piras and Smith, 2020).

Prior work has begun to establish computational and robotic 3D printing strategies for novel biobased hydrogels, yet each new formulation demands its own design and fabrication rules (Menges and Knippers, 2015). This study develops such bespoke strategies for a new biobased hydrogel based on yeast and cellulose biomass, which is abundant, renewable, and scalable. Yeast biomass can be sourced from underutilized brewing industry residues and rapidly grown on low-value, carbohydrate-rich food waste. Its unicellular morphology produces inherently homogeneous blends, while its polysaccharide-, lipid-, and protein-rich composition reinforces cellulose-dominated mixes, enhancing material flexibility, tensile strength, biodegradability, and overall renewability. Combined with cellulose from industrial by-products, this material enables 3D printing of architectural constructs with tuneable surface qualities. The aim of this work was to define the key computational design and 3D printing rules to guide visual and tactile effects in architectural tiles from this hydrogel.

While the authors' prior research focused on establishing 3D printable compositions of this material and evaluating its basic mechanical and aesthetic qualities relevant for architectural applications (Bektas et al., 2026), this work explores the geometric design and robotic fabrication rules for selected blends, to aid the manufacturing of architectural tiles with variable morphologies and visual expressions. A decorative modular tiling application was chosen to support comparative analysis between the units and showcase the material's ability to be manufactured as customizable units with individualized design expressions.

2. State of the Art

Hydrogels are characterized by complex rheology: viscous at rest, flowable under pressure, and shape-retaining once force is removed. Their 3D printability depends on composition-specific calibration (Choi and Yi, 2024). Architectural explorations have used computational design and robotic extrusion to tune hydrogel behaviour (Mogas-Soldevila et al., 2014), integrate material-driven patterning (Duro-Royo et al., 2017), optimize toolpaths for biological viability (Malik et al., 2020), and create humidity- and temperature-responsive structures (Panagiotidou et al., 2022).

Because hydrogels are wet when 3D printed and must dry to become solid objects, prior research examined their post-print shrinkage, cracking, and warping. Parametric mappings of deformation were proposed to support predictive toolpath design strategies (Campos et al., 2022). Napier (2022) used shrinkage-driven curling as a design parameter. Zboinska et al. (2023) examined correlations between deposition path geometry, layering, and different extrusion methods and deformation, shrinkage, textural effects, colour transitions, stiffness, and translucency in 3D printed architectural constructs from nanocellulose, alginate and food pigment hydrogels.

Collectively, prior work acknowledges the necessity of bespoke computational design and fabrication, carefully tailored to accommodate properties of specific biomaterial blends. The common feature of these strategies is that they permit form to emerge through a joint agency of design intent, deposition algorithms, matter, and environmental conditions. However, how final material effects relate to specific geometric features of the deposition paths, i.e., points, lines, arcs, curves, and relational attributes including intersection angle, spacing, and orientation, remains insufficiently studied. This raises the question: How can digitally mediated geometric material crafting strategies be leveraged to achieve material-specific aesthetic effects?

This study advances the current state of the art by introducing an early-stage framework for yeast-cellulose hydrogel crafting, aiding aesthetic material effects in 3D printed constructs by leveraging computational design of the material's deposition paths to accommodate material-specific rheological properties and drying behaviours. The work investigates how spatial configurations of geometric toolpath features (points, lines, curves) affect post-print transformations, linking the hydrogel's characteristics and deposition methods to emergent visual and physical properties. By leveraging computation as a mediating interface between design intent, material agency, and architectural expression, the study articulates rules and parameters guiding the design of architectural tiles made from the yeast-cellulose hydrogel.

3. Methods

3.1. MATERIAL FORMULATIONS

Three hydrogel blends featuring baker's yeast (*Saccharomyces cervisiae*), microfibrillated cellulose (MFC), alginate, glycerol and water are mixed mechanically in different ratios to achieve distinct viscosities, applied in robotic 3D printing experiments, and dried under ambient conditions (21.8 °C, 30.5 % RH) for 7 days. The detailed composition and preparation procedures for these blends are presented in Bektas et al. (2026). Blends A and B contain 13 % MFC, 3 % yeast, 1 % alginate, 5 % glycerol, and 78 % water. Blend C features 1 % MFC, 13 % yeast, 1 % alginate, 2 % glycerol, and 83 % water. Blend A is a high-viscosity hydrogel, exhibiting the highest stiffness among the three blends and moderate shrinkage in a dry state. Blend B is a medium-viscosity hydrogel, moderately pliable and exhibits high shrinkage in a dry state. Blend C is the least viscous among blends, is highly pliable, and exhibits the lowest shrinkage in a dry state.

3.2. PROTOTYPING PROCESS

The tile prototyping experiments comprised three steps: toolpath design, material blend selection, robotic fabrication through pressure-based extrusion, and post-print evaluation after drying. This sequence carried out once per prototype, with tile designs iterated in each consecutive round based on observations from the previous one.

3.3. GEOMETRIC DEPOSITION PATH DESIGNS AND EVALUATION

To examine how geometric 3D printing path features (points, lines, curves) affect final tile appearance, a matrix of tile design configurations was created (Figure 1). The matrix comprised three tile design types, classified based on the parametric modulation approach: geometric (Design type 1), cellular (Design type 2), and force field-based (Design type 3). Designs of type 1 were based on parametrically adjustable grids and polar/radial arrays of geometric primitives, with regularity guided by relational attributes as repetition, symmetry and constant spacing. This design type was defined to examine the effects of material layer sequencing, connection angles and intersection types between the 3D printed material strands. Designs of type 2 were based on irregular tessellations composed of primitives with asymmetrical variation in relational attributes as sizes, shapes, and orientations. This type examined the effects of layer connection angles and path spacing. Designs of type 3 were based on irregularly deformed geometric primitives and configurations. This type was defined to examine the effects of asymmetry and path spacing, ranging from tight to widely arranged.

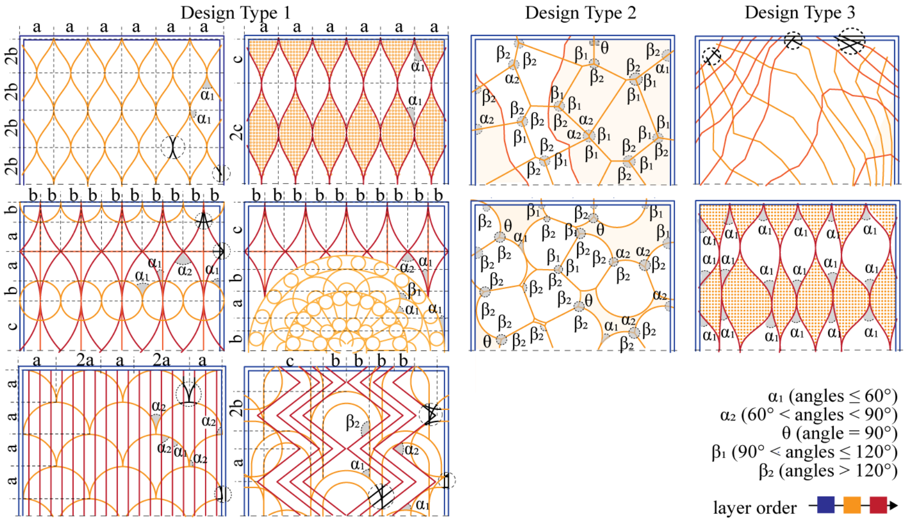

Figure 1. Matrix of design configurations: geometric (Design type 1), cellular (Design type 2), and force field-based (Design type 3).

Within each tile design type, different material deposition strategies were also examined: strand-based, in which the material was extruded as continuous lines, droplet-based, in which the material was extruded as discrete droplets, and injection-based, in which the material was extruded to spread from a single spot, following the material deposition strategies published in (Zboinska et al., 2023). For the last case, an additional parameter of robot waiting time was introduced, where printhead movement pauses at a specific point to allow prolonged material deposition and spread.

To evaluate the material effects in the fabricated tiles, three criteria were defined via qualitative observations and quantitative measurements comparing the tiles in wet and dried state: (i) dimensional accuracy, calculated as the percentage reduction in surface area, length and width; (ii) continuity without cracking, visually inspected for path overlaps and segment lengths; and (iii) interlayer cohesion, connecting the parametric values defining the path connection angles with visual assessment of material effects for different types of intersections.

3.4. DIGITAL FABRICATION SETUP

The prototyping experiments were conducted using an industrial robot KUKA Agilus KR10-1100-SIXX, with a custom end-effector for pressure-based extrusion, specified in Zboinska et al., (2023). The system comprises dispensing syringes connected via air hoses to adjustable pressure regulators allowing for real-time adaptation of air pressure during 3D printing to material viscosity. Geometric designs of the deposition paths were translated into robot commands using the KUKA|prc plugin for Grasshopper (Braumann and Brell-Cokcan, 2011) in Rhinoceros 3D, version 8 (Rutten 2021).

4. Results and Discussion

4.1. DIGITAL CRAFTING FRAMEWORK

The framework for digital crafting of yeast- and cellulose-based hydrogels using computational design and 3D printing is shown in Figure 2. It facilitates systematic tuning of the material through a stepwise, reproducible process featuring key parameters that can be altered to influence design effects of 3D printed tiles.

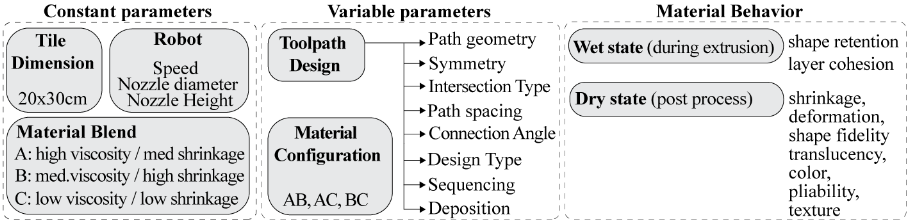

Figure 2. Yeast-cellulose hydrogel crafting framework with key design parameters.

The constant parameters in the framework include robotic 3D printing settings (nozzle diameter, deposition speed, nozzle height), tile size (standardized to 20 cm × 30 cm), and material blends (A, B, C). The variable parameters include material blend configurations (AB, AC, BC) and deposition path characteristics, namely, path geometry (points, lines, curves), design type (geometric, cellular, force field-based), spacing (distances between path features), deposition (strand-based, droplet-based, injection-based), layer sequencing (single, double, cross-layer), symmetry (symmetric/asymmetric along transverse or longitudinal axis), connection angle (0-180˚), and intersection type (point-based, tangential, extended, overlapping).

Considering various configurations of these constant and variable parameters, the framework enables design experimentation with comparative analyses of material effects in wet (immediately after 3D printing) and dry states (after one week of ambient drying). In the wet state, the key factors influencing the appearance of 3D printed objects include shape retention and interlayer cohesion. In the dry state, key factors are shrinkage, deformation, shape fidelity, translucency, colour, texture, and pliability.

4.2. TOOLPATH DESIGN AND MATERIAL BLEND SELECTION

Comparative analyses between 20 cm × 30 cm robotically 3D printed tiles, featuring different geometric designs of the 3D printing paths and different sets of parameters from the material crafting framework demonstrate how material blend selection can be done in connection with specific geometric feature types (Figure 3).

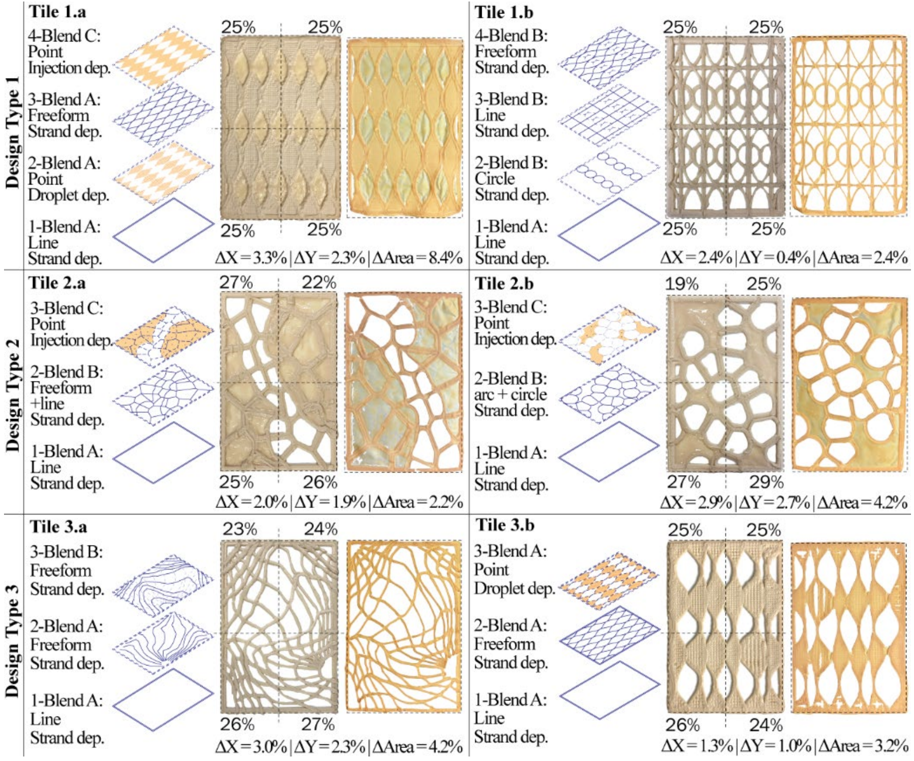

Figure 3. Tile configurations representing three parametric design types: geometric (1.a, 1.b), cellular (2.a, 2.b), and force field-based (3.a, 3.b), along with their toolpath geometry, layering sequences, material blend selections. Resultant tiles are shown in a wet and dry state with quadrant symmetry and shrinkage percentage data.

Tiles 1.a and 3.b demonstrate that material blend A is best fit for 3D printing of linear and point-based geometric features, helping maintain continuity along sharp angled paths without causing material drag or collision. Being highly viscous, blend A facilitates accuracy in extrusion, particularly for lattice-like or grid-based patterns with clear layer articulation. Tiles 1.b and 3.a show that blend B successfully accommodates constant and non-uniform directional changes during extrusion, balancing stiffness and flexibility for curved, radial, or freeform geometries, preventing deformation and cracking during ambient drying. In contrast, tiles 1.a, 2.a and 2.b show that blend C, due to its low viscosity, is most useful when applied as infill, surface finish, or to enhance interlayer cohesion between lattice-like patterns. Overall, aligning material viscosity with toolpath geometry is crucial for preserving feature fidelity and cohesion.

4.3. TUNABLE DESIGN EFFECTS

The application of the material crafting framework in the tile prototyping experiments display how strategic choices of material blends, layering, and deposition techniques in computational workflows allow craft-like tuning of material effects, including post-print geometric responses (tile outline dimensions, deformations, interlayer cohesion) and surface qualities (visual appearance, stiffness and texture).

Shrinkage and dimensional accuracy of tiles in the dry state can be regulated by applying the symmetry rules shown in Figure 4. Toolpath axiality and directionality are critical, as paths aligned with the tile's longer axis (in the case of rectangular tile shapes) tend to shrink more along the shorter axis. To minimize shrinkage, the material distribution should be balanced, with each quadrant containing 20–30% of the tile’s total deposited material. Values outside of this range (<20% or >30%) increase distortion. Fully solid tiles, such as Tile 1.a in Figure 3, exhibit 8.4% shrinkage despite symmetrical material distribution in each quadrant, due to the larger material volume and more water evaporation. Therefore, balanced material distribution across quadrants containing solid areas (Figure 3, Tile 2.a) is essential to preserve dimensional accuracy.

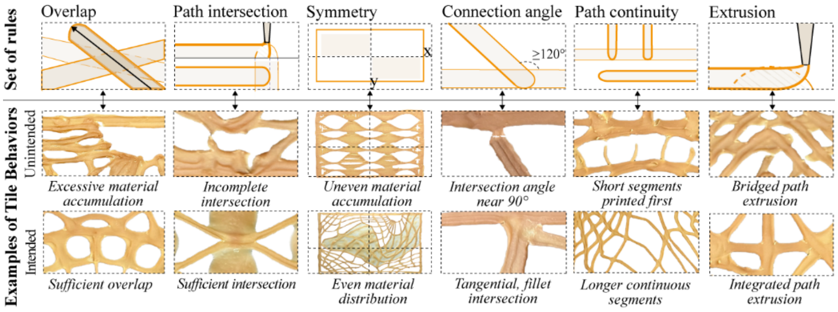

Figure 4. Computational geometric design rules and their resultant material effects in 3D printed hydrogels from yeast and cellulose.

The level of tile deformation can be controlled by reducing or eliminating the occurrence of dense, closely distributed path intersections, which cause surface irregularities arising from material accumulation at path intersections. Continuous deposition paths shrink less during ambient drying than those with fragmented segments. Short or isolated segments are prone to disconnections and cracking. Therefore, geometric designs of deposition paths should feature continuous, overlapping paths, where upper extrusions merge with lower layers, ensuring interlayer bonding in accordance with overlap, path intersection and continuity rules (Figure 4).

Interlayer cohesion can be enhanced by adjusting path connection angles and intersection types. Extruded paths should connect at a tangential (0°) or obtuse (≥120°) angle for stronger cohesion, as straight (90°) or acute angles (<60°) are prone to detachment. To further reinforce path end-point intersections, one can adjust the connection angle and select segment adjustment at intersection. This can be achieved by extending a printed path over another, changing a perpendicular connection to tangential, or adding an extra point at the connection for material accumulation. Together, these principles constitute a set of design rules illustrated in Figure 4, that enable the tuning of the geometric design of 3D printing paths to ensure dimensional accuracy, minimized deformation, and layer cohesion for yeast-cellulose hydrogels.

Surface qualities can be tuned by adjusting the framework parameters. Colour saturation and translucency can be varied by altering material deposition, path design, layer order, and blend selection (Figure 5a). Droplet-based deposition with Blend A forms pixelated nodes with high saturation, while changing layer-overlap frequency and path repetition produces darker or lighter zones. Blend B, being semi-opaque, enables tone gradients along layered linear and freeform curve paths. For controlled light transmission, Blend C can be injected in different thicknesses, creating graded translucency.

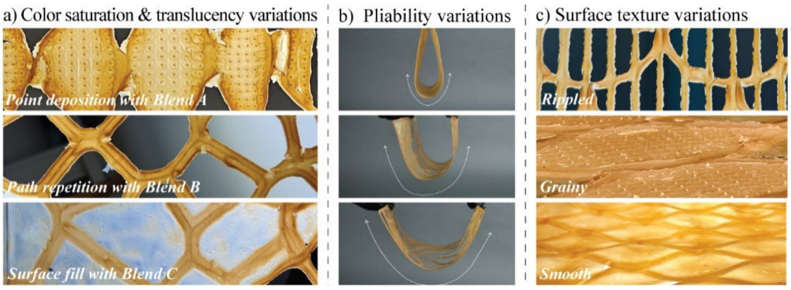

Figure 5. Craft-like tuning of visual and tactile properties of the yeast- and cellulose-based hydrogel.

Material blend choices and deposition path types also influence tile pliability (Figure 5b). Interlaced or dense lattice formations with Blend A produce rigid tiles (Figure 3, Tile 1.d and 3.b). Radial and curved geometries printed with Blend B create moderately flexible tiles (Figure 3, Tile 1.c and 3.a). Pliability increases when Blend C is used as infill between stiffer lattice lines (Figure 3, Tile 2.a and 2.b).

Surface texture can be tuned through deposition strategy and blend choice (Figure 5c). Rippled textures can be created by strand-based deposition with Blend A and B. Sharper and grainy textures, can be achieved using point-based droplet extrusion. Smooth surfaces with diffused toolpath traces can be generated via injection-based deposition with Blend C. Key design effects and parameters are compiled in Table 1.

Table 1. Mapping of geometry, material blend, and deposition parameters to design effects.

Geometry	Blend	Deposition	Design effect
Line/Freeform curve	A	Strand	Opaque, rippled, rigid
Point	A	Droplet	Opaque, grainy, rigid
Circle/Arc/Freeform curve	B	Strand	Opaque & translucent, rippled, moderately flexible
Point/Freeform curve	C	Injection	Translucent, smooth, highly flexible

5. Conclusion

This work contributes to architectural research on 3D printed hydrogel biomaterials by introducing digital material crafting strategies for a new yeast-cellulose hydrogel. The proposed rules for geometric path design, blend selection, and deposition strategies, offer adaptability to intended aesthetic effects, shape fidelity control, and help prevent drying-related deformation.

While this study advances understanding of geometry-material relations enabled by bespoke computational design and 3D printing, several methodological limitations remain. The prototyping series varied multiple parameters simultaneously and produced each configuration once, limiting attribution of effects to individual variables and reducing statistical confidence. These choices reflect the exploratory, research-by-design nature of the work but indicate the need for greater experimental control. Future research should use single-parameter testing and multiple replicates to address biomaterial variability and strengthen the framework's generalizability.

The material shows promise for lightweight, non-load-bearing interior and decorative applications but is not yet optimized for structural or exterior use, nor benchmarked against established standards. Observed shrinkage, interlayer cohesion, and cracking provide early insight into environmental and mechanical response. Further evaluation of moisture cycling, thermal expansion, and fire performance, along with natural post-processing coatings, will be required to improve durability.

Altogether, the findings demonstrate the computational and robotic crafting potential of the 3D-printable yeast–cellulose hydrogel, highlighting its architectural relevance and scalability toward larger panels, adaptive surfaces, and building skins. Its biodegradability makes it suitable for temporary exterior structures where controlled material change can become a design asset, while its light weight, stability, and tuneable translucency and texture enable interior uses as claddings, screens, partitions, and decorative elements. These qualities highlight its potential as a renewable, circular alternative to mass-manufactured, fossil-based products.

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Attribution Statement

Portions of this manuscript were revised with the assistance of Microsoft Copilot, which was used for text editing and clarity improvements. All conceptual content and conclusions are the authors' own.

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