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Bektas, Y., Zboinska, M., Geijer, C. et al (2026). Novel 3D printable yeast-based materials for architectural applications. *Frontiers of Architectural Research*, 15(6): 2337-2356.
<http://dx.doi.org/10.1016/j.foar.2026.01.003>

N.B. When citing this work, cite the original published paper.

RESEARCH ARTICLE

Novel 3D printable yeast-based materials for architectural applications



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Received 22 October 2025; received in revised form 18 December 2025; accepted 9 January 2026

KEYWORDS

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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Peer review under the responsibility of Southeast University.

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 (Gavrilidis 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 (Obodaïet 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 $21.8 \pm 0.5^\circ\text{C}$ and humidity $30.5\% \pm 4.4\%$). 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 $100\times$ 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 $1\text{ cm} \times 1\text{ cm}$ 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 $900\times$. The LED detector was used to capture secondary electron signals, and images were acquired at a scale of $10\text{ }\mu\text{m}$. Fine scan settings were applied 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 $2\text{ cm} \times 2\text{ cm}$ 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 $5\text{ cm} \times 5\text{ cm}$ and $7\text{ cm} \times 7\text{ cm}$, 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

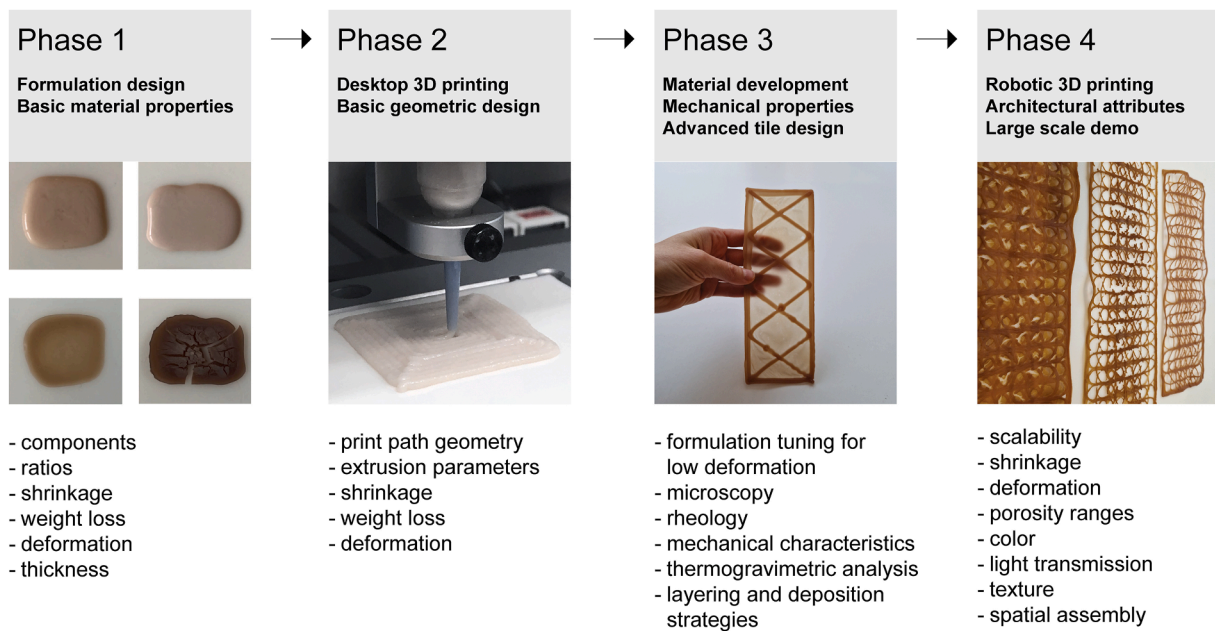


Fig. 1 Development workflow for yeast-based materials applied in robotic 3D printing of architectural wall tiles.

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 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 $30.5\% \pm 4.4\%$, for 2–3 days (for constructs measuring 2 cm $\times$ 2 cm, 5 cm $\times$ 5 cm and 7 cm $\times$ 7 cm), 3–5 days (for 7 cm $\times$ 20 cm constructs), and 7–10.5 days (for 20 cm $\times$ 50 cm constructs).

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

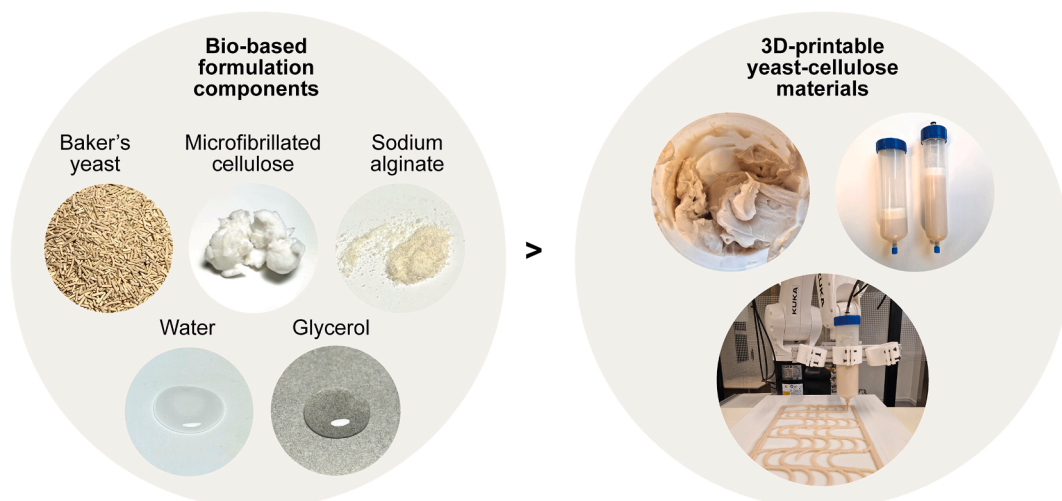


Fig. 2 Yeast material composition.

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

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):

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

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):

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

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 $20 \text{ cm} \times 50 \text{ cm}$ architectural tiles was measured using a digital micrometer (Limit MDA 25, Sweden) with a measurement range of $0\text{--}25 \text{ mm}$, resolution of 0.001 mm and accuracy of $\pm 0.002 \text{ mm}$. 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 $20\text{--}800^\circ \text{C}$, 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):

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

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-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, 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.

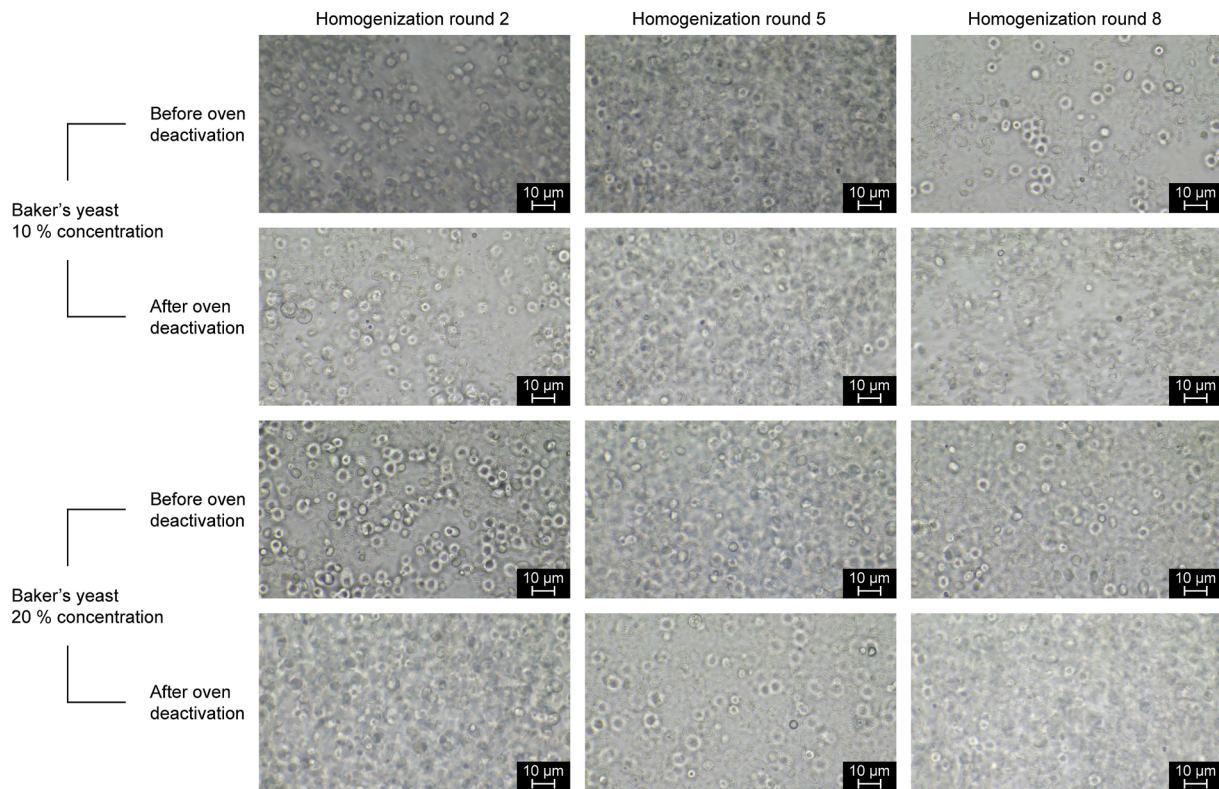


Fig. 3 Microscope images showing baker's yeast cell disruption after two, five and eight homogenization rounds at 10% and 20% concentrations.

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

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

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 than 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 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

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.

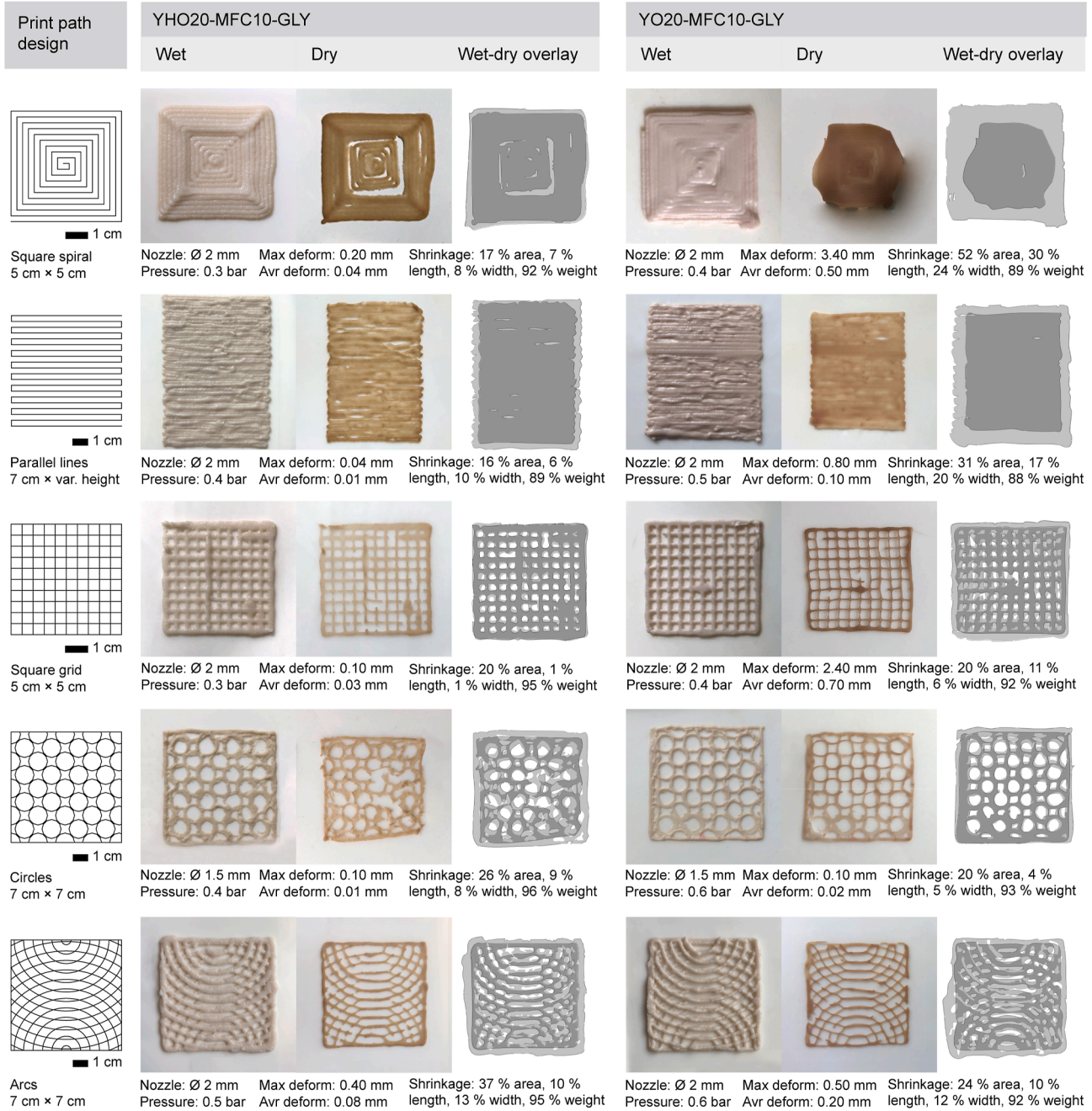


Fig. 4 Comparison between different geometric path designs for 3D printing and resulting deformations and shrinkage for constructs from homogenized (YHO20-MFC10-GLY) and oven deactivated (YO20-MFC10-GLY) yeast formulations.

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.

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 ($20,258 \text{ Pa}\cdot\text{s}$ 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 ($13,144 \text{ Pa}\cdot\text{s}$), 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 $25.2\% \pm 2.9\%$ and $19.1\% \pm 3.1\%$, 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 $7 \text{ cm} \times 20 \text{ cm}$ were 3D printed using a custom pressure-based extrusion system deployed on an industrial robot, using four formulations (Table 4) deposited 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., 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

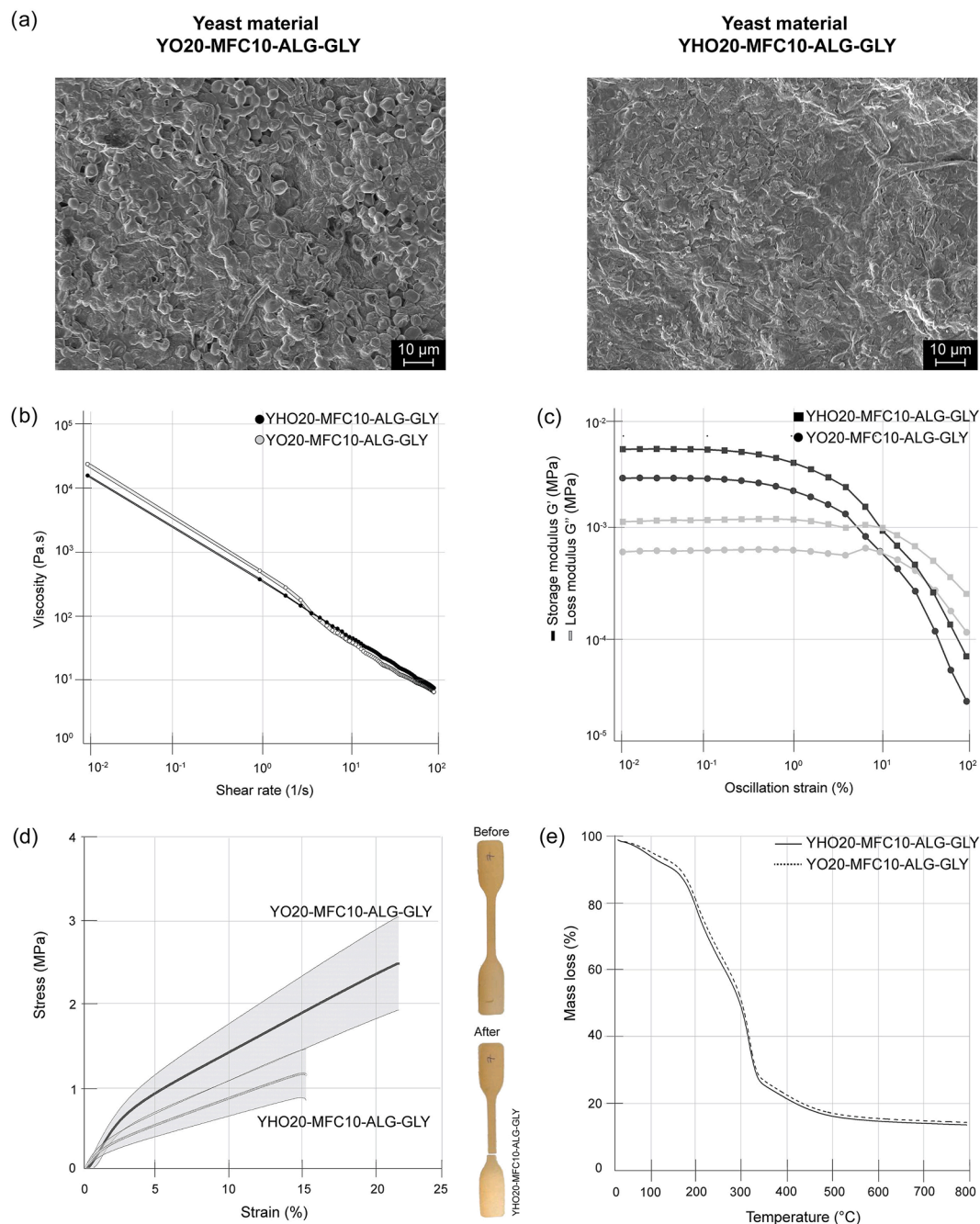


Fig. 5 Multi-scalar property characterizations for yeast-based formulations YHO20-MFC10-ALG-GLY and YO20-MFC10-ALG-GLY: (a) scanning electron microscopy (SEM) images, (b) viscosity versus shear rate profiles, (c) oscillatory strain sweeps comparing storage (G') and loss (G'') modulus, (d) stress–strain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

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-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

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	

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-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.

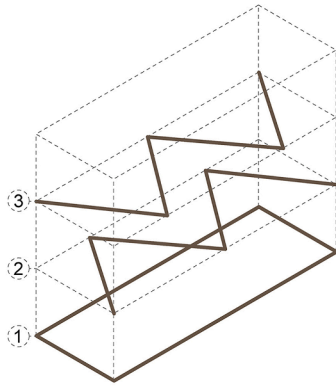
Table 6 Mechanical properties of comparable bio-based film materials.

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 <i>Saccharomyces cerevisiae</i> , glycerol) (Delgado et al., 2018)	3.1 ± 0.3	7.0 ± 1.8
Reinforced microbial film (homogenized yeast <i>Saccharomyces cerevisiae</i> , glycerol, rice husk cellulose nanofibers) (Delgado et al., 2021)	1.5 ± 0.2	11.0 ± 2.0
Reinforced microbial film (homogenized yeast <i>Saccharomyces cerevisiae</i> , glycerol, bacterial nanocellulose) (Delgado et al., 2021)	2.3 ± 0.4	18.0 ± 3.0
Bio-based composite microbial film (intact yeast <i>Meyerozyma guilliermondii</i> , bacterial cellulose, carboxymethyl cellulose, glycerol) (Atta et al., 2021)	2.2 ± 0.3	15.5 ± 0.8

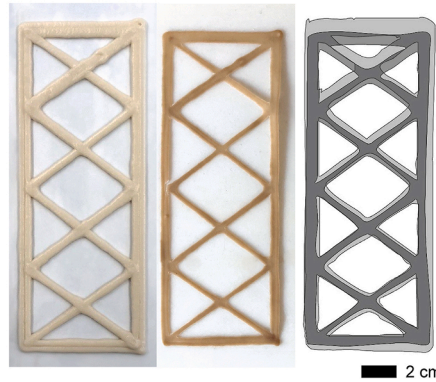
Material layering strategies

Tile fragments 7 cm × 20 cm

(a) Perforated design, no infill

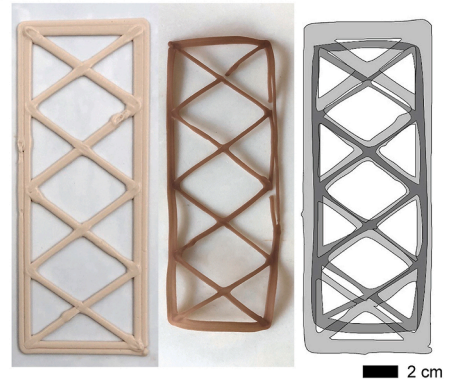


(b)



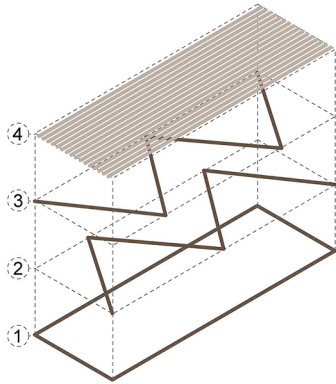
1. YHO20-MFC10-ALG-GLY Max deform: 3.50 mm
2. YHO20-MFC10-ALG-GLY Avr deform: 0.70 mm
3. YHO20-MFC10-ALG-GLY Shrinkage: 28 % area, 6 % length, 4 % width, 60 % weight

(c)



1. YO20-MFC10-ALG-GLY Max deform: 4.40 mm
2. YO20-MFC10-ALG-GLY Avr deform: 1.00 mm
3. YO20-MFC10-ALG-GLY Shrinkage: 52 % area, 12 % length, 10 % width, 53 % weight

(d) Solid design, overlaid infill

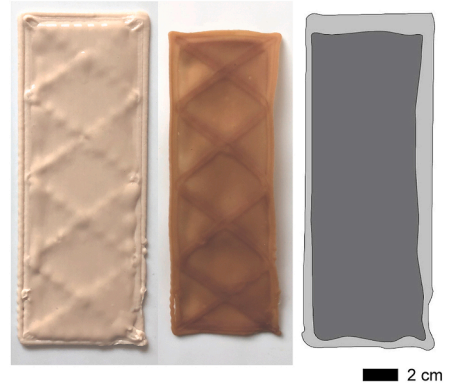


(e)



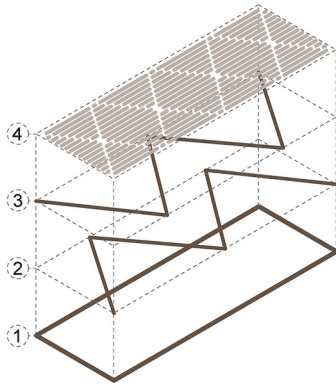
1. YO20-MFC10-ALG-GLY Max deform: 1.50 mm
2. YO20-MFC10-ALG-GLY Avr deform: 0.20 mm
3. YO20-MFC10-ALG-GLY Shrinkage: 14 % area, 4 % length, 7 % width, 68 % weight
4. YHO20-MFC2-ALG-GLY

(f)

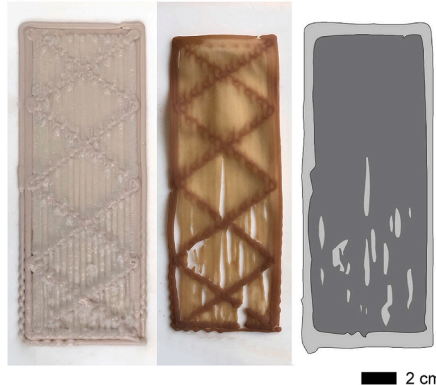


1. YO20-MFC10-ALG-GLY Max deform: 0.10 mm
2. YO20-MFC10-ALG-GLY Avr deform: 0.02 mm
3. YO20-MFC10-ALG-GLY Shrinkage: 23 % area, 8 % length, 14 % width, 56 % weight
4. YO20-MFC2-ALG-GLY

(g) Solid design, in-between infill

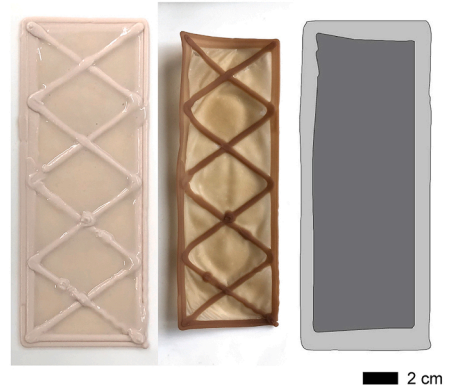


(h)



1. YO20-MFC10-ALG-GLY Max deform: 0.20 mm
2. YO20-MFC10-ALG-GLY Avr deform: 0.05 mm
3. YO20-MFC10-ALG-GLY Shrinkage: 24 % area, 9 % length, 10 % width, 67 % weight
4. YHO20-MFC10-ALG-GLY

(i)



1. YO20-MFC10-ALG-GLY Max deform: 0.40 mm
2. YO20-MFC10-ALG-GLY Avr deform: 0.10 mm
3. YO20-MFC10-ALG-GLY Shrinkage: 32 % area, 9 % length, 22 % width, 63 % weight
4. YHO20-MFC2-ALG-GLY

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

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

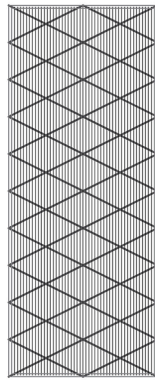
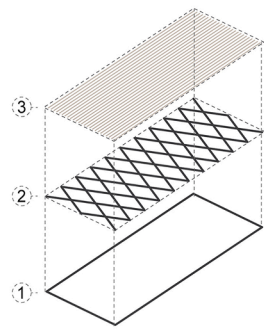
For the architectural application evaluation and demonstration, 17 rectangular tiles, each with outer dimensions 20 cm × 50 cm in wet state, were robotically 3D printed using three material formulations from Table 4, where YHO20-MFC10-ALG-GLY and YO20-MFC10-ALG-GLY were used as pattern material and YHO20-MFC2-ALG-GLY 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 (≥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 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.

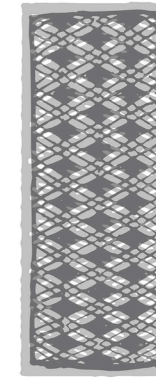
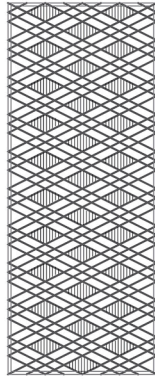
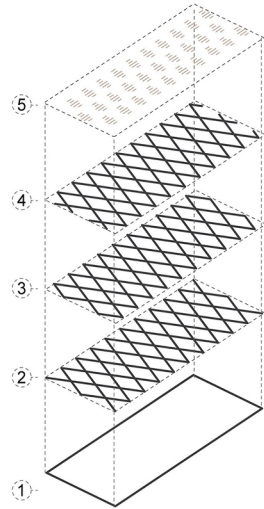
The outer edge deformation analysis (Table 9) revealed similar trends. The solid and perforated construct maintained consistent outlines, with average deviations of 0.17 mm and 0.11 mm, respectively, and maximum

Material layering strategies Architectural tiles 20 cm × 50 cm**(a) Solid design, full infill**

5 cm

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

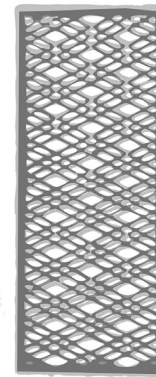
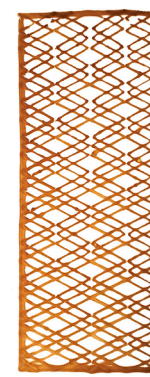
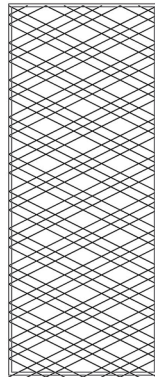
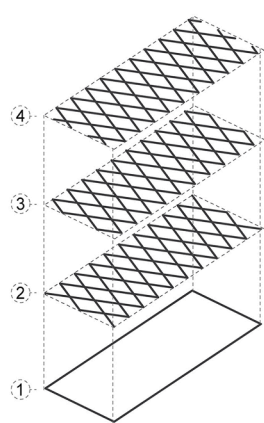
Shrinkage: 6 % area, 2 % length, 4 % width, 83 % weight
 Average thickness: 1.8 ± 0.2 mm (lattice), 0.4 ± 0.06 mm (infill)
 Maximum deformation: 0.27 mm
 Average deformation: 0.17 mm

(b) Hybrid design, partial infill

5 cm

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

5 cm

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.

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 $\times$ 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 light-weight, 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 light-weight 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 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 products from yeast and cellulose biomass. With further research addressing long-term durability and optimization

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

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

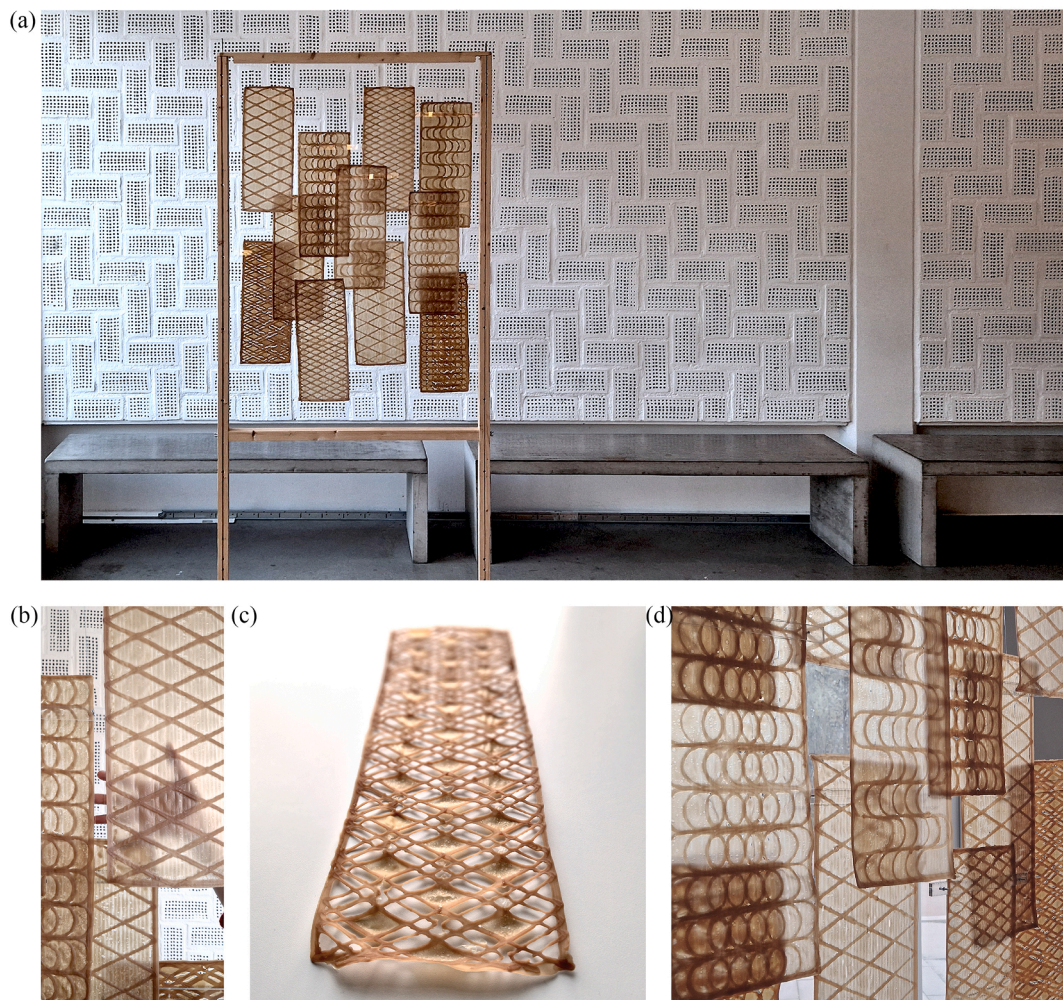


Fig. 8 (a) Architectural demonstrator featuring diverse yeast tile designs displaying aesthetic versatility of the yeast material through variable (b) translucency, (c) color and texture, and (d) layering effects.

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.

Acknowledgements

This work was supported by the Swedish Energy Agency (Grant Nos. P2022-00865, P2024-02409). The authors would like to acknowledge the support of Michael Martindale and Jonas Ravn with light microscopy, Eliott Orzan with tensile testing, Punchalee Montriwat and Vijay Raghavendran with homogenization, and the Chalmers Materials Analysis Laboratory (CMAL) with scanning electron microscopy (SEM). The authors would also like to thank the sustainable bio-refinery Borregaard for the generous MFC material sample provision.

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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