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Biobased coatings for architectural timber applied using the robotic 3D printing technique

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ABSTRACT
Materials applied for coating architectural timber are often environmentally harmful. This study examines a sustainable alternative – a coating from microfibrillated cellulose hydrogel applied for the first time on architectural timber using robotic 3D printing. The proposed solution is evaluated through architectural design and robotic 3D printing experiments, with patterned coating designs deposed onto eight architectural mockups. Through qualitative and quantitative analyses of coating features preproduction and postproduction, fundamental aspects affecting coating design are identified, namely, the 3D printing path geometry and layout, substrate type, and precoating material. These aspects are correlated with the final architectural coating qualities at the mesoscale and macroscale by characterizing dimensional stability, geometric features, and color appearance. The best coating effects are observed for pine substrates precoated with hydroxyethyl cellulose. By delivering new knowledge on biobased architectural coatings, this study contributes to the global effort of phasing out fossil-based materials in the built environment.

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Biobased building materials; nanocellulose hydrogels; architectural coatings; timber renovation; robotic 3D printing; toolpath design

Introduction

There is a pressing need today to implement circularity principles in architectural design when creating new structures and when reusing, renovating, and preserving the existing ones. The European Union has identified reuse and recycling as key strategies for a sustainable built environment (European Commission 2019). In the long-term, these strategies should be prioritized over new construction and demolition (Baker-Brown 2019). Consequently, it has become evident that an emerging generation of building materials that are reused and upcycled from waste streams exhibits great potential to replace more resource-draining solutions. Many of these new materials can be derived from the material side streams of the world's largest industries. One such material resource is biomass, which is an abundant byproduct of agriculture, forestry, marine farming, and the food industry. Currently, there is a strong research front developing new materials from biomass for various applications, including the built environment, where they could contribute to its sustainability. At the same time, these novel biobased materials exhibit properties different from those found in well-known building materials, and extensive research is needed to demonstrate their potential for near-future applications in architecture. For this reason, how to design building elements from these materials is one of the key topics addressed in architectural research today.

At present, diverse biobased building materials are being investigated, including natural materials, such as earth (Gomaa et al. 2021), clay, salt, and sand (Crawford et al. 2022; Kontovourkis, Tryfonos, and Georgiou 2020; Rael and San Fratello 2018), cellulose-based composites (Chiujdea and Nicholas 2020; Rech et al. 2022), algal hydrogels (Malik et al. 2020), chitosan (Duro-Royo, Mogas-Soldevila, and Oxman 2015), and microbial materials, such as bacterial cellulose (Hoenerloh, Sonne, and Nicholas 2024) and mycelium (Attias et al. 2020; Soh et al. 2020). This overview of published studies on architectural biobased materials indicates that hydrogel materials from biomass featuring small microcellulosic fibers, i.e. microfibrillar cellulose and nanocellulose, have not yet been the subject of investigation.

Furthermore, a major part of current architectural research focuses on demonstrating the use of biobased materials in the production of standalone building components. Conversely, studies on the application of these materials as a part of hybrid material systems that feature fusions of different materials are sparse and fragmented. Among these few studies, one has addressed the maintenance of damaged elements from a cellulose-based composite by proposing the 3D printing of reparative infills from the same material (Chiujdea et al. 2024). In the author's prior pilot study on the relevance of biobased coatings in the context of experimental historic preservation, coatings from microfibrillated cellulose were robotically 3D-printed onto substrates from birch (Rudin et al. 2023). Outside the realm of biobased material applications, two studies proposed to repair cracks in concrete and asphalt using 3D printing (Gong et al. 2022; Yeon, Kang, and Yan 2018). A congruent application of concrete through spraying and deposition onto existing vertical wall structures was also demonstrated (Lu et al. 2019; Lublasser et al. 2018). Further, product repair by 3D printing the missing or damaged parts was suggested in product manufacturing (Maidin et al. 2023; Van Oudheusden et al. 2023). Finally, the replication of ornamental building details

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through 3D printing and computer-numerically controlled (CNC) milling was demonstrated in heritage conservation (Bonora et al. 2021; Higueras, Calero, and Collado-Montero 2021; Jesus et al. 2023). Collectively, prior work shows increased research efforts toward validating the utility of 3D printing in repair interventions by combining new and existing materials. However, the use of biobased materials specifically for this purpose remains underexplored, representing a knowledge gap to be filled.

It is essential to fill this gap not only to complement the existing knowledge but also to implement the already mentioned policies in the EU and beyond, prioritizing building material renovation and reuse instead of combustion and landfill disposal. Because many reused components will require the re-establishment of their aesthetic qualities, it is paramount to develop solutions for their sustainable renovation. As mentioned above, the current knowledge on how materials from biomass could be joined with existing materials to revive or embellish them is very limited. One specific instance of this uncharted research topic embraces the coating of building components from timber. Timber is present in nearly every building. Coatings form its essential finishing layer. However, many materials for coating timber, such as acrylic paints, latex varnishes, and silicone rubber based primers, are fossil-based, environmentally harmful, and even detrimental if applied onto wood (Izzo et al. 2014; Larsen and Marstein 2016). Hence, given the commonality of coated timber elements in the built environment, it is essential to investigate more sustainable, biobased coating alternatives.

Contrary to the deficit of studies on biobased timber coatings in architecture, several studies exist in the adjacent field of heritage conservation. Therein, biobased material solutions for the repair and preservation of historic paintings, papers, textiles, and even architectural timber are being explored (Fornari et al. 2022; Wang, Feng, and Liu 2023). Notably, the use of biobased hydrogel coatings featuring microsized and nanosized cellulose fibers was reported (Basile et al. 2018; Böhme et al. 2020; Cianci et al. 2022; Nechyporchuk et al. 2018). However, in these studies, the coatings were examined only in small samples. Therefore, their application on a larger scale remains unexplored. Furthermore, the characterizations of these coatings were performed at the nanoscale and microscale, and were regarding the mechanical and chemical properties, such as tensile strength and surface charge. Therefore, the properties of these coatings at the mesoscale and macroscale are not well known, and the properties at those two scales are paramount for establishing their application in buildings. Consequently, the work presented herein fills these gaps by providing new insights into the architectural-scale applications of biobased coatings from microfibrillated cellulose for building elements from wood.

Another novelty of this work is the use of custom robotic 3D printing as a coating application method, in contrast to current approaches based on manual brushing, spray coating, bar coating, dip coating, roller coating, spin coating, and foam coating (Cherian et al. 2022). The choice of 3D printing arises from its sustainable trait of being waste-free (Beyhan and Arslan Selçuk 2018; Oke, Atofarati, and Bello 2022) and its capability to discretize the distribution of the material on the treated surface. As such, 3D printing presents a novel method that brings in the benefits of material efficiency and a high level of customization that are not present in the other coating techniques.

The application scope for coatings in this study was limited to their use as patterned embellishments for timber details. In future studies, this scope can be broadened to address the functional properties of the material. However, in this work, the focus was intentionally limited to aesthetic qualities as they are fundamental from an architectural design perspective while providing an essential basis that will inform future functional property studies. The investigated coating material was microfibrillated cellulose (MFC) hydrogel. Contrary to synthetic paints made from harmful chemicals including plasticizers, silicone oils, defoamers, stabilizers, and metal soaps, the MFC material has a simple composition comprising cellulose nanofibers dispersed in water as a hydrogel suspension. Such nanofibers can be obtained from side-stream products of large global industries that handle cellulosic biomass from plants and trees, i.e. forestry, paper mills, and agriculture. The acquisition of nanofibers from biomass can be conducted in a sustainable process in which microbial enzymes break down cellulose pulp into nanoingredients (Hüttner et al. 2017; Kumar et al. 2022). In this way, the abundant biomass does not become waste but is rather upcycled to create new materials.

On the basis of the identified research gaps and the research scope defined above, the objectives of this study were the following:

(1) to demonstrate the first architectural application of bio based MFC coatings for timber using robotic 3D printing;
(2) to demonstrate the potential of various future applications of these coatings not only in new timber elements but also in the renovation and historic preservation of aged timber;
(3) to identify and characterize the key design aspects affecting the final appearance of the coatings at the mesoscale and macroscale.

It was essential to conduct this study from its global impact perspective because the delivered findings are relevant for many stakeholders and fields of research and application. In addition to the new knowledge contribution that addresses the current research gaps and serves as a springboard for further scientific studies of biobased coatings, the study also provides essential insights for practice and industries. The expected beneficiaries of this study are architectural designers, historic preservationists, construction and renovation companies, property owners, and manufacturers of paints, varnishes, and coatings. The characterizations of biobased coatings applied onto existing surfaces provided in this work can also be relevant for advancing other industrial applications, beyond buildings and their components, such as in the design and manufacturing of interior fittings, tapestries and acoustic paneling, appliances and product design, furniture, automotive, and all other industries that deliver consumer goods made from coated or painted wood.

Materials and methods

The research rationale behind this study is non-hypothesis-driven and is based on inductive reasoning because of the novelty of the undertaken topic. Systematic literature studies conducted by the author have not allowed the identification of prior work that could form a reliable basis for hypothesis formulation, theory deduction, and direct comparison of findings. Owing to its novelty, the purpose of the study is to fill the current knowledge gap by providing the first comprehensive overview and deeper understanding of the topic. The overarching aim is to introduce the architectural science community to biobased coatings from MFC for architectural applications, providing the missing knowledge foundation that enables further basic and applied research.

Consequently, as there was no hypothesis to test or theory to apply, large dataset collection and statistical analyses thereof were not applicable. Instead, an experiment-driven inquiry was implemented. Prototyping experiments, in which the MFC hydrogel was robotically 3D-printed onto physical wooden mockups, were conducted to allow for a bottom-up construction of the missing knowledge foundation. This approach, known as research by design (Foqué 2010; Groat and Wang 2001; Verbeke 2013), is established in the architectural research field and is widely applied in the subfield of digital design and robotic fabrication (Ramsgaard Thomsen and Tamke 2016). By developing knowledge through the conduct of design and prototyping experiments, this method facilitates wider research impact on practice because it conveys the findings through the hands-on medium of the prototype, which is easily comprehensible by practitioners (Zboinska 2021). Further, the characteristic means of the architectural research inquiry used herein, i.e. qualitative observations and visual analyses of the prototypes at mesoscale and macroscale, supplemented with basic measurements and quantification of the most essential effects identified through visual observations, are geared to promote the effective reception and swift uptake of new solutions by the architectural design community. Thus, during the experiments, the coating material transitions upon ambient drying were rigorously documented in digital photographs, and the analyses of this photographic evidence, together with the systematic ocular inspection and comparative analysis of the prototypes, have led to the establishment of the design aspects and architectural characteristics of 3D-printed biobased coatings at the macroscale and mesoscale.

Architectural prototyping procedure

The experimentation procedure in the study followed the steps presented in Figure 1. Four architectural details from existing buildings were reproduced as scaled mockups using two types of timber commonly used in construction, namely, spruce and pine, resulting in a total of eight fabricated prototypes. The reason for investigating two timber types was to compare how well the MFC hydrogel coatings adhere to these two types of wood and to determine the differences in the aesthetic presentation of the final coatings for these two substrate types.

Architectural detail selection and physical mockup prototyping

Four architectural details for the prototyping experiments were chosen to capture a basic range of geometric expressions typically found in such details – from simple planar features to more complex, ornamental ones. All details are found in buildings located in Gothenburg, Sweden. They comprise fragments of wall cladding, a mezzanine railing, a frieze, and a sculpted beam (Figure 2).

These details were photographed on-site from various angles, to create their digital twin models using the photogrammetry technique featured in the software Agisoft Metashape. The resultant meshes representing the details were then imported into McNeel's Rhinoceros 3D, subjected to mesh face count reduction, and scaled to match real-world dimensions. In the next step, a quarter of each detail was extracted from the main mesh, copied, and mirrored using a custom parametric procedure in Rhinoceros Grasshopper to generate four identical quarters. The identical quarters were needed for comparative analyses in the later stages of prototyping and coating.

The scaled detail replicas were manufactured using three-axis CNC milling (Figure 3). First, eight spruce and pine substrates, each with total dimensions of 39 cm × 39 cm × 4 cm, were prepared by gluing three layers of material planks with a wood

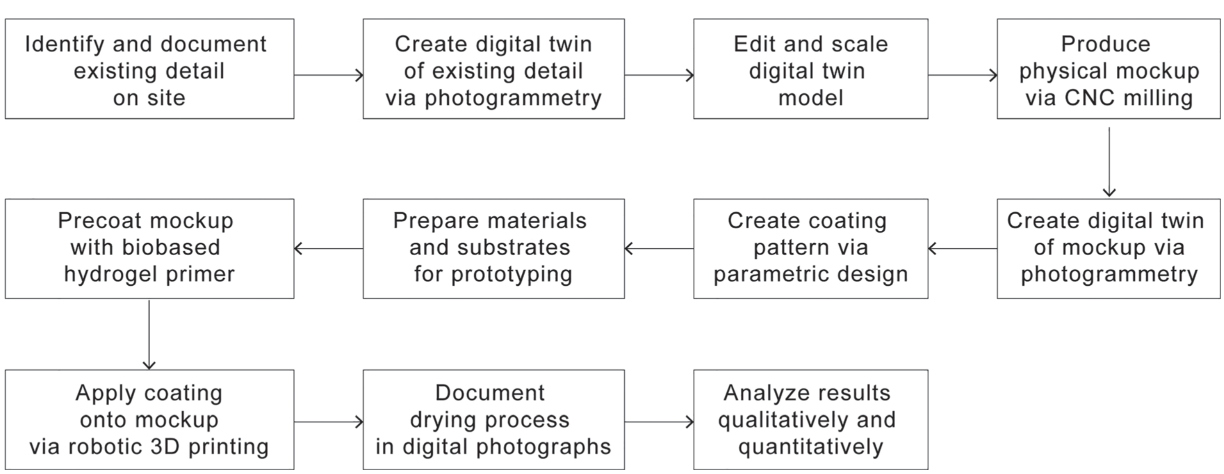

Figure 1. Architectural experimentation procedure applied in the study.

Figure 2. Architectural details sampled from existing buildings in Gothenburg, Sweden. (A) Wall cladding at Bergsjöns kyrka (1975, architect: Bo Cederlöf). (B) Mezzanine railing at the Natural History Museum (1923, architect: Ernst Torulf). (C) Frieze at Masthuggskyrkan (1914, architect: Sigfrid Ericson). (D) Sculpted beam at Masthuggskyrkan.

Figure 3. CNC-milled mockups of architectural detail fragments sampled from existing sites. (A) Wall cladding fragment. (B) Mezzanine railing fragment. (C) Frieze fragment. (D) Sculpted beam fragment.

adhesive. Then, the substrates were subjected to milling based on the digital twin model data. The milling paths were generated in a CNC routing program GibbsCAM based on the meshes in. STL format imported from Rhinoceros 3D.

Architectural design of coating patterns

Four different pattern designs for coating the selected timber details were created in Rhinoceros 3D and parametrically

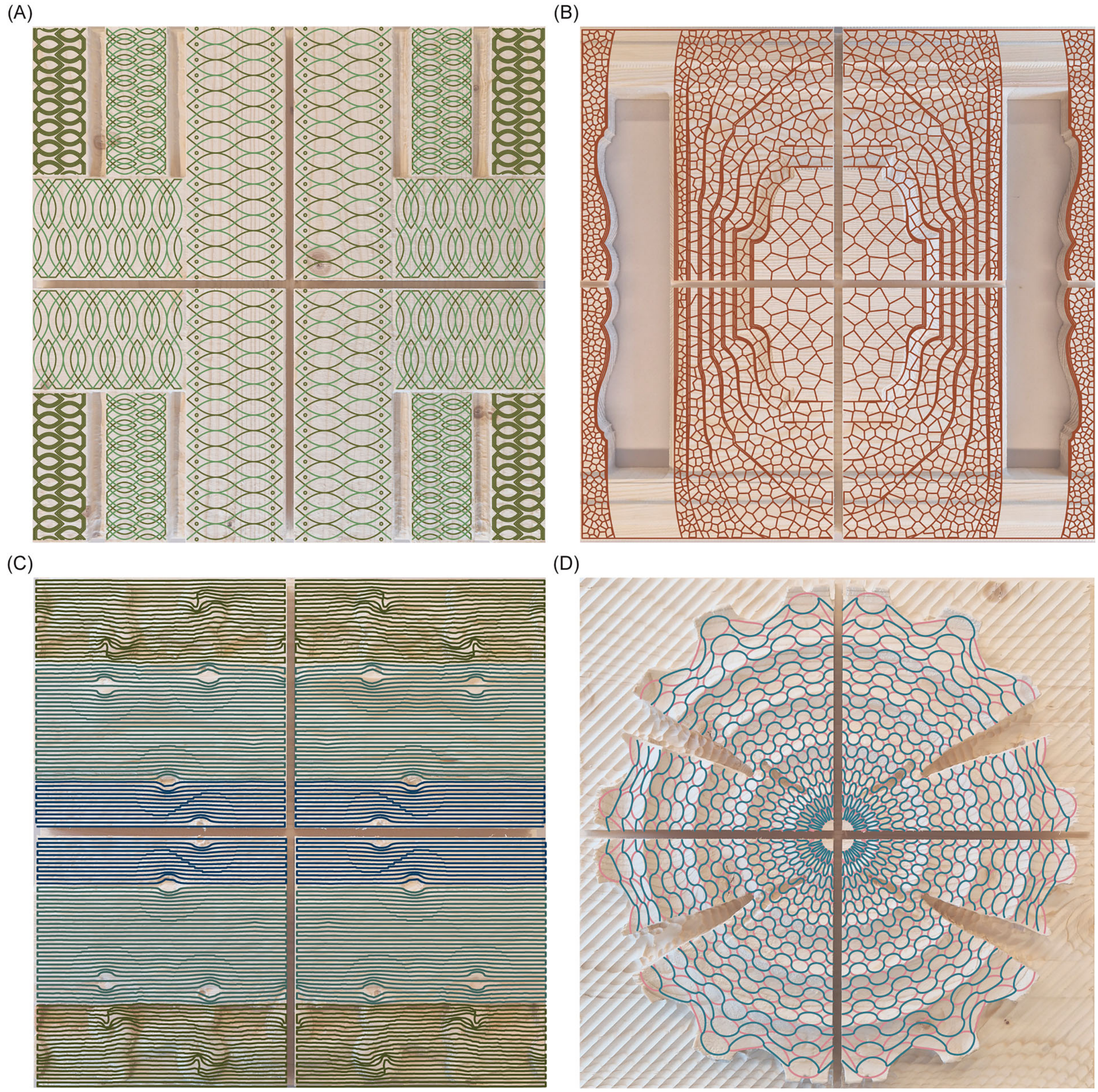

Figure 4. Parametric designs of coating patterns overlaid with mockup photographs. (A) *Ichthys* pattern for the wall cladding fragment. (B) Voronoi pattern for the mezzanine railing fragment. (C) Flowline pattern for the frieze fragment. (D) Circular pattern for the sculpted beam fragment.

defined using Grasshopper. The pattern designs aimed to conceptually refer to the architectural symbolism of the spaces in which they were located, while also seeking to represent diverse architectural expressions through varying geometric features, spacing, distribution, and coloring schemes (Figure 4). In the final stage of preparation for fabrication, all pattern designs were simplified and approximated into points, line segments, and polylines, to enable robotic 3D printing based on linear movements.

The wall cladding detail in the baptismal church Bergsjöns kyrka from the 1970s, shown in Figure 4(A), was designed to convey the symbolism of Christianity, encapsulated in the *ichthys* symbol. It was expressed in the pattern as mirrored arcs, multiplicated and distributed symmetrically in diverse densities, sizes, and arrangements across the plain surface of the detail. The pattern for the mezzanine railing of the Natural History Museum from the 1920s, shown in Figure 4(B), was designed to relate to the nature-based theme of the museum. It was inspired by the dragonfly wing structure. This pattern was created using a parametric procedure of Voronoi cell distribution and through curvilinear edge tracing following the detail's boundaries. The patterns for two details of the 1910s church, the Masthuggskyrkan, were designed to convey the naval symbolism upon which the original church design was based. The coating pattern for the frieze detail, shown in Figure 4(C), was generated by applying a parametric force field and flow lines adapted to the surface imperfections found in the frieze and in the final pattern symbolizing the sea waves. The coating pattern for the second detail, a sculpted beam section, shown in Figure 4(D), was based on an array of radially distributed, alternating half-circles. Through this, the pattern aimed to refer to the curvatures of ship hulls and to be congruent with the globally circular geometry of the treated detail.

Preparations of biomaterial blends

The MFC hydrogel investigated as a coating material was Exilva F-01-L (2% concentration of microfibrils), which was provided by Borregaard (Norway). The colored hydrogel was obtained by mixing the MFC suspensions with water-soluble food pigments from Oetker Group (Germany). The mixing was performed by dosing the pigments into syringes containing the hydrogel in estimated quantities and syringe-to-syringe mixing to evenly disperse the pigments in the material. The material quantities used in the study are compiled in Table 1.

In addition to the hydrogel blends for 3D printing, three hydrogel mixes for the precoating of the wooden substrates were prepared to compare their effectiveness in adhesion improvement for the main 3D-printed MFC hydrogel blend. The reason for precoating was to improve the main coating adhesion based on the findings from the author's pilot study (Rudin et al. 2023). The first precoating mix comprised pure MFC hydrogel. The second mix comprised sodium alginate powder from Special Ingredients (United Kingdom), mixed with water at 3% w/v concentration. The third mix comprised hydroxyethyl cellulose powder from Crearome (Sweden), mixed with water at 1% w/v concentration. The two latter hydrogel blends were prepared by weighing the powder in desired quantities and by gradually adding water while mixing at 18,000 rpm using a Bosch Ergo Mixx stirrer for 30 s. The blends were then left to gel for 30 min and dosed into syringes. Afterward, they were brushed manually onto the quarters of the milled mockups. This was performed in three layers, always in the same sequence and at the same quarter in each model (Figure 5). The mockups were then left to dry for approximately 1 h.

Robotic 3D printing and ambient drying of the coatings

To allow for the 3D printing of the coatings onto the CNC-milled mockups, they were digitalized using the photogrammetry technique via Agisoft Metashape. Once the digital twins of the mockups were created, the pattern designs representing the paths for robotic material depositing were adapted to follow the mockup geometries.

The instrumentation for the digital fabrication of the coatings included an industrial robot KUKA Agilus KR10, that was fastened to a table and equipped with an in-house built, pressure-based hydrogel extrusion nozzle mounted to the robot's flange (Figure 6). The mockups were placed on a printing bed mounted to the same table as that of the robot. To ensure that the physical setup matches the digital placement of the models and their accompanying coating pattern designs and to compensate for the

Table 1. Material quantities used in the 3D printing experiments for coating the spruce and pine substrates.

Prototype	Color	Material				
		MFC hydrogel(mL)	Red pigment(mL)	Blue pigment(mL)	Yellow pigment(mL)	Green(mL)
Cladding	bright green	180	–	–	–	0.20
	dark green	280	0.30	–	0.90	2.30
Frieze	blue	100	0.04	0.20	–	–
	Green	180	0.02	–	–	0.30
	blue–green	220	0.05	0.40	–	0.40
Railing	brown	480	1.50	–	1.60	1.00
Beam	red	150	0.10	–	–	–
	Blue	150	–	0.10	–	–

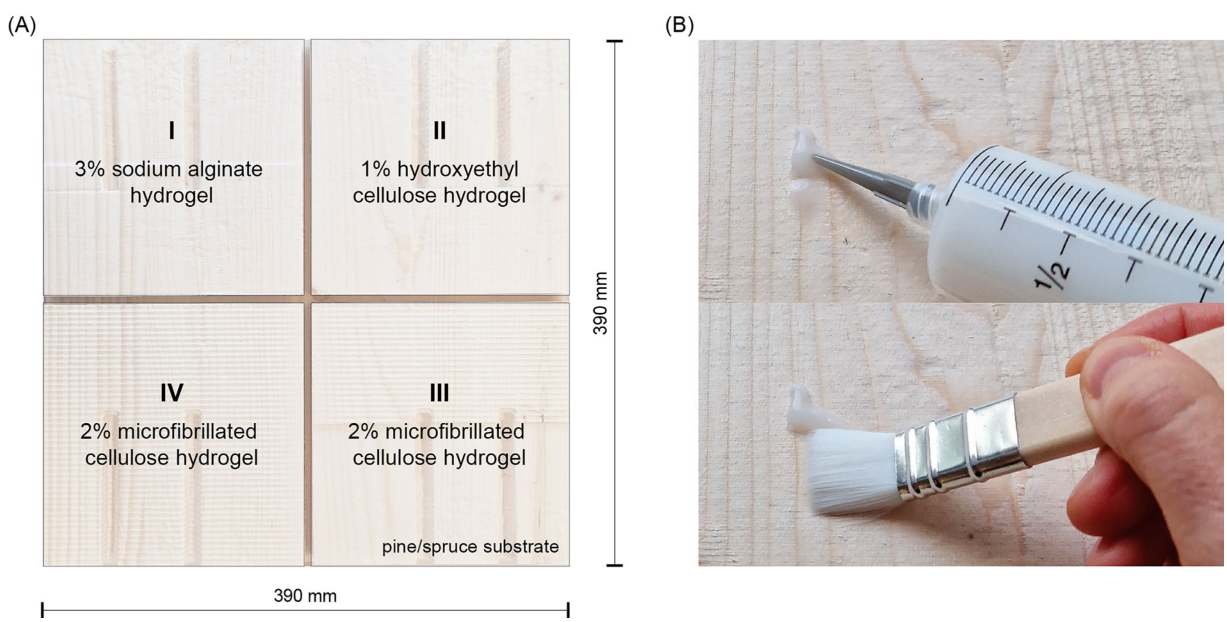

Figure 5. Precoating logic for the mockups. (A) Precoating arrangement for each substrate. (B) Application of the precoating via manual brushing.

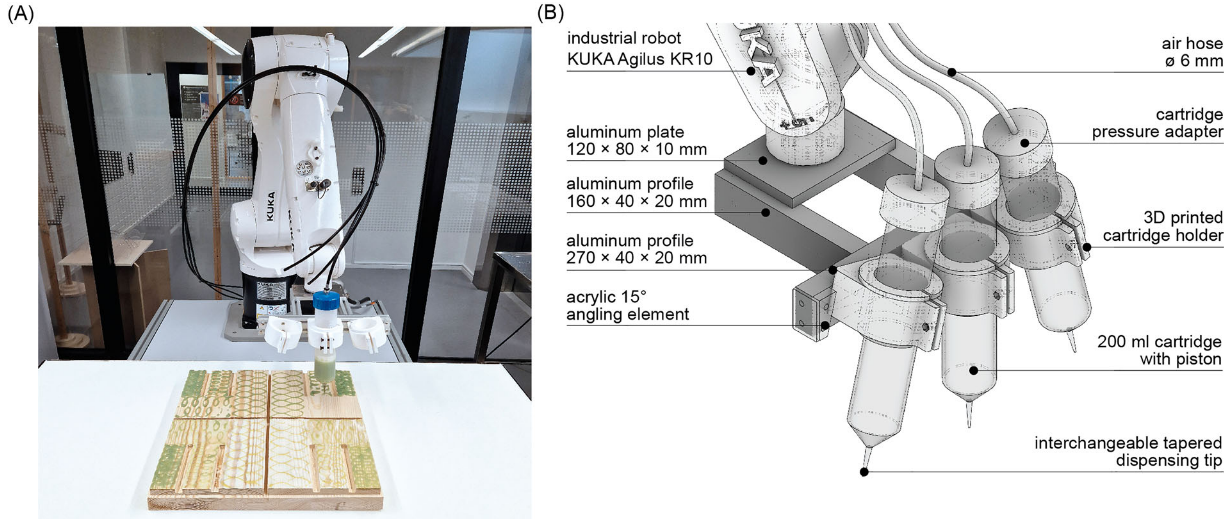

Figure 6. Digital fabrication setup for the prototyping experiments. (A) Robot cell. (B) Robot end-effector design for hydrogel extrusion, built in-house.

deformations of the physical mockups due to substrate shrinkage caused by varying humidity and deformations induced by CNC milling, for each mockup, a positioning procedure was executed. The corners of each physical model were realigned to match the actual physical positions of the robot nozzle at characteristic points in the designed pattern. After mockup placement recalibration, the 3D printing sequences were executed from. SRC files defining the robot programs, earlier generated through the KUKA|prc add-in for Grasshopper. The coatings were applied to each quarter of the physical model. The coating material was extruded at an average pressure of 0.25 bar and a constant linear movement speed of 0.07 m/s. After the 3D printing of the coatings onto the mockups, they were subjected to ambient drying at an average room temperature of 20°C ± 1°C and humidity of 36% ± 5%. For each model, the coating fabrication sequence and the drying process were always documented in digital photographs.

Analytical methods used to examine the coating effects

The analytical methods used to examine the coatings are based on previously published methods (Zboinska, Sämfors, and Gatenholm 2023). To facilitate the analyses of the coating pattern dimensions, shape, adhesion, and color, all models were documented in top view using a 12 MP digital smartphone camera Samsung Galaxy S22. The photographs were taken at regular time intervals, i.e. directly after fabrication and then after 6, 12, 24 and 48 h, until the models were fully dry. The photographs were framed to capture the whole substrate and zoomed in to capture each differently precoated quarter in the substrate. For the fully dried models, photographs of coating features at a close distance were also taken.

To establish potential changes in pattern dimensions and shape definition, a comparative graphical analysis method was devised. The method was based on first identifying the areas of the models representing distinct coating effects through ocular inspection. Then, in the Adobe Illustrator software, version 27.8.1, the photographs of these zones in the initial wet and final dry states were cropped, scaled, and juxtaposed with the graphic representations of the corresponding 3D print path designs. Then, digital measurements were performed and annotated in the images. The measurements were taken for the most characteristic parts of the patterns and included distance measurements between points and corners where paths changed direction and for offsets between curves. The features in the original digital path and the photographs of the wet and dry coatings were always measured. For the dry models, an additional graphic representation of the original path was laid over the coated model photograph to highlight the changes and to facilitate visual comparisons.

To analyze the adhesion effects, the same routines as above were applied. In addition, a more detailed graphical comparative analysis of adhesion effects was conducted for the mockup where delamination was most evident. Close-up photographs were taken to capture the delamination and emergent geometric transformation effects observed in the coating, and these effects were compiled in graphic form to facilitate ocular comparisons and discussion of the results.

To analyze the color transitions, qualitative and quantitative investigations were conducted. First, qualitative ocular comparisons between the digital photographs of the models in the wet and dry states were conducted to identify the basic color transitions, embracing visible changes in hue and brightness. Then, the visual observations were cross-checked quantitatively. This was performed by sampling the color values from the digital photographs using the color sampling tools in the Adobe Photoshop software, version 25.6.0. After sampling the basic red, green, and blue color hue values (RGB) and the saturation (S) and brightness (B) values in the most characteristic regions of the models identified via ocular inspection, numerical comparisons were made for wet and dry models and their different precoating types.

Results

This section presents the results of the prototyping experiments, focusing on the coating aspects that are essential from an architectural design standpoint, i.e. pattern definition and dimensional fidelity, adhesion effectiveness, and color effects.

Coating pattern dimensions and shape definition

When examined visually at the macroscale, the 3D-printed pattern shapes resembled the geometric types underpinning them, i.e. points, polylines, arcs, circles, and free-form curves. The point-based pattern features occurred as material dots, and the digitally designed lines, polylines, arcs, and curves followed an initial design of the features (Figure 7). When measured physically at the mesoscale and compared through graphical analysis with the original digital designs, the final coating dimensions were comparable with the original ones. In most cases, the 3D-printed lines of the patterns maintained their designed locations (Figure 8). The detected material relocations did not exceed 1–2 mm in relation to the centerline of the original digital path.

Simultaneously, deviations in pattern shape definition were observed. These deviations were represented by geometric and textural artifacts that were not designed initially. The artifacts included rounded corners, irregular edges, blended colors, interconnected material strands, and material fragments that were broken, curled, bridging, and detached (Figure 9).

Coating adhesion

For all mockups, the 3D-printed material strands designed with a large spacing between individual paths or material strips (3.8 mm and above) and a path height and total width not exceeding 3 mm have resulted in an overall good adhesion of the material (Figure 10). However, for these paths, some differences were also observed between the different timber substrate types and precoating biomaterials used. Good adhesion was observed for the pine substrates precoated with alginate hydrogel. The adhesion was worse in the spruce substrates and

Figure 7. Architectural features of biobased coatings at the macroscale, with final appearances resembling the initial digital pattern designs. (A) The *ichthys* pattern discernible on the wall cladding fragment. (B) The Voronoi pattern discernible on the mezzanine railing fragment. (C) The flowline pattern discernible on the frieze fragment. (D) The circular pattern discernible on the sculpted beam fragment.

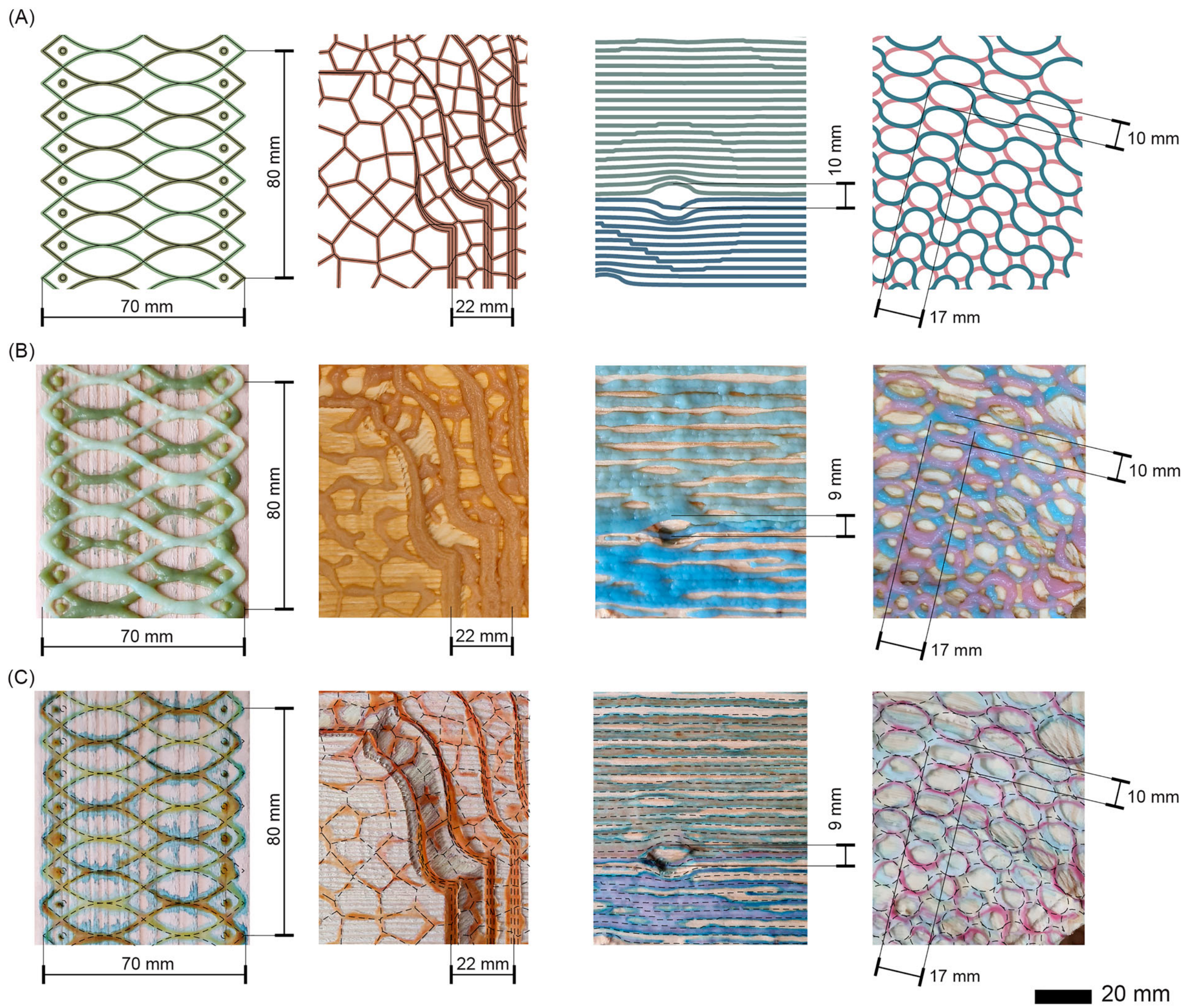

Figure 8. Architectural features of biobased coatings at the mesoscale exemplified in selected mockups, indicating dimensional and locational accuracy of the coating patterns. (A) Dimensional and formal features of original digital paths. (B) Dimensional and formal features of 3D-printed coatings in a wet state. (C) Dimensional and formal features of 3D-printed coatings in the final dry state.

substrates precoated with the MFC hydrogel and the hydroxyethyl cellulose hydrogel, resulting in minor local material detachments, as shown in Figure 10(A).

Conversely, the tightly spaced material depositing paths that were tangent or overlapping and that formed wide material strips with total width and height exceeding 3 mm have more often led to material detachment and, in some cases, local material tear. The detachment and tearing were most pronounced in spruce substrates precoated with alginate hydrogel, as illustrated in Figure 10(B). In contrast to this, good adhesion of tightly spaced material strips was observed in the pine substrates precoated with MFC, as shown in Figure 10(C).

For the different substrates and precoatings investigated, the observed adhesion effects can be summarized as follows. The hydroxyethyl cellulose precoating promoted high adhesion across the different substrates and for the different coating pattern designs while not causing pronounced material tearing. For this precoating, the coated zones exhibited the least tendency to detach, even for the wider material strips deposited with tighter path spacing, as illustrated in Figure 11(A). For the alginate precoating, adhesion effectiveness was intermediate. In this case, the coating areas featuring more tightly spaced paths and wider material strips exhibited frequent detachment and tearing, as shown in Figure 11(B). Finally, for the MFC precoating, the most uniform detachment effects without large ruptures and tearing were observed. However, the coatings still detached in large areas, making the MFC precoating the worst performing among the three investigated precoatings. The effectiveness of this precoating was strongly correlated with the material layer thickness, i.e. thinner layers of the material adhered better, and thicker ones detached to a higher extent, as shown in Figure 11(C).

Coating color transitions upon drying

In the analyzed mockups, the initial coating colors underwent visually pronounced transitions upon drying (Figure 12). The observed transitions were twofold. The first effect was the observable darkening and intensification of color, most pronounced in the mockups precoated with alginate hydrogel (Figure 12(A)). The second effect was the change in color hue, most pronounced in the mockups precoated with MFC hydrogel (Figure 12(B)).

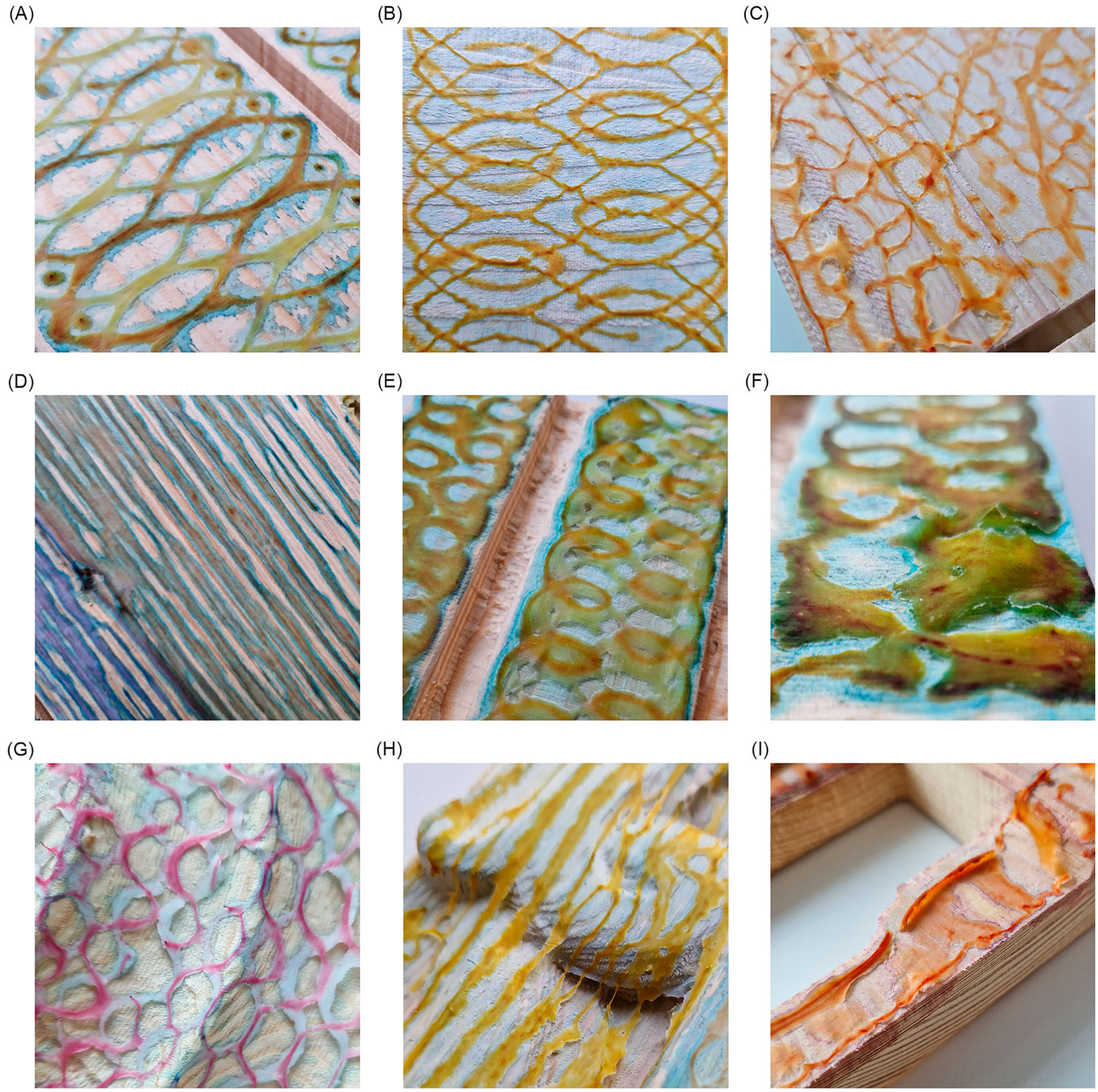

Figure 9. Unexpected architectural features of biobased coatings at the mesoscale emerging due to the drying process, exemplified in selected mockups. (A) Edge rounding. (B) Path curling. (C) Edge irregularity. (D) Path merging. (E) Color blending. (F) Discontinuities and ruptures. (G) Detachment. (H) Bridging. (I) Edge curling.

These effects were confirmed by numerical comparative analyses of color values sampled from digital photographs of the wet and dry mockups (Figure 13(A)–(D)). The mockups precoated with alginate hydrogel, regardless of substrate type, exhibited increased color saturation and decreased brightness values (Figure 13(B)). The mockups precoated with hydroxyethyl cellulose hydrogel did not exhibit profound color brightness value changes. However, a significant increase in the saturation value of the coating parts featuring the yellow pigment component was observed (Figure 13C). The blue pigment component decreased to a lesser extent compared with that for the alginate precoating, as suggested by the changes in the sampled B value in the RGB scale. Conversely, for the red and green pigment components, the precoating offered color stability and less dramatic changes in color values compared with the alginate precoating.

The mockups precoated with the MFC hydrogel exhibited the largest changes in color upon drying. The blue pigment component decreased significantly, leading to strong color saturation losses, large color hue alterations, and dyeing of the uncoated areas of the substrate. The presentation of the most stable pigments, namely, yellow and red, remained intact to some extent, whereas the less stable blue pigment was absorbed (Figure 13(D)).

Discussion

In this section, inferences from the prototyping experiments are drawn to facilitate a deeper understanding of the coating design aspects. The discussion is structured to directly link to the coating results presented in the previous section. Thus, coating pattern dimensions and shape definition, adhesion, and color

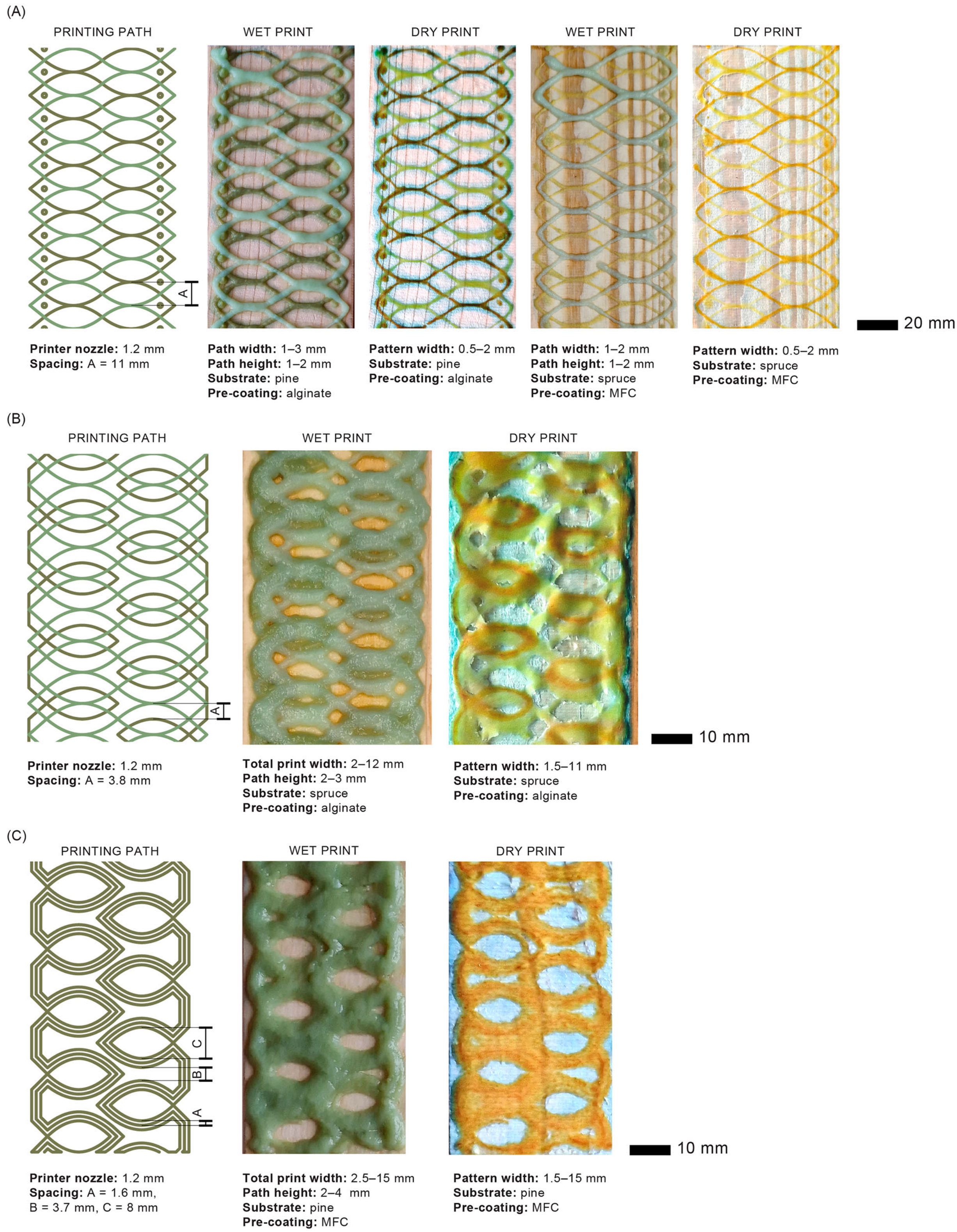

Figure 10. Coating adhesion characteristics of various path designs, precoatings, and substrates exemplified in selected mockups. (A) Widely spaced path design resulting in good adhesion for pine and spruce substrates precoated with alginate and MFC hydrogels. (B) Densely spaced path design resulting in detachment on the spruce substrate precoated with alginate hydrogel. (C) Densely spaced path design resulting in good adhesion on the pine substrate precoated with MFC hydrogel.

transformations are interpreted, and their probable causes are explained using references to prior research as support. The section concludes with a discussion of the global implications of the study for architectural design, in the context of published work in the field.

Coating pattern dimensions and shape definition

The best results in terms of dimensional accuracy and shape definition were observed in the pine models precoated with MFC hydrogels, where pattern designs featured single material

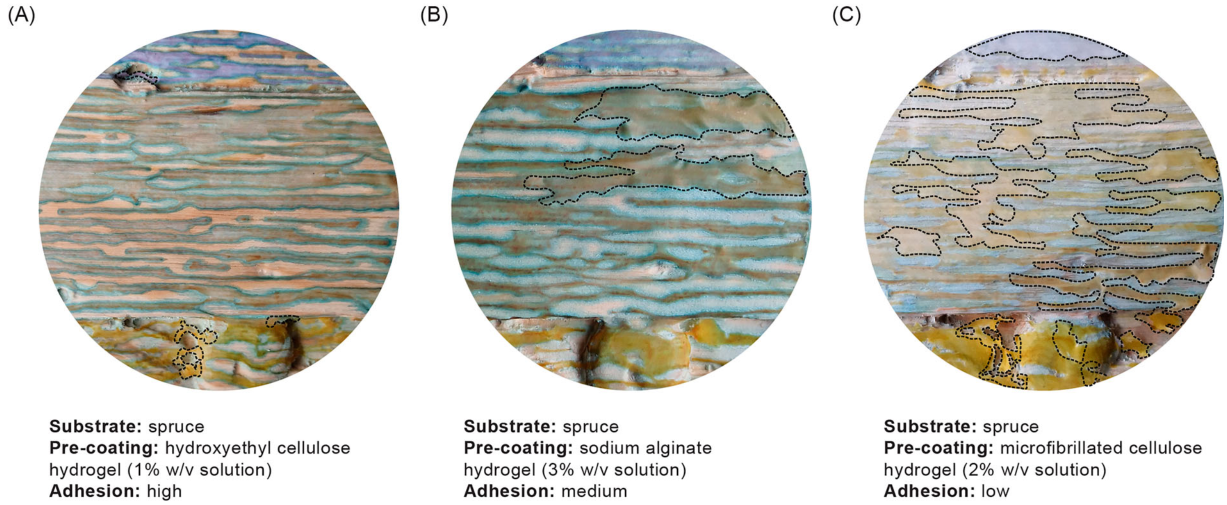

Figure 11. Comparison of the coating adhesion effectiveness of the three investigated biobased precoating materials. Dashed lines demarcate detached coating zones. (A) Hydroxyethyl cellulose precoating yielding good adhesion. (B) Sodium alginate precoating yielding medium adhesion. (C) Microfibrillated cellulose (MFC) precoating yielding low adhesion.

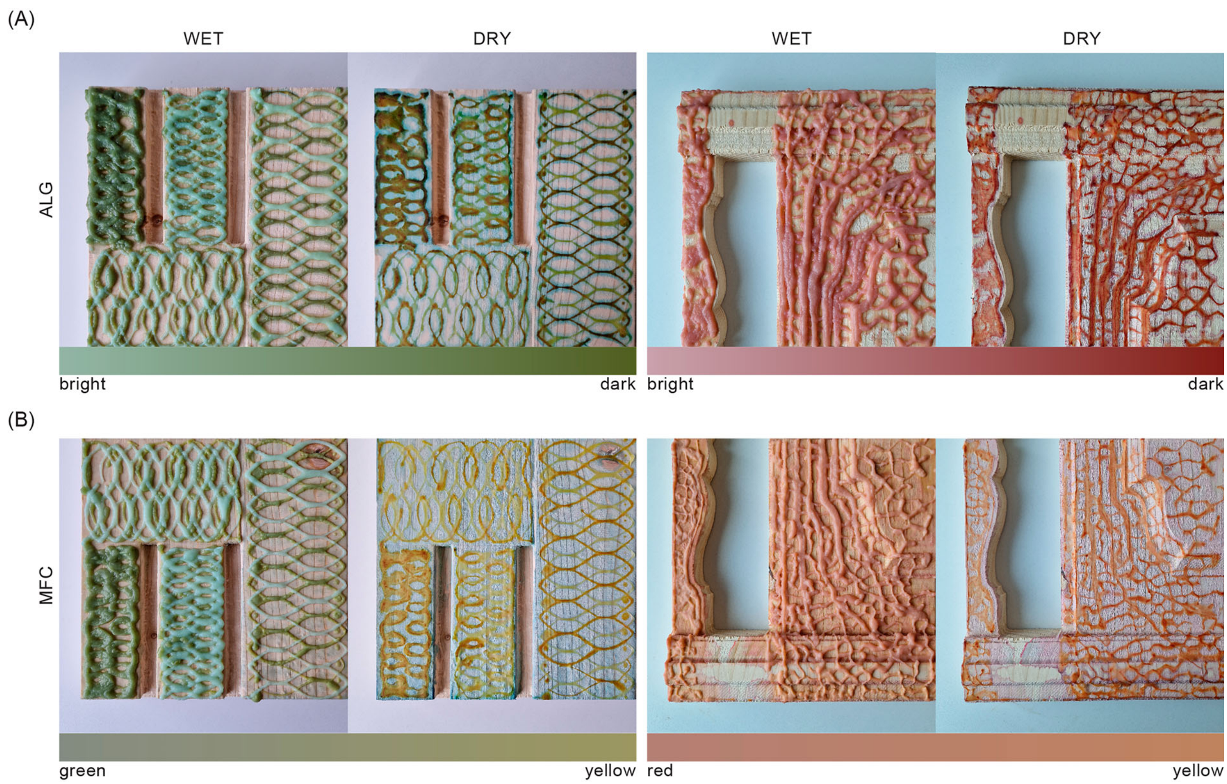

Figure 12. Comparison of coating color transitions of the two biobased precoatings yielding the most striking effects, namely, the sodium alginate (ALG) precoating and the microfibrillated cellulose (MFC) precoating. (A) The ALG precoating, causing significant color darkening. (B) The MFC precoating, causing color hue changes due to absorption of less stable pigment components (green in the model to the left and red in the model to the right).

strands with large spacing. The reason for the best performance of the pine substrates is their established better performance in coating adhesion than that of spruce (Jirouš-Rajković et al. 2007). This better performance is due to the higher content of adhesion-promoting substances in pines, i.e. lignin and extractives (Gindl et al. 2004; Jaić et al. 1996; Mantanis and Young 1997).

The observed best performance of the MFC hydrogel precoating in promoting shape fidelity is likely due to its compatibility with the 3D-printed top layer, also from MFC. For the other precoatings, the materials of the bottom and top layers differed, which yielded smudged and merged pattern outlines. This is expected because biopolymers interact with each other when assembled in multiple layers (Merindol et al. 2020; Podsiadlo et al. 2007).

However, overall, regardless of the precoating type, the geometric patterns in all prototypes were legible, and differences in their quality were minor. The unique rheological properties

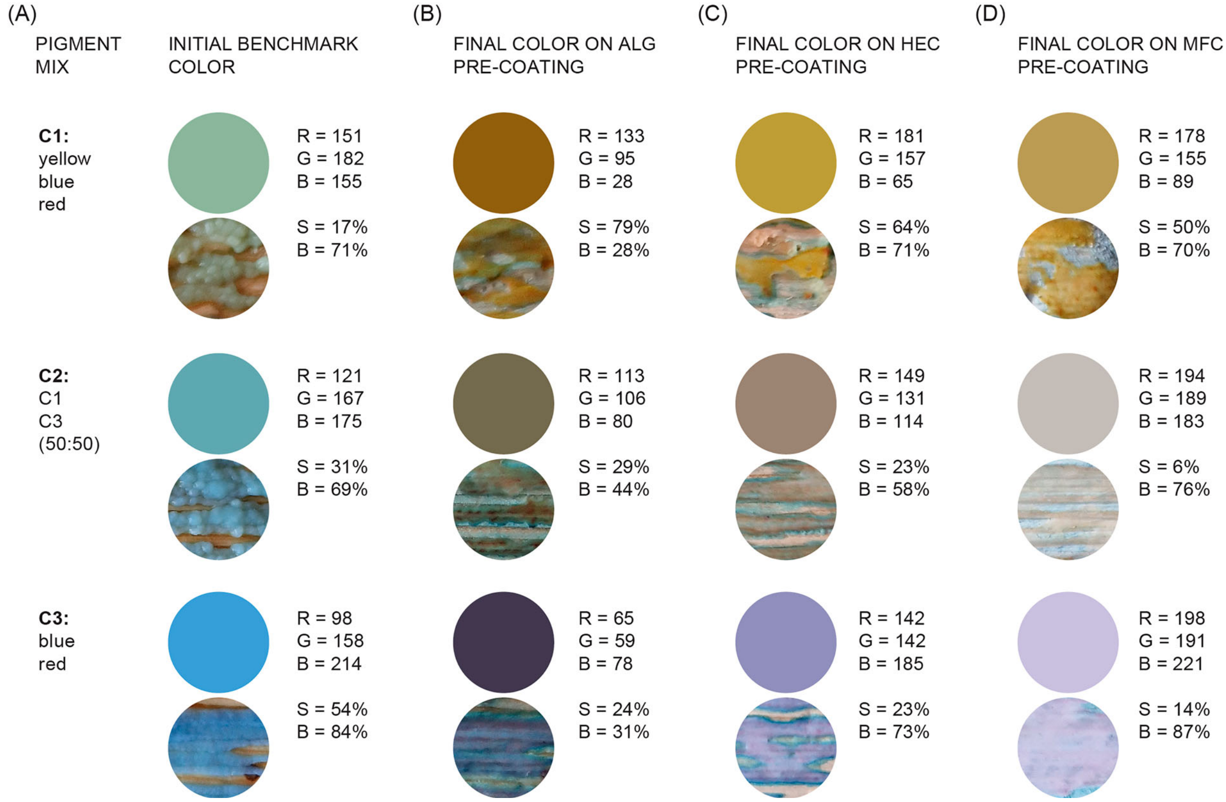

Figure 13. Transitions of red, green, and blue (RGB) color values, as well as saturation (S) and brightness (B) values, compared for coatings in the wet and dry states, for the three investigated precoatings. (A) Initial values in the wet state used for benchmarking the color transitions. (B) The values for dry coatings applied on substrates precoated with sodium alginate (ALG). (C) The values for dry coatings applied on substrates precoated with hydroxyethyl cellulose (HEC). (D) The values for dry coatings applied on substrates precoated with microfibrillated cellulose (MFC).

of the top layer, the MFC hydrogel, have guaranteed this satisfactory fidelity effect. In particular, the shear thinning property of the MFC hydrogel enabled its shape retention after extrusion instead of spreading or flowing, despite the 98% water content (Nechyporchuk, Belgacem, and Pignon 2014; Rezayati Charani et al. 2013; Shao et al. 2015). The geometric stability of the 3D-printed MFC hydrogel observed here aligns with the results reported in other studies outside the field of architecture (Chinga-Carrasco et al. 2019; Jain et al. 2023; Ko et al. 2023; Wang, Wang, and Xu 2020; Xu et al. 2018).

Coating adhesion

The adhesion of the main MFC coating was dependent on the precoating material's characteristics. The key finding was that MFC precoatings were the worst at improving the adhesion of the main 3D-printed MFC layer, especially if it featured wide and thick material strands, and the sodium alginate and hydroxyethyl cellulose precoatings performed better. This can be explained by the fact that the latter two precoatings formed hybrid coating systems with the top MFC layer. If different biomaterials are combined in layers, advanced functional properties can be achieved (Martin and Jean 2014). These hybrid systems, especially the ones combining different types of celluloses and nanocelluloses, as well as other biopolymer materials, are known to be more effective than monomaterial coating solutions because they mobilize the functional properties of each involved material (Merindol et al. 2020; Podsiadlo et al. 2007). In this study, the precoating from MFC formed a monomaterial system when combined with the 3D-printed top coating layer, also from MFC, thus performing the worst in terms of adhesion promotion. Conversely, the precoatings from alginate and hydroxyethyl cellulose hydrogels were forming heterogeneous, and thus more robust, coating systems with the top MFC layer, yielding better adhesion.

In the hybrid system featuring sodium alginate, alginate contributed with its unique properties of enhanced film formation (Walsh-Korb et al. 2022). In particular, when applied onto wooden substrates, it follows the cell wall structure of the wood, thus exhibiting improved adhesion and outperforming microcellulose and nanocellulose in this respect (Caruso et al. 2023).

In the hybrid system featuring hydroxyethyl cellulose, the good coating adhesion can be attributed to two properties of this material. First, it is known for lowering the rate of moisture absorption and delaying the release of moisture during desorption when applied onto wood (Ekstedt 2002). Second, it is more ductile than nanocellulose (Sehaqui, Zhou, and Berglund 2011). Taken together, these two properties have likely contributed to the less abrupt shrinkage and peel-off of the upper coating from MFC. Further, this material combination has yielded fewer ruptures and better adhesion than the one featuring alginate, for which these effects were more pronounced.

Coating color transitions upon drying

The color transitions of the pigmented coatings observed upon their drying correlated strongly with the absorptive properties of the two types of wood used in the experiments and with the precoating material properties. For the former, the stronger tendency for water absorption by pine compared with spruce (Iejavs et al. 2021) was likely causing a stronger permeation and bleeding of water-based pigments into the pine substrate. This has yielded significantly larger color deviations of the dried coatings from the original coating color in the wet state.

Regarding the precoating influence on the final color presentation, the precoatings from hydroxyethyl cellulose, once dried, exhibited colors most closely resembling the initial color in the wet state. Hydroxyethyl cellulose is widely used in the paint industry as a thickener for various types of paints and varnishes because it is translucent when dried and it does not alter or interact with the pigments in a polymeric suspension system (Erkmen 2018). These neutral features have likely caused the least changed color appearance of the top coating compared with the other precoating materials used.

Conversely, the precoatings from sodium alginate resulted in darkened and deeper colors of the dried coatings compared with their wet versions. This also aligns with prior research findings demonstrating that alginate has properties that enhance the depth, brightness, and evenness of colors, which is also the reason for its frequent use in various pigmented coating systems (Wang, Zhu, and Lu 2013).

Finally, the precoatings from MFC permitted the strongest absorption of pigments into the substrates, as shown in the pronounced color bleed of some pigments in the substrates and the lightened color of the coatings. These observations also correlate with already published findings. Upon drying and shrinkage, MFC tends to change the pigment appearance by whitening it. The reasons are the high concentration of cellulose fibers on the surface when the hydrogel dries and the white tint of these fibers in the dry state, causing lowered light transmittance and the observable whitening effect (Salo et al. 2015). These fibers do not bind with and absorb the pigment molecules but rather they sediment alongside (Dimic-Misic and Paltakari 2012), which also contributes to their whitened appearance in the dry state.

Examples of potential practical applications of MFC coatings for architectural timber

Globally, the findings of this study align well with the previous findings that indicated the exquisite compatibility of coatings from the MFC hydrogel with wood, which is due to the presence of cellulose in both materials (Camargos et al. 2022; Fornari et al. 2022; Kryg et al. 2024). The overall good performance of the MFC hydrogel as a coating of wooden substrates observed in this study also aligns with the findings from the field of heritage conservation, in which the effectiveness of nanocelluloses, including MFC, in the consolidation, conservation, and protection of wood-based artifacts was demonstrated (Cipriani et al. 2010; Wang, Feng, and Liu 2023; Younis et al. 2024). Thus, this study shows that biobased coatings are a valid alternative to less sustainable synthetic paints, varnishes, and synthetic fillers and can be robustly applied onto wood in various architectural contexts of historic and common buildings.

Regarding the former, worldwide, there are numerous historic timber buildings in which such biobased materials could be applied using the 3D printing technology to achieve high fidelity of the features to be reconstructed, repaired, or protected. Some examples in the European context include the timber stave churches in Norway and the numerous timber structures and ornaments in the medieval, renaissance, and baroque churches in Europe, e.g. in Austria, Italy, and Poland. In these buildings, the wooden elements are often decorated using historic paints based on natural ingredients from the past. However, these ingredients are usually based on fossil resources, such as minerals, metal oxides, chalk, kaolin, and binder glues of animal origin (Freeman et al. 2021; Haghighi et al. 2024). Today, these resources may be inaccessible or impossible to extract for environmental, economic, and ethical reasons. Thus, the repair of historic wood using these ingredients might not be justified, opening a possibility for replacing these materials with biobased ones, such as those examined in this study.

Other examples of a relevant application in historic buildings in the contexts of Asia and Australia are the timber temples, shrines, and pagodas in China, Japan, and Korea, as well as the timber heritage buildings Marae of the Māori communities in New Zealand. In these buildings, synthetic materials, such as silicone, epoxies, and acrylic paint, are used as immediate means against water and moisture ingress. However, these synthetic materials have a proven degrading effect on wood, accelerating its decay and aging through evaporation blockage (Larsen and Marstein 2016). Thus, the use of MFC as a biobased, breathing material alternative with a high vapor transmission rate (Spence et al. 2010) could be justified also for such applications.

Finally, the successful application of the coatings onto two common construction timber types, i.e. spruce and pine, demonstrated in this study, indicates the application potential in a wide range of coating and repair solutions, beyond historic conservation. These coatings could be applied in numerous commonplace products, in timber building elements, and in a wide range of consumer goods made from wood, to finish the newly produced ones and to repair those requiring renovation.

Architectural design implications of novel material interfaces featuring biobased materials

The dimensional accuracy, shape fidelity, adhesion, and coloration effects observed in the biobased coatings in this study are the paramount design aspects from an architectural standpoint. A high-quality coating or repair intervention should follow the initial design intent. However, minor deviations and imperfections, such as the ones observed at the mesoscale in the prototypes produced in this study, could also be embraced as an inherent feature of a biobased coating solution, adding unique aesthetic qualities to its appearance. Haptic effects, such as irregularities and artifacts, and the resultant one-of-a-kind expression of each biobased product coalesce with the features of the crafted products, in which material indeterminacies are desired and evoke enriched multisensory experiences beyond the sense of sight (Pallasmaa 2012; Pye 2008; Risatti 2009; Zumthor 2006). In addition to the organic appearance that aligns with similar traits found in other natural materials, such as stone and wood, and highly appreciated by users, biobased products introduce an element of environmental friendliness, requested by a growing number of consumers (Karana, Pedgley, and Rognoli 2015; Manu et al. 2022).

The value of the custom and nonrepetitive effects demonstrated in the prototypes produced in this study resulting from the distinct properties of the materials being interfaced is widely acknowledged and studied in architectural research focusing on digital fabrication. Therein, the implementation of customized manufacturing techniques, such as robotic fabrication and 3D printing, offers novel material crafting opportunities and aesthetic design possibilities (Anzalone, Del Signore, and Wit 2018; Atwood 2012; Dickey 2019; Gürsoy 2018; Zboinska 2019; Zboinska and Dumitrescu 2021). Beyond aesthetic design advances, the fusion of novel materials and digital manufacturing techniques propels architectural innovation and promotes sustainability, with digital techniques such as 3D printing allowing for boundary-pushing explorations of sustainable materials that would be unattainable using standard techniques (Berdos, Agkathidis, and Brown 2020; Ramsgaard Thomsen 2019; Stein 2011; Veliz Reyes et al. 2019). Such explorations help in reframing and advancing the mainstream approaches to architectural design through transformative, biobased design practices that can considerably reduce the carbon footprint of construction (Yang, Wang, and Man 2024).

Conclusion

Herein, an architectural application of patterned coatings from pigmented MFC hydrogel applied onto wooden substrates using robotic 3D printing was demonstrated for the first time. The three research objectives stated at the beginning of the study were achieved as follows. First, the coating aspects at the mesoscale and macroscale, pertaining to dimensional accuracy, shape fidelity, adhesion, and coloration were characterized qualitatively and quantitatively. This was performed for two timber substrate types commonly used in construction, namely, pine and spruce, and for three biobased precoating materials as adhesion support, i.e. alginate, hydroxyethyl cellulose, and MFC. The experimental findings suggest that the best coating quality is achieved for pine substrates precoated with hydroxyethyl cellulose.

Second, the eight wooden mockups successfully coated with MFC hydrogel demonstrate the potential of these coatings to replace less sustainable, synthetic coating solutions for architectural timber. The findings presented herein show that these sustainable coatings can be pigmented using natural colorants, and precisely deposited as diversely designed geometric patterns onto the treated surfaces using the 3D printing technique. This demonstrates the versatility of MFC as a design material but also emphasizes the exquisite design customization opportunities introduced when robotic 3D printing is used as a coating application technique.

Finally, the study results successfully exemplify the implementation of biobased coatings as integral parts of existing architectural material systems featuring simple and complex shapes, presenting a promising outlook on a wide array of potential applications. These applications can range from coating newly produced timber elements through renovation of damaged reused timber to historic preservation and conservation of aged and deteriorated timber. As such, the proposed coating solution can have a large industrial impact beyond architecture in all business sectors that design, manufacture, and handle coated timber products – from automotive, through furniture, to consumer products.

In the global perspective, the currently missing characterization of the properties of these coatings at the mesoscale and macroscale delivered by this study forms a basis for continued research and applications that align with the worldwide efforts to achieve a decarbonized, resource-efficient built environment and a global circular economy.

Limitations and future work

A significant observation arising from the comparison between the different coating designs, substrate types, and precoating materials in this study is that the coating design is a complex task where the material properties mutually influence each other, with some of these interactions being so intricate that they are difficult to clearly define and generalize. Further investigations beyond the field of architectural design and tapping into other relevant knowledge areas, such as biopolymer chemistry and wood engineering, are needed to develop viable architectural coating solutions for industrial applications. Thus, this study should be seen as the first step in a larger process of accumulating knowledge for future research and implementations.

The two striking characteristics of the examined biobased coatings that have an essential influence on the design strategies for these coatings, affecting their aesthetic appearance and functional properties, are the transitions in the drying phase. As shown in the investigation, a complex interplay of factors affects this, including the characteristics of the materials used and the layout patterns and properties of the material layers being assembled. Acquiring a good and accurate understanding of how these factors, alone and altogether, influence the coating appearance is not a trivial task and requires further research.

As an immediate step of advancing knowledge on biobased coatings for timber, continued research should, among others, focus on aspects not addressed in this study but essential in the further coining of opportunities and limitations of applying these coatings. First, a wider range of wooden substrate types, such as timber that is painted, oiled, impregnated, or treated in other ways, should be studied. Second, the characteristics of the substrates onto which the coatings are applied, such as humidity, acidity, age, and degree of weathering, will be necessary to investigate further because of their paramount influence on aspects such as adhesion and dimensional stability. Other factors that will affect the coating appearance and its functional performance and that are essential to examine in further quantitative research include contact angle, wetting, swelling, water absorption and retention, gas barrier properties, resistance to UV light, fire resistance, and microbial resistance.

Further studies are also needed to demonstrate the potential of the MFC hydrogel coating and its applicability range beyond the coating function. It should be studied also as a repair and infill material, adhesive, varnish, and healing layer. As a step in this direction, in an ongoing project led by the author, the

MFC hydrogel is combined with a microbial hydrogel featuring yeast cells and other biobased ingredients to derive a novel material formulation for renovation that features enhanced 3D printability, adhesion, coating thickness and volumetric coverage, reduced shrinkage, and streamlined aesthetic appearance (Zboinska 2022). This research endeavor, as well as others in a similar direction, will open the door to a wider proliferation of robust and versatile biobased materials for buildings, addressing the pressing need for more resource-efficient solutions in the built environment.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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