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# Biopolymer Composites in Circular Design

## Malleable Materials for an Instable Architecture

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1 Activation of a biopolymer's thermoplastic properties to achieve cascading through material malleability

## ABSTRACT

This paper examines temporality within material and architectural cascades. It takes point of departure in the perception of bio-based materials as abundant within the emerging framework of bio-based circular design, and the need for materials that can incorporate flexibility to local availability, ecological implications, and cost. In this paper we introduce a specific biopolymer composite composed of interchangeable constituent materials from agricultural waste streams, and describe the malleability of this material through the processes of material composition and robotic fabrication, and the re-activation of its thermoplastic properties. We examine the design opportunities this opens for cascading, and how processes of repair, refitting, and recycling of a malleable material create ongoing instabilities of the object that can be conceptually and practically exploited at both architectural and material levels. We identify and describe these opportunities within the context of 'Radicant', a 3D printed wall paneling system made from the bio-polymer composite. We also present a series of experiments that exemplify how the strategic localized reactivation of the printed material can ideate new architectural strategies of repairing, refurbishing, and recycling.

## INTRODUCTION

The conceptualization of the Planetary Boundaries (Rockström et al. 2009) has fundamentally challenged the idea of resource as readily available and fundamentally abundant. Instead, we have entered an era with increased awareness of the ecological, social, and political repercussions of globalized resource extraction, along with an acute awareness of the reality of running out of materials, as virgin materials are lost in 'take, make, dispose' consumption patterns. Circular design challenges resource ignorance (Swilling et al. 2018) by creating methods for preserving natural capital, optimizing resource yields, and minimizing system risks by managing finite stocks and renewable flows (Stahel 2016). Bio-based materials are seen as half the solution space for circular design (Ramsgaard Thomsen et al. 2023).

Idealized as a new class of materials, bio-based materials will diversify the fundamental materiality of buildings. Understood as fundamentally renewable and abundant, they are perceived as material resources with little or no impact on their environment as they are either fully consumed, ultimately ending up in energy production through incineration, or returned to the earth systems through composting. Sourced from biological residues and waste streams that would otherwise be burnt, landfilled or allowed to decay, valorizing them within biopolymer composite architectural elements stores and transfers their carbon into architectural material flows. This ability to act as a carbon sink extends the role and performance of architecture by reconceiving the built environment as a store of atmospheric carbon.

However, the emerging implementation of circular design presents new dynamics in resource flow. As materials are reintegrated into new use-cycles they become scarcer, and their ready availability and perceived abundance can no longer be assumed. True circular design for bio-based materials must, therefore, be conceptualized as a dynamic system that incorporates a degree of flexibility in the kinds and sources of materials so that it can accommodate changes in the supply chain. This dynamic makes biopolymer composites an interesting case for bio-based circular design. Composed from agri-, aqua- and silvicultural waste streams, their recipe logic makes it possible to strategically substitute one material for another. This necessitates a fundamental material malleability that can adapt to local availability, ecological implications, and cost. The ability to substitute key ingredients depends on in-depth knowledge on their performative impact and the corresponding ability to flexibly update material design models for both fabrication

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2 Radicant: A 3D-printed biopolymer composite wall paneling system. The panels are composed of interlacing print beads and varying material recipes

3 Close up of Radicant printed panel and the interweaving strategy

4 Dog bone samples of differentiated material recipes including various waste streams, such as cotton, seagrass, bark, and wood flour.

5 The design geometry is composed of trunk, branch, and infill layers.

6 3D printing a Radicant panel using a custom-built robotic extruder.


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and analysis. At the same time, bio-based materials need to be malleable to engage and expand the cascading logic of circular design (Ramsgaard Thomsen et al. 2023) and ideate ways of enriching and extending architectural strategies of reuse, repair, refurbishment, recycling, and recovery (Cheshire 2021).

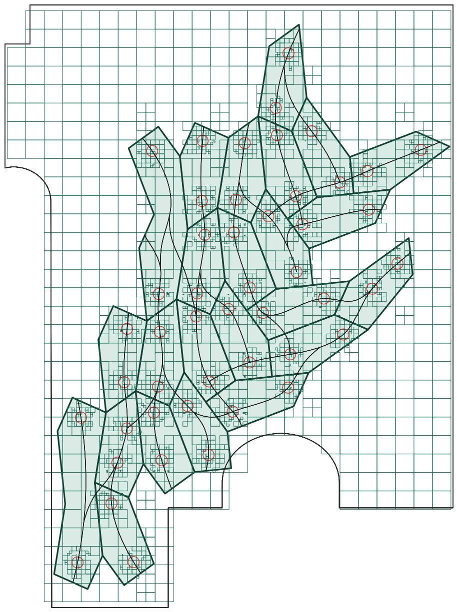
In this paper, we expand upon the malleability of a specific biopolymer composite and follow this concept through processes of material composition, robotic fabrication and cascading through material re-activation (Figure 1). We identify opportunities for material malleability within the demonstrator project "Radicant" (Figures 2 and 3), a 3D printed call paneling system made from biopolymer composites deploying interchangeable constituent materials from agricultural waste streams. At the material level, we examine the ability to vary a base biopolymer recipe by changing the constituent fibers and fillers (Figure 2). We look at the ability to combine the constituent materials and their potential for substitution. We describe methods for creating multi-material architectural panels that employ the different recipes through strategic interweaving, and describe the fabrication protocols by which to accommodate this material variation. Lastly, we examine how this biopolymer can incorporate cycles of architectural cascading. Specifically, we look at reactivating the malleability of the material to ideate new architectural strategies of repairing, refurbishing, and recycling.

## STATE OF THE ART

Biopolymer composites are designed materials (Ramsgaard Thomsen and Tamke 2022) that compose multiple material streams. They are composed of a binder – the biopolymer- mixed into a solvent and reinforced by fibers and fillers to create a composite. They can be 100% biodegradable under natural conditions and produced on a large scale (Rech et al. 2022; Dritsas et al. 2020). The attractiveness of biopolymer composites lies in their malleability and adaptability: the choice of materials, their proportions, and their interfacing with fabrication systems give the material its key properties. By varying the choice and ratio of fibers and fillers, differing mechanical, absorptive, and expressive properties can be achieved. Robotic printing of bio-polymer composites offers the opportunity to create multi-material 3d printed elements at architectural scale (Duro-Royo et al. 2017; Lee et al. 2020).

Working with biopolymers opens new unique opportunities for material design and control, which are not possible with traditional materials. By interfacing designers with processes of material tuning, they gain agency over the composition and grading of their materials and, therefore, control their performance and aesthetics, as well as their sourcing and afterlife. Our understanding of material design can, therefore, be extended to integrate considerations of locality and circularity into the chosen constituents.

In architecture, the circular design framework for material cascading is conceptualized through six central actions:



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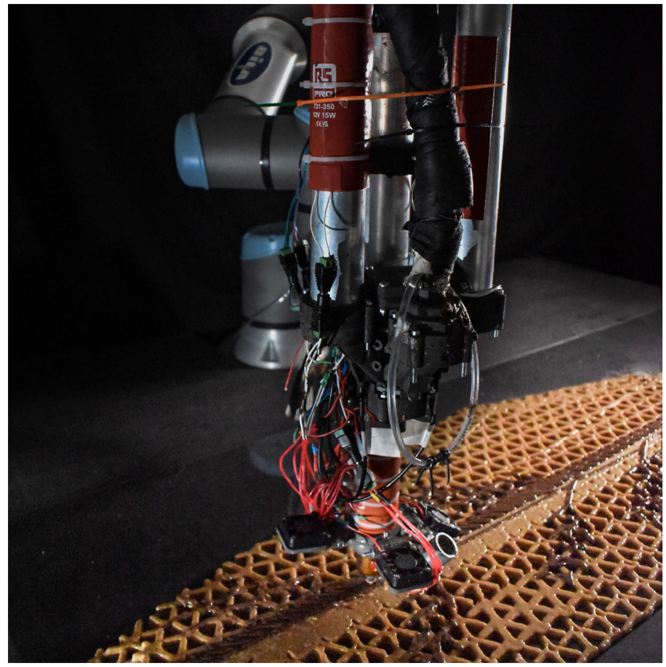

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retain, refit, refurbish, reclaim and reuse, remanufacture, and recycle (Cheshire 2021). These cascading actions have the aim to preserve absorbed carbon and increase total quantity of material (European Commission 2018) by retaining different degrees of value of the designed artifact. Bio-polymer composites are easily processable and quick to remanufacture. These qualities increase the ease of their cycling and can be used to create new architectural cascade thinking. Three of the cascades described in Ramsgaard Thomsen et al. 2023 are of particular relevance to this paper: Retain – through processes of repair; Refurbish – through processes of adaptation; and Recycle through processes of decomposition and re-composition.

## METHOD

Radicant is a bespoke interior wall-paneling system fabricated using a biopolymer composite material reinforced with differing types of cellulose from agricultural and other waste streams. Installed at AEDES gallery, located in Berlin, Germany, during December and January 2022, the panelized structure demonstrates varying material compositions to create a branched interwoven form extending over six meters. As a retrofitted interior cladding, Radicant is sited within the changes and cascades that affect interior spaces. Interior fit-outs are short-life construction propositions, and are characterized by regular cycles of change. Their average lifetime is less than 10 years (Forsythe 2017) and, when removed, only between 20 to 30% of the fit-out elements are recycled or reused, with the remaining 70 to 80% becoming landfill (Casas-Arredondo et al. 2018).

In the following sections, we describe how design opportunities associated with cascading and processes of repair, refitting, and recycling can be enabled by malleability that begins at the material level.

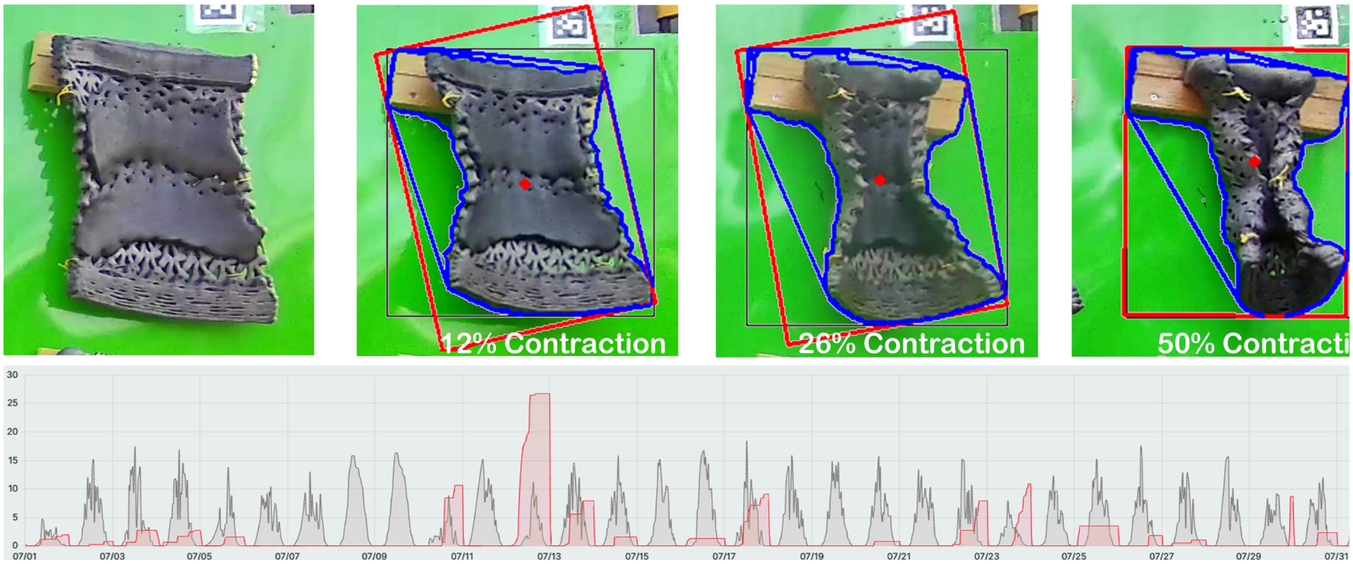
### Composing a Malleable Material

For Radicant, we developed a material recipe that combines a collagen-glue binder with cellulose fillers derived from various waste streams which are specific to our local context. We utilized seagrass, a source of blue biomass, bark and wood flour originating from the timber industry, and cotton sourced from clothing recycling. The selection and blending of fibers impact the structural properties of the mixture, while also influencing its texture, color, and scent.

By thinking exploratively, rather than towards single recipe optimization, we utilize the breadth of the recipe space and grade transitions from one composition to the other. In Radicant, we explore numerous combinations and interactions between different fillers and their proportions, and create a recipe range that allows a material response informed by resource availability that can meet functional and aesthetic-driven requirements.

### Creating Multi-Material Panels

The Radicant panels are composed of multiple recipes that are interwoven through a layered design. The interweaving of the materials in the panels follows a computational geometric design approach. At the global




7 The behavior of panels installed on an outdoor rig are autonomously tracked in intervals of 10 minutes using a computer vision-based algorithm. This detects the changing area of the panels and correlates these to data of a local weather station.

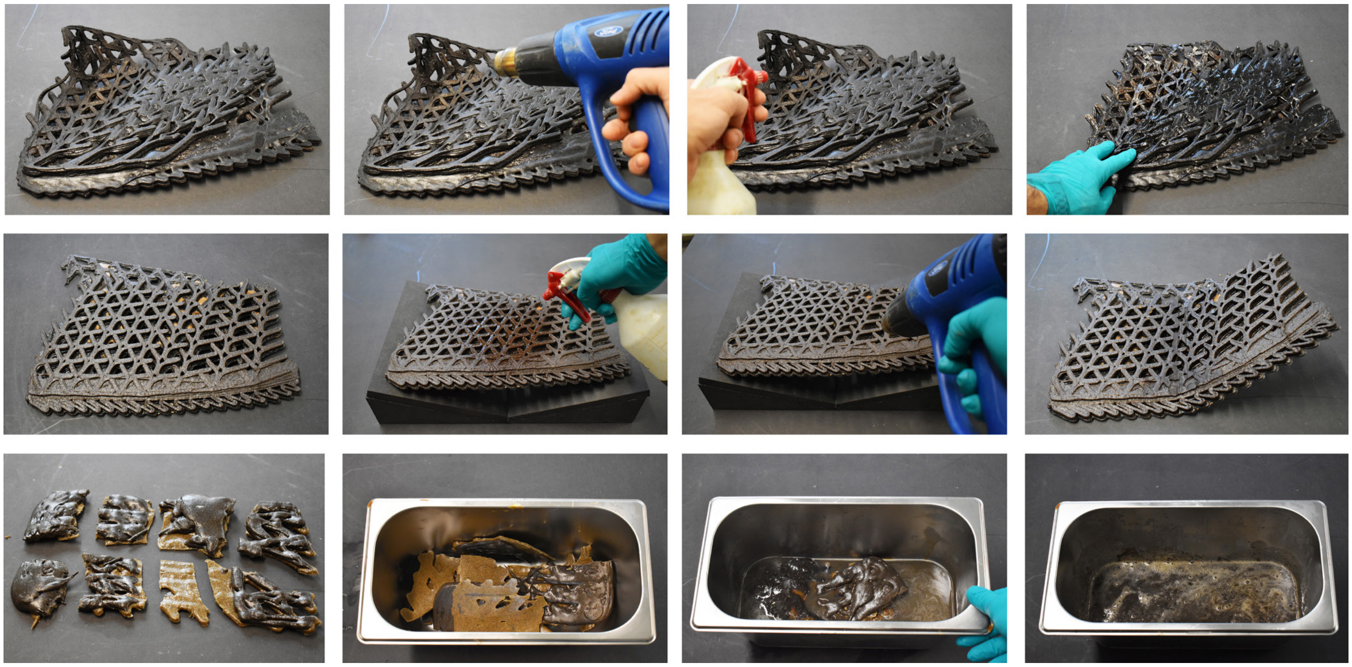
level, the strategy creates a "trunk structure" and a set of "branches". A leaf-venation informed growth algorithm generates the underlying geometry for these features (Figure 5). The strategy is further described in Nicholas et al. 2023. At the base level, the algorithm is interfaced with an agent-based system to create a structured underlying infill with no path collisions. This geometric approach supports the generation of a single print path, enabling continuous printing of each consecutive material, as well as maximizing the surface area to speed the curing and reactivation processes. The different materials and geometries of the three layers have distinct properties, and their interweaving gives the panels a continuously varying local porosity.

Variations in the recipe affect the rheology of the biopolymer composite. The panels are printed using a robotically steered 3D extrusion process that can accommodate these variations. Before printing each material is composed, and the fillers and fibers specified for a given layer are mixed into heated collagen polymer using a laboratory grade disperser to achieve a homogeneous mix. After mixing, the biopolymer composite material can either be used directly or refrigerated for later use.

Collagen polymers are thermoplastic. The biopolymer composite can, therefore, be melted and cooled multiple times without changing properties. This allows us to prepare substantial amounts of material ahead of printing, and demonstrates the material's capacity for reactivation. To 3D print the biopolymer composite, we use a bespoke heated printing system (Figure 6) that can keep the material at stable and precise temperatures throughout the entire manufacturing process. A custom end-effector is used to print the bio-polymer composite. It incorporates features that control the delivery, flow, and stability of the collagen polymer.

## Encountering Material Uncertainties and Enabling Material Cascades

The 3D printed biopolymer composite panels exhibit ongoing behavior across the fabrication process. This occurs directly after printing, where panels shrink as water content evaporates. To incorporate this post-print shrinking, material changes are registered after the drying process has completed through 3D scanning to determine the final geometry. Behavior also occurs in situ in response to heat and humidity changes in the exhibition environment. After installation, we tracked the overall geometry of the paneling system with an autonomous monitoring system, in which a novel algorithm, employing computer vision techniques, detects the type and magnitude of these ongoing behaviors (Figure 7). The algorithm, as well as the analysis of 3D scans of Radicant after two months of exhibition, show small amounts of swelling, contraction, and warping (Tamke et al. 2023). These behaviors become magnified in external conditions, where rain and solar radiation induce very high levels of temperature and humidity in the material, in comparison to the



8 Rows from top to bottom: A: Retaining through repair, B: Refit and Refurbish through adaptation, C: Recycling through decomposition and re-printing

sheltered interior environments. Computational analysis of long-term outdoor exposure of the panels show failures, breaking, and deformation (Figure 7).

These behaviors can also be leveraged as part of strategies for deliberate transformation and architectural cascading. In further studies, we have investigated methods of manipulating these behaviors by re-activating the thermoplastic malleability of the material. These studies investigate four scenarios for Repairing, Refurbishing, and Recycling biopolymer composites (Figures 8 and 9)

### Retaining Through Processes of Repair

Collagen-based biopolymers are brittle, and the slim dimensions of our panels make them prone to breakage. Due to the nature of the material, breaks are clean. To repair a break, and re-attach the broken fragment, the adhesive property of the biopolymer is reactivated at the break through heating and added moisture. This makes it possible to reattach the broken piece and make a materially seamless connection.

The in-situ response to heat and humidity can cause local warping. To straighten a panel, it can be detached from the overall installation. To reactivate the malleability of the biopolymer within the warped area, heat and moisture are applied locally to activate. Once malleable, the corner area can be pressed back into place.

### Refit and Refurbish Through Processes of Adaptation

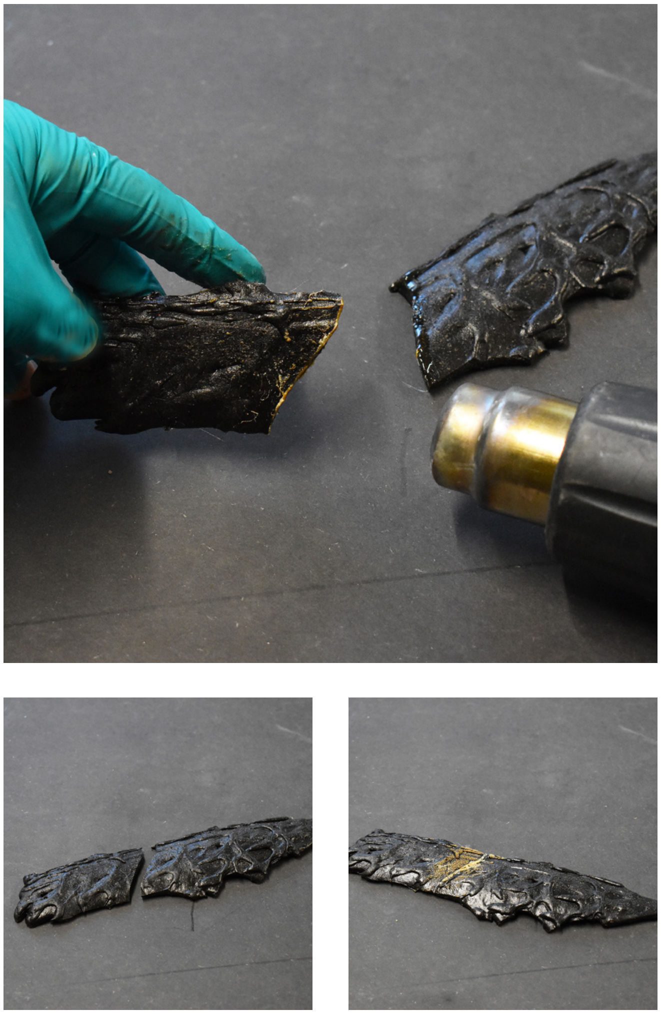
Collagen biopolymers are thermoplastic and, as such, do not form any chemical bond when curing, making them re-moldable and recyclable. This means that we can reform panels for second life-cycle installations which demand changed geometries. In this scenario, we examine the bending of panels to accommodate a corner condition. Each panel is individually treated. They are placed into an angled formwork. To reactivate the malleability of the biopolymer material along the bending seam, moisture and heat are applied locally. To conform the panel to the mold, force is applied along the seam until the material cools and becomes form-stable.

### Recycling Through Processes of Decomposition and Re-composition

At the end of its lifecycle, the paneling system can be separated into smaller pieces and melted down. Additional water is added to achieve the required viscosity for 3D printing, and there is the opportunity to add new fillers. 3D printing a new object gives a new lifecycle to the biopolymer composite material.

## CONCLUSION

In this paper, we expand upon the malleability of a biopolymer-based material system by following it through processes of material composition, robotic fabrication, and cascading through material re-activation. This investigation is contextualized within the emerging implementation of circular design, which presents new dynamics in resource flow.



9 Radicant: A 3d-printed biopolymer composite wall paneling system. The panels are composed of interlacing print beads and varying material recipes.

Our material is designed to be flexible to the changing availability of waste streams through the ability to interchange constituent materials in response to locality, availability, and performance. Using the case of demonstrator project Radicant, the paper has described this ability to incorporate and vary different constituent fibers and fillers within a base recipe, to strategically interweave different recipes within single panels, and how fabrication tooling can be developed to accommodate this material variation.

Building upon the need for flexibility in relation to resource flow and the conceptualization of biopolymer composites as inherently malleable at multiple scales, we have then explored how this material system can incorporate cycles of cascading. Specifically, we have reactivated the material's inherent thermoplastic behavior to retain through processes of repair, refit, and refurbish through processes of adaptation; and recycle through processes of decomposition and reprinting. These experiments, while preliminary, exemplify how biopolymer composites can open novel opportunities for repairing, refurbishing, and recycling on the basis of properties not possible with traditional materials. The next stages of this research will further engage and explore how biopolymer composites can expand and enrich the cascading logics of circular design.

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## IMAGE CREDITS

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