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Re-materialising design: Material agency and the reconfiguration of creative practice

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Abstract: This paper examines biobased materials as agents of creative and systemic transformation within design practice. Drawing from a university course on circular building product design, several graduation theses, and two research projects -one focused on food waste valorisation and another on load-bearing mycelium composites- it investigates how engagement with biobased, regenerative materials reconfigures the designer's role across the value chain, from sourcing to post-use reintegration. By situating material experimentation within ecological and socio-technical transitions, the paper argues that biobased materials enable a re-materialisation of design knowledge, where making becomes a mode of inquiry into interdependencies between nature, technology, and culture. These practices reposition material agency as a co-creative force, expanding the epistemic and ethical dimensions of design towards circularity, resilience, and care. Ultimately, the paper proposes that such engagements cultivate new forms of creative practice grounded in regeneration and relational materiality.

Keywords: biobased materials; circularity; regeneration; ecological worldviews

1. Introduction

Materials are omnipresent: from stone and clay to metals like gold, copper, bronze, iron and steel, human civilization relies fundamentally on the advancement of materials knowledge and the human capacity to process and manufacture objects with them (Sharma, 2022). The number of materials is currently expanding at a rate faster than we can study them, with recent estimates identifying more than 160,000 unique materials worldwide (Solanski, 2018). Novel materials can now be produced solely on data and data-driven computational methods (Himanen et al., 2019). Over the past century, the production of anthropogenic mass has exceeded Earth's biomass, marking a shift from predominantly biomass-based materials at the beginning of the twentieth century to predominantly mineral-based materials by its end (World Economic Forum, 2021).

Consumerism and the commodification of goods and services still demand the fast and careless use of materials. Even happiness and well-being have been tied to material possessions, a phenomenon commonly referred to as materialism (Kasser, 2002). Emphasis



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on growth and progress heavily perpetuate extractive practices and design for obsolescence (Till, 2020), whereas signs and visual analysis are being prioritized over the haptic and tacit knowledge of the materials. Moreover, the introduction of look-alike materials that emphasize surface over substance has further compromised human perception of materiality leading to what Böhme (2016) describes as “an aestheticization of material and a dematerialization of aesthetics.”

The distance between us (humans) and the material world has increased (Monbiot, 1999). There are two main ramifications of this shift. For one, materials are being perceived *atmospherically* through their effects on us rather than just their physical traits (Böhme, 2016). We have lost our connection to materials’ synesthetic qualities: materials can be, for example, rough, smooth, rigid, or flexible. Moreover, their touch or smell can evoke emotions and memories (MAKE). Materiality stores, transmits and shapes cultural memory (Leworthy, 2024). Furthermore, materials embody skills and craftsmanship and by that they capture the evolution of knowledge, tools and techniques over time. Material craftsmanship also captures the power of imagination that underpins technical understanding (Sennett, 2008).

Second to that and by extension, we have gradually progressed to a state where there is little understanding of where materials come from, what they are like to work with, or how they are assembled (Cooke, 2022). We also lack an understanding of the multiplicity of actors involved in all these processes and the dynamics of the social systems these actors operate in. This continues to foster low appreciation, bad design choices, and sub-optimal end-of-life scenarios.

Considering contemporary societal challenges such as climate change, waste generation, environmental degradation, scarcity, forced labour, exploitation and injustice, rethinking materiality and material production for the built environment is paramount. Current decarbonization goals, as expressed by the UN (2023), encourage avoiding the extraction and production of raw materials; shifting to material practices wherever possible by using ethically produced, low carbon, earth- and biobased building materials whenever possible; and, improving methods to radically decarbonise conventional materials such as concrete, steel and aluminium. Sustainability concerns, however, exceed mere technical decarbonization goals: they rather depend on people’s ability to innovate across multiple domains. The questions are about how to set goals for the materials performance, how to regulate science, how innovation interacts with commercialism, and how far ethics can, and should, shape the questions we ask (Ball, 2022).

To date there are two primary schools of thought laying the groundwork for more sustainable material futures: the first and oldest is Material Culture (MC), and the second and more recent is the post-humanist theory of New Materialism (NM), also supported by Science and Technology Studies (STS). MC interprets how objects express cultural norms and ideologies, revealing the intentions and identities of those who engage with them (Grassby, 2005). New Materialism (NM) theory, on the other hand, explores the interconnectedness of matter and meaning. It challenges anthropocentric thinking, framing human, social and political relations within broader ecological frameworks that demand planetary-scale analysis (Joyce, 2015). Lastly, STS posits that society and materiality co-constitute each other, mutually shaping one another through processes such as translation, inscription, and enactment (Rohracher, 2015). Meaning is seen as a temporally emergent property of

material engagement -the ongoing blending of mental and physical dimensions (Malafouris, 2013). NM and STS together advocate a rigorous attention to materials' origins, agencies, and eventual destinations -laying the groundwork for more sustainable futures.

In this light, the two most prominent frameworks currently promoting NM and STS principles are circularity and regeneration. They both encourage thinking about materials as a process rather than a product and they both ask for the recalibration of the human actor and the systems responsible for materials' production and management. Whereas circularity focuses mainly on regulating material loops towards a zero-waste performance, regeneration pushes the ambition higher by aspiring to net-positive results. Nevertheless, they both bring forward the need to maximize the value and lifespan of resources and minimize waste. What they also share is a mutual belief in the development of biobased materials for achieving said goals.

This paper argues that biobased materials can function as active agents of change in design practice. Section 2 outlines the theoretical foundations of circularity, regeneration, and material agency. Section 3 introduces the Circular (Building) Product Design Canvas, which frames material exploration across four interconnected domains: materials, design, manufacturing, and management. Drawing on a university course on Circular (Building) Product Design (CPD), several graduation theses, and two research projects on food-waste valorisation and load-bearing mycelium composites, the paper examines how hands-on material experimentation enables designers to engage with sourcing, fabrication, and post-use reintegration. Lastly, the discussion and limitations sections (4-5) reflect on how these experiences reshape design knowledge, skillsets, and collaborative practices, while acknowledging the methodological limits of exploratory, proof-of-concept research.

2. Circularity, regeneration and the shift to biobased materials

As sustainability debates mature, the built environment is increasingly shaped by concepts that move beyond efficiency toward systemic transformation. Circularity, regenerative development, and the rapid emergence of biobased materials together signal a shift from linear, extractive models toward approaches that value continuity, reciprocity, and ecological integration. These frameworks not only redefine how materials are sourced, designed, and cycled, but also expand the role of architectural practice in contributing to broader social and environmental resilience.

2.1 Circularity

Circularity focuses on prolonging the lifecycles of existing biotic or abiotic or technical material resources to ensure these can remain functional during their entire expected service life (Illankoon & Vithanage, 2023). It manifests both as an operational scheme and a value system: any one of the 10R's, the most prominent heuristic framework for circularity, translates into a clear strategy and at the same time inherently supports the values of caring and sharing (Ioannou, 2023). Following Casson and Welch's (2018) view of circularity as "an imagined future", it becomes clear that circularity informs and motivates different areas of the social world through "a range of rhetorical, representational, organizational and material activities." The 'material activities' include all stages from raw resource sourcing, to

processing, designing and fabricating products, maintaining them and then ultimately reintegrating the materials they are composed of back in the loop. Circularity thus addresses systemically design concerns, manufacturing workflows and management aspects and first and foremost, materiality. Materials are central to circularity starting with the ex-post rationalization of the cycles of technical, abiotic materials employed in buildings and infrastructure, all the way to ex-ante use of biotic, biobased materials that offer the unique possibility to biodegrade and thus minimize waste.

2.2 *Regenerative Development and Design (RDD)*

Regeneration is rooted in ecological science, and living systems and whole systems theory (Camrass, 2023). In current literature, regeneration is positioned both as an antithesis to current extractive and exploitative practices, and as an alternative economic and political theory that argues for a deep transformation of worldviews (East, 2020). The mechanistic view (where humans are separate from and manage nature) is replaced by an ecological worldview that sees cities as living, adaptive systems in flux, where humans are co-creators embedded in complex webs of relationships (Du Plessis, 2012; Benne & Mang, 2015). This worldview calls for a deeper integration of ecological, cultural, and economic perspectives, emphasizing interconnectedness, emergence, and transformation. Regeneration advocates are claiming that the current environmental crisis reflects a loss of vital human evolutionary experience as we -humans- have been progressively detaching ourselves from nature, creating cognitive, experiential, and emotional “faulty lines” (Muñoz & Branzi, 2021). By extension, the critical foundation for our outer development is the inner development of new levels of capacity, consciousness, cultural identity and will, both in ourselves as practitioners and in the communities and systems we work within (Regenes Group, 2017). In (material) practice this translates into [i] sourcing renewable feedstocks such as agricultural byproducts, and waste streams, [ii] using green chemistry production methods that prevent the use of toxins and enable biodegradability, and [iii] designing compostable materials that ensure nutrients are cycled back to support soil health at the end of life.

2.3 *The shift to biobased materials*

The expansion of biobased product availability and their extensive utilization in modern buildings is one of the top priorities of the European Union. The term ‘biobased materials’ is attributed to materials having partly or wholly of biological origin (European Commission). For this reason, wood, as well as fibres and bio-composite materials are being systematically researched with the support of both EU funding and private investment. Biobased materials’ aesthetics are also being explored, leading to a renewal of the architectural language with new material expressions that favour the haptic experience of materials over the symbolic one.

Biobased materials are closely tied to circularity and regeneration ambitions as [i] they are produced locally and thus minimize transportation, [ii] they sequester carbon and thus have a low environmental impact, [iii] they have a favourable weight-to-load-bearing capacity ratio, and [iv] they have clear benefits on human health related to their capacity to reconnect people with nature and thus, enhance well-being (Sandak et al., 2019).

Nevertheless, biobased materials and products also come with several risks (Dams et al, 2023): [i] some of their physical properties, such as moisture content and combustibility

make it difficult to certify their performance, [ii] durability and vulnerability to infestation are also common concerns, [iii] consistency between different cycles and availability often hinder their uptake in the construction industry, [iv] reaching the desired performance per application while following buildings' regulations may compromise their biodegradability by the integration of non-biodegradable components, [v] additionally, higher costs have been reported.

3. Enacting circularity and regeneration principles in biobased materials research for architects and architectural engineers

Developing biobased materials requires a holistic and ecological worldview, a reweaving of the artificial world with the natural one. This is mostly reflected in the fact that the making of such building materials is situated in the crossovers of the disciplinary fields of material science, structural and mechanical engineering and architectural and industrial design with knowledge domains that are not traditionally consulted like biology, and agroforestry, but also art and crafts (Rognoli et al., 2023).

Architects and architectural engineers are not usually the ones designing building products and usually adopt an application driven approach when evaluating and benchmarking materials' performance. Nevertheless, with their capacity to think in a designerly way, architects can also actively contribute to materials research and discover new potentials in a way similar to that of industrial designers (Barati & Karana, 2019). This perspective resonates with the Material Driven Design (MDD) approach, which positions materials not merely as technical inputs but as drivers of experiential and conceptual design exploration (Karana et al., 2015). Given the growing need for architects and architectural engineers to engage more deeply with materials research and to navigate these interdisciplinary terrains, tools that structure this complex inquiry become essential.

In this light, members of the aFP research group of the Faculty of Architecture and the Built Environment of TU Delft (ABE), have developed the Circular (Building) Product Design Canvas (Ioannou, 2024). The Canvas (see Figure 1) is a thinking tool designed to support decision-making by highlighting key issues in developing circular building products. It presents sets of questions and considerations across four domains: materials, design, manufacturing, and management.

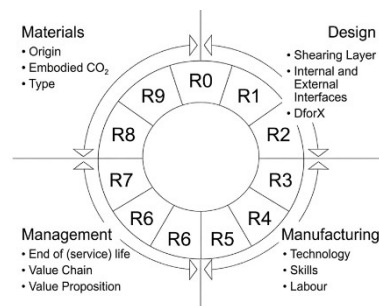


Figure 1 A simplified version of the Circular Product Design Canvas with the 10Rs featured in the middle (R0-R9). The choice of R strategy affects the four domains, and so does any choice across them.

The Canvas deciphers the systemic nature of circular and regenerative initiatives. Its structure implies that changes in one domain inevitably influence the other three. If materiality is the starting point of an inquiry into circular building products, the Canvas guides the student or researcher through design, manufacturing, and management considerations, thereby revealing the broader range of disciplines and actors involved.

This approach is reflected in three different material research directions: [section 3.1] revisiting and revising the use of natural material resources like raw earth, [section 3.2] opening to entirely new biotic (renewable) resources like agricultural residuals, and [section 3.3] exploring living materials like mycelium.

Integrating these themes in education comes with adaptations in the pedagogy as well. The experimental exploration of biobased materials' unique qualities requires having the lived experience of working with them. Making offers space to experiment and to rethink of objects, bodies, materialities and their mutual relationships. Through making, the maker not only "writes" with material to construct the logic of a system but also makes sense of the relationships between the user and technology. Hands-on experimenting and prototyping have become a new norm further enhancing unexpected and unprecedented collaborations with a wider network of makers and companies.

This study adopts a qualitative reflective research approach drawing on teaching activities, graduation research projects, and two applied research projects. These activities are treated as exploratory case studies that demonstrate how biobased materials can function as catalysts for new forms of design inquiry. The Circular Product Design Canvas was used as an analytical lens to structure the interpretation of these cases. Observations were documented through project reports, prototypes, photographs, and reflective documentation produced by students and researchers. The analysis involved mapping material experiments and design decisions onto the Canvas domains to identify how engagement with biobased materials expanded the scope of design practice. Because many of the projects involved exploratory prototyping and early-stage material research, the cases should be understood as proof-of-concept demonstrations rather than statistically generalizable evidence. The aim of the analysis is therefore interpretive: to identify emerging patterns in how material experimentation reshapes design thinking, collaboration, and knowledge production.

3.1 Revisiting and revising past practices

Material research in this case focuses on retracing previously used biobased materials and product configurations that have become obsolete. Examples of such practices include the integration of log timber in structures (see Figure 2), or straw thatching for roofing or cladding (see Figure 3), rammed earth construction (see Figure 4) and raw earth bricks. These practices enable building with locally harvested materials and in the case of rammed earth enable a waste excavation material to become a valuable new resource. Material resources are collected within a close range either from companies or farmers directly (for fibres). Additionally, these raw resources' processing requires limited energy consumption during production and can be carried out with simple tools.

What is interesting about this line of research is that it seeks to translate obsolete building materials and techniques into modern building components. It transcends a mere revival of a certain method to investigate how it can inform present construction performance

requirements. In the examples shown in this section, in the case of timber, it brings back the use of non-engineered wood, in the case of thatching it experiments with façade cladding besides roofing and in the case of rammed earth, it brings forward a revised aesthetic vocabulary that features the material's haptic qualities, its colour, its texture.

What is more, projects like these usually also aspire to increase the biobased content in these material compositions. So, the choice of DLT signifies making toxic glues redundant, and the reed cladding replaces more conventional energy-intensive cladding materials like bricks. The graduation project on the rammed earth (see Figure 4), explored natural binders for rammed construction to make the use of cement redundant.



Figure 2 Students of CPD experimented with developing a DLT structure. After cutting all wooden elements in the desired dimensions, the planks were assembled using wooden dowels.



Figure 3 Thatching is one of the emerging trends not only as a finishing layer for roofs, but also for cladding. Students of CPD experimented with layering the reed batches on a façade and tried to perform thatching rituals to achieve the desired texture.

Another interesting aspect lies in the making process itself. Even though the technology required is standard, the skills required for some of the operations are quite unique. Students and researchers are often confronted with the reality that something that looks as simple as a reed cladding or a rammed earth brick, requires a lot of practice, hard labour, and applied expert knowledge (rules of thumb). In the case of CPD, a collaboration with the Regionaal Opleidingscentrum of Amsterdam (ROCvA) for vocational learning addresses this discrepancy and further contributes to developing a learning environment that nurtures the collaboration between designers and makers.



Figure 4 Experimenting with natural binders for rammed earth construction brought about a lack of established protocols for testing rammed earth in the NL. The graduation thesis of Fieke Konijnenberg (2024) identified a series of potential natural binders as well as a clear set of testing protocols based on archival research, literature review, and interviews.

It is worth noting here that reviving past practices is not so straightforward as it sounds. The process can be hindered by lack of references or access to relevant information. While this increases the difficulty of carrying out said research, it also increases the creativity of the researchers. In the case of rammed earth, for example, the graduate student had to perform archival research and conduct interviews to retrieve testing protocols and experiment on her own with various testing methods to be able to safely claim the performance of the natural binders in the mix.

Each one of these examples, begins with a material exploration, but nevertheless, it also addresses aspects of design, fabrication and maintenance over time. Guided by the Canvas framework, students and researchers also tackle management aspects in terms of the skills and competences needed to perform certain tasks, managing supply and quantities, workflows, timelines and thinking ahead for the materials' end of life-scenarios but also thinking about regulatory frameworks and how these are challenged by the new materialities.

3.2 Towards 100% biobased

Material explorations in this second line of research focus on developing building products from either food waste in the form of beans, shells or pits, or from agricultural residues like plant leaves or stems. In the case of graduate education, this can take the form of simply mixing fibres with binders such as hemp with lime (see Figures 5-6) to understand the ratios between the different materials in the composite. Design and fabrication are also prominent here as for most of the students this is the first time they engage in working with biobased materials and therefore have little experience on how to design moulds or compact the mixed materials. What stands out in most of these cases is the realization of the amount of labour required for the fabrication process (drying time, layering etc.). And how, despite the roughness of the final product, there is a very strict procedure and protocol that needs to be followed.



Figure 5 Hempcrete construction through the stages of mixing, ramming and even 'jumping' to achieve compaction during the CPD course.

Bio-composite material research falls in this category as well. The major material components in this case can be either fibres or fillers usually mixed with biobased resins. As this research is far more complex, it is more likely to occur within graduation or research projects. Fibres can be employed here also in textile formats such as flax cross-woven textiles and layered in bio-composites using biobased film resins like PLA (see Figure 6). Sheet materials produced through this technique are later tested for their potential to be used in different applications. The difference here, is that the potential application is identified after the bio-composite is generated.



Figure 6 The graduation thesis of Tom Boom (2025) on hempcrete construction research with varying manufacturing parameters such as layer height, compaction factor, orientation and binder type.

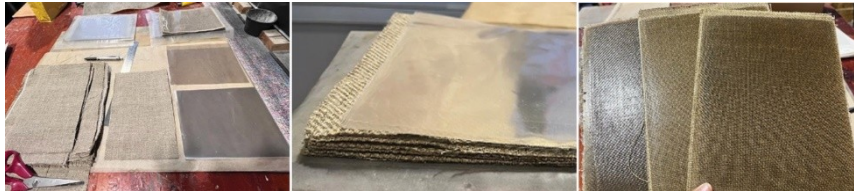


Figure 7 The graduation thesis of Samanwita Ghosh (2024) experimented with bio-composite generation using flax cross woven textile and PLA laminate layering.

Research on bio-composites might also involve food-waste streams. The intention in this case is to not only produce a 100% biobased material but to also minimize waste. Various food-waste streams have been investigated in education and research, such as coffee and cocoa beans, walnut shells and cherry pits (Neuhaus et al., 2025), but also hazelnut and pistachio shells, beer brewing waste, avocado and mango pits and date seeds (see Figure 8) (Ioannou & Konijnenberg, 2026). Assuming different granularity through milling and mixed with biobased resins in different ratios, these material resources can produce different types of bio-composites with high mechanical performance (comparable to those of conventional technical materials like aluminium) that allows them to even be considered for external, façade cladding applications. What is important to consider here is that despite the more obvious material, design and manufacturing explorations, management considerations and end of life scenarios also enter the picture. This happens either through mapping waste supply chain stakeholders, redesigning waste collection, and rethinking resource processing. But it is also evident in the increasing tendency to consider end-of-life scenarios even for biobased products through *recycling* and the subsequent reintegration of the recycled composite into new mixes as is the case for materials in Figure 8 or even remanufacturing by repeated forming and reforming of the materials in complex geometries for new uses as is the case with materials in Figure 7.



Figure 8 Food-waste streams mapping, and material sampling using the food-streams as fillers and a 98% biobased resin.

3.3 Living materials

A third and last branch of new materials research in ABE is looking into living materials such as algae, bacteria, or mycelium. What is particularly compelling about these organisms is their capacity for carbon sequestration combined with the low-energy processes required for their cultivation and fabrication. In contrast to more conventional biobased approaches, this research line is perhaps the closest to material-driven exploration, where it is the behaviour, potential, and limitations of the material itself that set the research agenda, rather than a predefined architectural application. This largely stems from the inherent uncertainty of working with living organisms and from their apparent incompatibility with current construction systems, standards, and expectations.

Despite the challenges associated with long-term viability, durability, and user acceptance, these material resources are already emerging in preliminary applications. Mycelium, for example, is often encountered in the form of building blocks for wall applications (Fig. 9), thermal insulation or acoustic panels.

Bacteria-based materials are also now in development either as coatings or surface treatments or binders. These early manifestations do not simply indicate technical feasibility; they also signal a broader shift in how we understand the role of materials in architecture, no longer as inert building components but as agents with their own behaviours, requirements, and ecological entanglements.

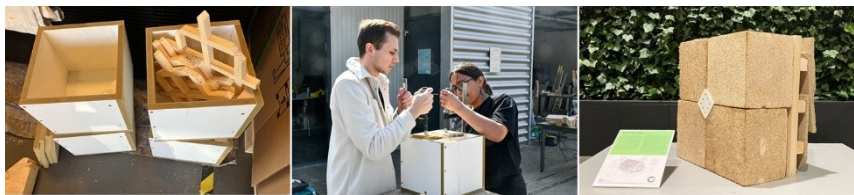


Figure 9 Mycelium building blocks made using moulds, timber reinforcement and compression during the CPD course.

4. Discussion

The cases show biobased materials as active agents in design rather than passive resources, aligning with NM and STS perspectives on socio-material co-constitution. In projects using mycelium and food-waste composites, material properties directly shaped decisions, shifting toward a material-driven inquiry. The Canvas showed how decisions in one domain shape others. In the food-waste composite case, sourcing required mapping waste supply chains (management), influencing processing (manufacturing) and ultimately geometry and application (design), highlighting the systemic interdependencies central to circular and regenerative frameworks.

Material-driven research opens a wide range of possibilities for architecture by raising awareness of the processes responsible for making the built environment. Although not all approaches are new, what changes in this working paradigm is that **these aspects are considered proactively from the early stages of design**. Following circular and regenerative principles, and using the Canvas methodology, students and researchers think through the

entire life cycle, from sourcing to end-of-life, and across the entire ecosystem of actors and stakeholders responsible for these processes from the start.

Throughout these three main lines of research explored in the previous section several arguments can be made:

- **Student and researchers' skillset is enriched:** Although students or researchers may not continue producing these materials in practice, knowing the intricacies of making expands their understanding of fabrication methods and -even more importantly- enhances their design competence. The embodied familiarity with materials deepens their ability to make informed design decisions. This is mainly evident in student testimonies such as that of the group developing the DLT structure "(...) The building week was a great reminder that systems on paper always turn out different in practice, but we were pleasantly surprised with how well we could translate our idea from paper to reality." Similarly, a student claimed that they "gained confidence in detailing knowledge" while another stated that "using the practical technical skills is refreshing."
- **Uncertainty stimulates creative problem-solving:** Many of these explorations involve high levels of complexity, often compounded by limited data or information. Nevertheless, the resilience of students and researchers was noteworthy. This is reflected in students' contemplation of their shortcomings. The group developing the hempcrete blocks commented: "(...) One block was too moist and had to be relieved from excess water by jumping on top of it. The other block was too dry and brittle to stay intact without the formwork. We managed to repair it in the end, but it showed us that either the design was not sufficiently optimized for this production method or that we made too many mistakes during the production of the prototype." Uncertainty was addressed either by broadening their research methods or by engaging in iterative, trial-and-error processes to better understand what was at stake and what directions could be pursued. According to another one of the groups working on a CNC milled cassette structural system: "(...) During these construction weeks, we encountered several challenges and had to think creatively to find on-the-spot solutions. This was often done in close cooperation with the ROC students."
- **Transparency in communicating research supports continuation and further enables the development of a community of practice:** Reporting back and communicating is an essential part of the learning processes. Just as these students benefited from their former peers' research, they too necessitate to share back with the next cohorts. All learning outputs (mock-ups, reports, papers, etc) follow open science principles to support the continuation of research across the three themes. Student prototypes have been exhibited in the Future Facades event in 2025 in Utrecht and the

Climate Action program in 2025 at TU Delft campus. The entire range of student group work from conceptualization to implementation and reflection is visually and verbally documented in a report students must submit at the end of the course. Graduation theses are publicly shared in the TU Delft repository and are often points of reference in new projects. Similarly, research projects' findings are published in open-access journals and shared amongst the groups to guide and to inspire future projects. As a result, students frequently consulted one another and often reached out to alumni for advice, support, or materials. These exchanges fostered a growing sense of community around biobased materials one that enables knowledge to be passed from one cohort or student to the next. Very often, new CPD participants can build directly on the experiences of those before them. For example, the graduation thesis on rammed earth became the basis for a group engaging with this material a year later.

- **Transdisciplinary collaboration expands material inquiry and supports systemic thinking:** Following the Canvas, and its four domains, all examples of student or research projects presented in this paper extend beyond the disciplines of design and engineering. CPD collaborations with scientists (e.g. material scientists or chemists), companies, practitioners, and makers broadened the scope of the research and deepened the collective understanding. Graduation theses are usually supported by a company partner. At the same time, both research projects are supported by companies and a living lab. Questions and pathways are thus situated within larger ecological, social and technological contexts. This involves a holistic understanding of materials within the larger construction ecosystem and even beyond it. Material choices intersect with other sectors, such as the food or the agricultural sector when working with food-waste streams. Systemic thinking encourages students and researchers to view materials as nodes in broader networks of production, use, and regeneration, revealing both constraints and opportunities for circularity and regeneration.

Overall, research into biobased materials is not only about exploring new materialities, but also about opening pathways to new modes of **design practice**. Rather than focusing exclusively on product outcomes, these practices involve learning to work with others, experimenting (and even playing) with materials, developing new aesthetic vocabularies, and most importantly, shifting to an ecological worldview. While the cases presented here are exploratory, they indicate how material experimentation may foster new forms of ecological awareness and collaborative practice within design education.

5. Limitations

This study relies primarily on exploratory case studies derived from educational and early-stage research contexts. Many of the material prototypes presented were developed

through iterative experimentation and trial-and-error processes rather than standardized testing protocols. As a result, comprehensive performance data—such as long-term durability, fire resistance, or supply-chain scalability—are not yet available for all materials explored.

Furthermore, several examples originate from student projects conducted within limited timeframes. These prototypes should therefore be interpreted as proof-of-concept demonstrations rather than fully validated building products. Future research should complement these exploratory investigations with standardized mechanical testing, lifecycle assessments, and supply-chain analyses to evaluate the broader applicability of the materials developed.

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