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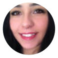

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Biobased Material Computation and Digital Fabrication for Bacterial Cellulose-Based Biofabrics

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The collaboration with biological organisms, biomaterial computation, and digital fabrication offers new possibilities for reconsidering the relationship between human and non-human living forms. These organisms allow for the creation of materials, design and manufacturing processes, and end products to become more closely aligned with natural systems and processes, as they are derived from renewable resources and have a lower environmental impact than synthetic materials. In this research, by focusing on nature and non-human living organisms, biobased material computation and digital fabrication were explored to develop biofabrics. This research offers a fully biodegradable process with zero waste and unlimited supply, enhanced with the resources provided by nature, including nature's design and manufacturing methods. To create this sustainable, circular cycle, one of the most abundant materials in the world, the purest form of cellulose, is produced by bacteria such as Acetobacter Xylinus (A. xylinus). In collaboration with A. xylinus, bacterial cellulose-based biofabrics were grown and harvested. The methodology was divided into four main stages: Digital fabrication of a customized fashion dummy which involves 3D modeling, laser-cutting, and assembly of a fashion dummy; a stochastic scaffold design for the bacterial cellulose biofilm layer; biobased material formulation for developing a biofabric; and bio-assembly. The outcome has been exhibited at Good Design İzmir 7, a national curated exhibition among the invited guests' section, and had a chance to meet a larger audience to raise awareness. As a result, it was seen that incorporating biobased materials into the digital fabrication process has the potential to not only improve the performance and sustainability of materials but also to encourage designers to reconsider the relationship between humans and ecology. Future studies can include the scalability of such systems for broader design realms, such as biobased architectural solutions for buildings, especially lightweight structures, as well as industrial design products such as packaging.

Keywords: *Material based Computation, Biobased Materials, Digital Fabrication, Biofabrics, Bacterial Cellulose*

INTRODUCTION

Material computation has emerged as a cutting-edge field that seeks to bridge the gap between the digital and physical worlds (Oxman and Rosenberg, 2007). It involves using algorithms and computational tools to design and fabricate complex structures and materials, blurring the lines between material science, engineering, and computer science (Menges, 2012). With a focus on exploring novel materials and their properties, material computation has the potential to revolutionize various industries, from construction and architecture to biomedical engineering and beyond (Stepney, 2008).

One key area of current research in material-based computation is the biobased materials, such as plant-based or microbial polymers and biocomposites, at various scales (Zhou et al., 2021). In recent years, there has been a growing interest in exploring the use of biobased materials in material computation and fabrication (Choi et al., 2022; Turhan, Varinlioglu and Bengisu, 2023). Biobased materials, which are derived from natural sources, have the potential to offer a more sustainable and environmentally friendly alternative to traditional synthetic materials (Yadav and Agarwal, 2021). By leveraging the unique properties of biobased materials, researchers in the field of material computation have been working to develop new fabrication techniques and applications (Shreepad and Ravi, 2015; Xie et al., 2019; Sayem, Shahariar and Haider, 2020; Turhan, Varinlioglu, and Bengisu, 2021). The transition from digital design to physical prototyping is one of the critical challenges in biomaterial computation due to the challenging properties of biologically active materials that require various controlled parameters for growth, manufacturing and maintenance (Provin et al., 2021). Therefore, digital fabrication plays a crucial role through a set of techniques that use digital design data to control the manufacturing process, allowing for the creation of complex and intricate forms with high accuracy and precision (Kamath, 2013). Researchers can explore new frontiers in developing novel materials and structures by combining biobased material computation with digital fabrication.

In this paper, the intersection of material computation, biobased materials, and digital fabrication is explored through a case study in the realm of fashion design that demonstrates the potential scalability of this approach in the design and fabrication of various products, including industrial design and architecture. We also discuss the challenges and opportunities presented by this interdisciplinary field and propose future directions for research. Overall, this study highlights the potential of biobased material computation and digital fabrication in developing sustainable and innovative materials for various design applications by reconsidering the collaboration with biological entities.

THEORETICAL BACKGROUND

The Anthropocene, defined as the geological epoch in which human activity has become the dominant force shaping the planet, has brought about a multitude of environmental challenges (Corlett, 2015). Climate change, resource depletion, and pollution are a few issues facing society today (Arora, 2018). As a result, there is an urgent need to develop sustainable and biodegradable materials for design applications. The concept of sustainability, which encompasses environmental, social, and economic dimensions, has been increasingly important in recent years. Sustainable materials are those that are produced and used in a way that minimizes negative environmental and social impacts while also ensuring long-term economic viability (Olivetti and Cullen, 2018). the cradle-to-cradle design approach calls for the development of regenerative products and systems that can be reused indefinitely (Sherratt, 2013). Similarly, the circular economy, which emphasizes the reuse and upcycling of materials, has gained popularity as a way to address the challenges of the Anthropocene (Sikdar, 2019). Therefore, the cure for the effects of the Anthropocene is circularity.

Circular Economy

Circularity refers to creating a closed-loop system to extend and preserve the value of products and materials for as long as possible (Megevand et al., 2022). As stated through the sustainable development goals (SDG), the United Nations (UN) has highlighted the circular economy as a critical component of sustainable development. The Target 12 of the SDGs focuses on sustainable consumption and production, with a particular emphasis on the circular economy as a way of accomplishing this objective. The circular economy seeks to reduce waste and pollution by extending the life of products and materials as much as possible, hence lowering the environmental effect of production and consumption. The United Nations has acknowledged the necessity of implementing circular economy concepts in all sectors of society, including industry, government, and civil society (UN, 2015).

On the other hand, circular design is a key component of the circular economy as it aims to create products that are designed for durability and longevity, design for recyclability, and design for assembly or zero-waste by adopting 5R (rethink, reduce, reuse, repair, and recycle) to increase the value of the products (Tserng, Chou and Chang, 2021). While it can be challenging for a designer to develop a process that integrates ethics and aesthetics, the material choices, design approaches, production processes, and manufacturing conditions also affect the development of potentially sustainable products and systems.

Bio-Design

In the design field, there has been an increase in the number of bio-terms, such as biomimicry, biomorphism, and biophilia, in recent years (Chayaamor-Heil, 2023). Overall, each approach embraces the inspiration from nature to create sustainable materials and systems at different scales. By mimicking the structure and properties of natural materials or incorporating these materials into design applications, superior performance while being environmentally friendly can be achieved (Zhang, McAdams and Grunlan, 2016). However, as with any approach, some limitations and deficiencies must also be considered. One of the main criticisms is that they are often undertaken as an approach to form generation or creation of harmonious relationships with nature, rather than considering the process and outcome as a whole (Marshall and Lozeva, 2009). As a result, there is an urgent need to reconsider and develop materials that fully capture the sustainability and efficiency of natural systems.

Most of these bio-terms can overlook important aspects of material selection in terms of the life cycle analysis such as the environmental impact of raw materials, their assembly and disposal. Therefore, it is crucial to consider emerging approaches that focus on materiality by borrowing methods and tools from materials science and engineering as a holistic and systems-oriented approach by incorporating the methods and tools of digital fabrication and computation. It can potentially offer researchers and designers to develop materials that are biodegradable, self-efficient, sustainable, and environmentally friendly and that address the environmental challenges of the Anthropocene.

Biobased material computation and digital fabrication involve the use of various computational methods in order to benefit from biobased materials more efficiently. Material ecology is closely related to material computation and can interact with each other in a symbiotic way. In the literature on bio-based design and computation, the potentials of this kind of approach are discussed widely, to create innovative materials and structures. By the integration of the digital fabrication technologies, additive and subtractive approaches and methods such as laser cutting and 3D printing it is possible to accelerate research and practice in the bio-design field (Turhan et al., 2022).

There is an accelerated landscape of such biobased materials employed in different engineering and design fields. The examples include bioplastics which are composed of renewable biomass sources, such as cornstarch, sugarcane, and potato starch, used in various applications such as packaging, disposable cutlery, and 3D printing. The biocomposites have been also made from natural fibers such as hemp, flax, and bamboo, combined with a biopolymer matrix including PLA. There are bioceramics that have been derived from natural sources such as bones and teeth to be used in medical implants such as dental implants, artificial joints, and bone grafts. Biopolymers produced from renewable biomass sources such as cellulose, chitin, and lignin have been employed in various applications, including food packaging, textiles, and biomedical equipment.

Collaboration with Acetobacter Xylinum

This paper approaches biobased material computation and digital fabrication in the case of textile and fashion design by collaborating with Acetobacter Xylinum (A. Xylinum) for biodegradable products. A. Xylinum is a gram-negative, aerobic, and rod-shaped bacterium that is found in environments with high levels of oxygen including vinegar, kombucha, or other fermented foods (Skinner and Cannon, 2000). It is commonly used in industrial and biomedical applications for its ability to produce cellulose by a sophisticated process that involves the secretion of cellulose synthase complexes, which catalyze the polymerization of glucose into long chains of cellulose (McManus et al., 2016). These chains are then extruded from the cell and joined together to form a highly ordered and crystalline structure (Vasconcelos et al., 2017). A. Xylinum generates high-quality cellulose with particular features such as high crystallinity, purity, and tensile strength (Sheykhnazari et al., 2011) that make it a promising material for use in various design applications such as the production of biodegradable and sustainable fabrics, especially development of bio-composites with the integration of other natural fibers including hemp, flax, and bamboo (Naeem et al., 2020).

METHODOLOGY

The methodology was divided into four main stages: Digital fabrication of a customized fashion dummy; a stochastic scaffold design for the bacterial cellulose layer; biobased material formulation; and bio-assembly. (Figure 1) The first stage of the methodology involved the use of digital fabrication to create a customized fashion dummy. This dummy served as a template for the subsequent phases of the bio-fabrication process through a precise and accurate representation of the desired shape and size of the human body, allowing for further interventions that may not be achievable using traditional fabricated counterparts.

The second stage of the methodology involves the design of a stochastic scaffold for the bacterial cellulose layer. The scaffold provides a support structure for the bacterial cellulose to grow on and allows for the creation of a three-dimensional structure. The use of a stochastic design allowed for the creation of a random pattern, which enhanced the aesthetic appeal of the final product.

The third stage of the methodology involves the formulation of a biobased material that was used to create the bacterial cellulose layer. The material composition was carefully considered to ensure that the additives were compatible with the bacterial cellulose and would allow for optimal growth. Biobased materials were preferred over synthetic materials as they are more sustainable and environmentally friendly.

The final stage of the methodology involves the bio-assembly of the customized fashion dummy, the stochastic scaffold, and the bacterial cellulose layer. The scaffold and the bacterial cellulose layer were carefully assembled onto the fashion dummy to create the final product.

The process of fabricating a customized fashion dummy is crucial for developing and testing new materials and designs in the fashion industry. Traditional methods of creating dummies have limitations, such as size constraints and difficulty in replicating human body shapes accurately. More importantly, creating a customized scaffold on a conventional ready-made dummy is challenging due to restrictions caused by material that consists of petroleum-based plastic casts. To address these limitations, the use of 3D modeling and fabrication technology was adopted. The purpose of 3D modeling in our study was to create a precise and customized fashion dummy that would not only replicate the shape and size of a real human body, but also allow us to manipulate it for a customized scaffold construction. A 3D dummy was modeled

Figure 1
Methodology

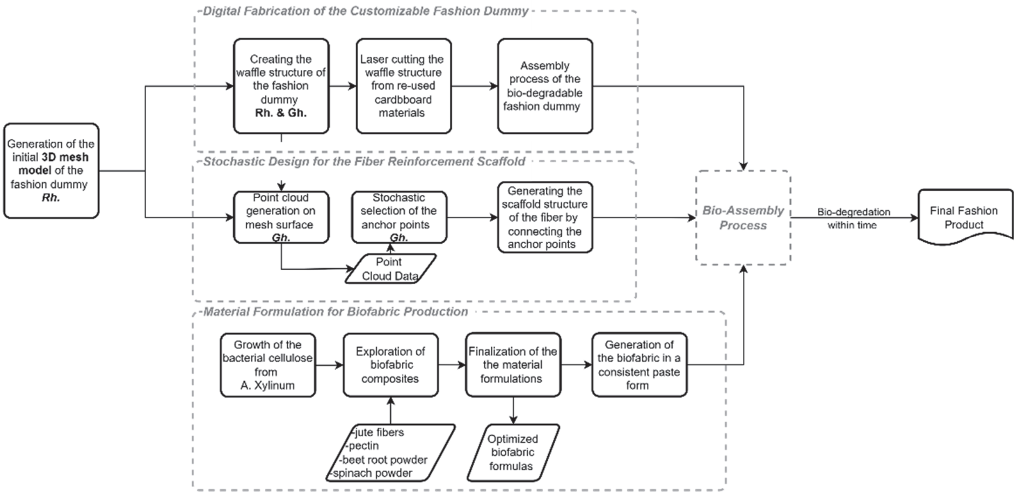
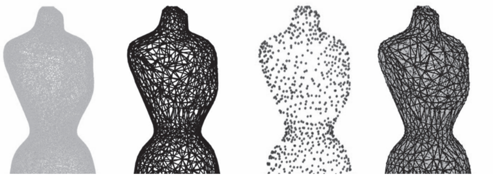


Figure 2
3D modelling, laser cutting and assembly stages of the customizable fashion dummy

Figure 3
Computational stochastic scaffold design for the fiber reinforcement



and imported into Slicer software. The software gives the layout with optimum nesting conditions of cut-out pieces when the fabrication type is selected.

Laser cutting was used to accurately cut the dummy parts from durable, flexible and lightweight cardboard leftovers collected from an institution. Finally, the assembly process involved fitting the cut-out parts together to create a fully functional fashion dummy. (Figure 2) The result was a customized fashion dummy that could be used to test and develop biobased materials for the fashion industry.

Stochastic Scaffold Design for the Fiber-Reinforced Scaffold

In this study, the surface of the customized fashion dummy was used as the base to create a point cloud (Figure 3). Once the point cloud was generated on Grasshopper, Rhinoceros 3D, a stochastic approach was used to select anchor points in a random manner. The resulting points were then connected using jute strings, forming the base for the web application that would act as the scaffold for the bacterial cellulose biofilm layer. Therefore, the scaffold mimicked the irregular and unpredictable nature of natural structures while still providing the necessary support for the bacterial cellulose biofilm layer. Additionally, the use of Grasshopper Rhinoceros 3D allowed for a high degree of precision and accuracy in the creation of the scaffold, ensuring that it met the exact specifications required for the study.

Material Formulation for Biofabric Production

The nature of BC was first explored through several observations within the early explorations, including the texture analysis with a digital microscope with 500x amplification (Figure 4) and different material compositions consisting of pure BC; BC+pectine+beet root powder; BC +jute+pectine;BC+jute+spinach powder+pectine (Figure 5). The culture used in fermentation and production was Acetobacter Xylinum (A. xylinum). The production of BC biofilm (Figure 6) took place within 1 L. of water, added with 4 gr. of green tea that was infused for 10 minutes at 100°C. 100 gr. of sucrose and 30 ml. of fermented liquid were added for acidification. After adding 90 gr. of BC biofilm piece, the culture was cultivated at 20 ± 2 °C and 65 ± 5% moisture in static conditions for 34 days. After 34 days of cultivation, the biofilm on the surface of the container was removed. The pretreatment of the biofilm was skipped to let the bacterial growth continue. The grown biofilm was sliced apart into pieces. 15 gr. of it was kept as inoculum in the subsequent fermentations for another 34 days. The procedure was adapted from the research conducted by De Filippis et al. (2018) and Sederaviciüte, Domskiene and Baltina (2019). The remaining 75 gr. of the biofilm was used to develop biofabrics together with the 30 ml. fermented liquid and 20 gr. pectine.

Bio-assembly Process

Bio-assembly refers to the process of assembling biological components, such as cells or tissues, into a functional structure in the medical fields. In the case of bacterial cellulose-based biofabrics, bio-assembly involves the arrangement and attachment of the bacterial cellulose layer onto a pre-defined scaffold or template. After the scaffold was constructed on the customized dummy with needles and jute fibers, the mixture was applied (Figure 7). The scaffold provided a support structure for the bacterial cellulose to grow on and allowed for the creation of a three-dimensional structure.

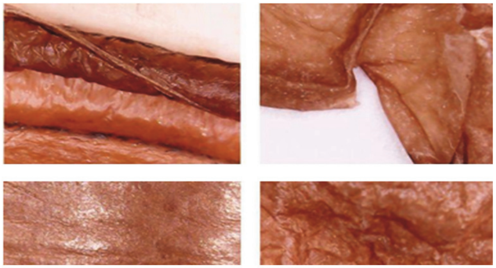


Figure 4
Texture analysis with a digital microscope with 500x amplification

Figure 5
Examples from composite explorations

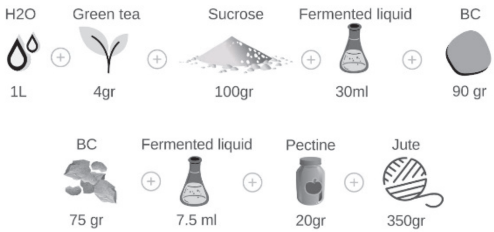


Figure 6
Biobased material formulation

Figure 7
Bio-assembly of dummy, scaffold and biobased material application

Figure 8
Biofabric collection

The bio-assembly process must be carefully controlled to ensure that the bacterial cellulose grows in the desired pattern and adheres securely to the scaffold. The goal of this approach was to create complex and functional materials using biological components and advanced manufacturing techniques. Since the mixture contains living organisms due to the removal of the sterilization stage, it was anticipated that the biofabric would grow when proper environmental conditions were provided. Therefore, the bio-assembly process also involved the use of environmental controls, such as a dual temperature controller ZFX-ST3012 to make sure that the average value falls around 20 ± 2 °C and a humidity controller XH-W3005 with a dehumidifier and humidity probe to ensure that the value falls around 65 ± 5%, to promote optimal growth of the bacterial cellulose. The mixture containing the ingredients of the growth medium was sprayed onto the fabric at three-day-long intervals while keeping the prototype in a heat- and humidity-regulated setup.

RESULTS AND DISCUSSION

Working with bacterial cellulose, a biobased material, poses challenges in close maintenance. These include the risk of microbial contamination, the need to meet specific nutrient requirements, pH and temperature control, ensuring proper oxygen supply, maintaining sterility and hygiene, scaling up production, and the time and cost involved. Despite these challenges, bacterial cellulose offers advantages such as high purity and unique properties, making it attractive for various applications. Overcoming maintenance challenges can lead to innovative and sustainable materials with diverse uses.

The outcomes of the present study were showcased as a fashion collection, along with two additional outputs (Figure 8), at a nationally curated exhibition. They were presented within the invited guests' section for 11 days. Since the growth of the biofabrics continued, changes in the color and pattern were quite visible, adding another dimension, "time" to the design.

This exhibition provided an opportunity for the research outcomes to be disseminated to a wider audience, thereby increasing awareness of the potential of biobased material computation and digital fabrication for sustainable material production. The exhibition platform served as an effective means to promote the significance of the research, highlighting the importance of interdisciplinary approaches in creating innovative and sustainable materials. The presentation of the research outcomes in this manner facilitated engagement with a broader community, promoting public understanding and appreciation of the potential of biobased material computation and digital fabrication in addressing the challenges of sustainable material production against the irreversible effects of the Anthropocene.

The field of biobased material computation and digital fabrication represents a rapidly growing and interdisciplinary area of research that offers numerous challenges and scalable opportunities for the development of sustainable and innovative materials for especially architectural construction. By reconsidering the collaboration with biological entities, this field has the potential to transform the way we design, produce, and consume building materials, offering new avenues for sustainable and environmentally friendly material production.

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