A Scalability Assessment of Biofabrics as an Alternative Architectural Construction Material

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Abstract. This research explores the scalability of biopolymer applications in recent biobased textile design applications for architectural construction. It particularly focuses on the transition from laboratory experimentation to architectural construction practice with the aid of computational design and digital fabrication. The research aims at harvesting spatial structures through the re-characterization processes for desired material properties. The methodology is divided into four steps: Modification of the biofabric formulation derived from bacterial cellulose (BC); tensile strength tests; computational design and digital fabrication of a catenary geometry as a scaffold; bioassembly process; and observations at different environmental conditions after the removal of the scaffold. The results have shown that the material properties such as the tensile strength, structural integrity, high capacity of water detention, and heat insulation differentiate bacterial cellulose-based biopolymers as circular alternatives to the current conventional architectural construction materials and processes, having us reevaluate our connection with nature through architecture.

Keywords: Biodigital architecture, Biodigital design and ecosystems, Biobased materials, Circular design, Bacterial cellulose

1 Introduction

Biopolymers, derived from renewable resources and living organisms, represent a sustainable alternative to traditional synthetic polymers due to their eco-friendly composition for reduced environmental impact and increased biodegradability (Patti & Acierno, 2022). In recent years, biopolymers have gained traction in the fashion and industrial design sectors, offering innovative materials that align with the growing demand for environmentally conscious products. For instance, in industrial design, these versatile materials find applications in products like packaging, providing a greener alternative to conventional materials and promoting a shift towards eco-friendly manufacturing processes , as well as offering multifunctional properties such as being biocompatible, biodegradable, and in some cases improved mechanical properties, which makes them a promising option for automotive applications (Bouzouita et al., 2017).

The emerging needs and functional uses in the textile industry, such as the production of smart and medical textiles, have also influenced the fashion industry through the development of more environmentally friendly production processes. Biopolymers derived from living organisms such as plants, bacteria, and fungi are transforming the textile industry by offering a circular alternative to traditional materials for a wide range of applications from apparel and accessories to home furnishings and technical textiles. These materials have been influential in the development of textiles with enhanced properties such as increased strength, flexibility, moisture management, and antimicrobial functionalities (McCarthy, 2011). Such developments are responding to the dynamic and challenging changes in the fashion industry, offering unique properties engineered specifically for fashion applications, beyond their significant environmental benefits. Proteins, soy protein, wheat gluten, whey, collagen, and gelatin are among the biopolymers used to develop biodegradable films and coatings for textiles, improving their functional and aesthetic properties. These coatings can impart water repellency, wrinkle resistance, and antifungal or even wound healing properties to fabrics, while biopolymers are designed to have specific properties such as breathability and durability, demonstrating their versatility (Smet et al., 2020).

The adoption of biopolymers in the textile industry, characterized by enhanced functional and environmental properties, represents a significant shift towards circular applications impacting various fields, including architecture. While biobased materials hold great promise for ecological architecture, the field faces certain challenges that impede a complete transition. The durability and structural properties of biobased materials may not always match the stringent requirements of construction, limiting their widespread use (Chayaamor-Heil et al., 2023). Additionally, the adaptation of biobased materials in architecture requires extensive testing and validation to meet regulatory standards, which can slow down their integration. The construction industry traditionally relies on well-established materials and methods, creating resistance to the rapid adoption of newer, biobased alternatives. Moreover, architects often face budget constraints and concerns about the long-term performance of biobased materials, further contributing to a cautious approach to embracing these innovations. Despite these challenges, ongoing research and advancements in biotechnology offer the potential for a gradual shift toward more sustainable architectural practices in the future.

2 Theoretical Background

The transition from the traditional linear economy, characterized by the take-make-dispose model, to the circular economy, represents a shift aimed at addressing the unsustainable patterns of production and consumption that currently dominate global economies. The simple flow of the linear model - extracting resources (take), producing products (make), and disposing of them as waste after use (dispose) - has led to significant environmental degradation and resource depletion (Kalmykova et al., 2017). The circular economy is a restorative economy, which aims to utilize all resources, whether man-made, human, or natural, and transform resources into a productive form that can be reused to maintain their highest value in the long term (Gursel et al., 2022). Circular economy principles also apply to biobased materials and composites, advocating a systemic shift from linear to circular flow in materials sourcing. This shift could reduce dependence on fossil resources, increase resource efficiency and promote the utilization of waste and residues, thus contributing to environmental sustainability and the maintenance of planetary boundaries (Niinimäki, 2017).

One of the disciplines and practices that adopted the use of biobased materials, the textile industry, previously was obliged to use synthetic fibers derived from non-renewable petroleum in textile production which increases carbon dioxide emissions and energy consumption. This results in worsening the environmental impact of the industry and emphasizing the importance of adopting a circular approach in textile applications. Principles such as reuse, material recovery, and new business models are now at the heart of fashion's circular economy, which challenges traditional linear economic models by prioritizing the expanded use of resources (D'Itria & Colombi, 2022). Similarly, the shift towards bio-based textile solutions in the fashion industry underlines the commitment to environmentally friendly and economically viable materials and supports a circular bio-based economy.

The textile industry is leading the innovations that resulted in a wide range of bio-based materials, ranging from plant-based fibers such as bamboo and banana to protein-based fibers such as fibers derived from milk protein and synthetically produced spider silk, to cellulose-based polymers and bioplastics. Seaweed-derived alginate fibers represent another frontier in bio-based textiles. Fibers made from these materials are biodegradable, renewable, and can be produced with minimal impact on the soil.

This application demonstrates the potential of biobased materials to go beyond conventional textiles to provide innovative solutions in the medical and health-related fields. The root structure of fungi, mycelium, is also utilized in the production of skin-like materials. Mycelium is characterized by its rapid growth, feeding on agricultural waste, and minimal water and pesticide requirements. By being biodegradable and feasible in a range of densities, the resulting material provides an environmentally friendly substitute for synthetic and animal leathers. Piñatex® is another revolutionary material made from pineapple leaf fibers, a by-product of the pineapple harvest. This material provides a sustainable alternative to leather and an additional income stream for farmers. Piñatex® is durable, biodegradable, and requires no additional resources for its production, making it an exemplary model of the circular economy. Transitioning from the agricultural innovation exemplified by Piñatex®, the discourse shifts towards the biotechnological advancements in the textile industry, where bacterial cellulose emerges as a further illustration of the remarkable potential inherent in bio-based materials. This transition highlights the industry's broader move towards circular alternatives that encompass both natural and engineered solutions.

One of the most abundant materials in nature, bacterial cellulose, is a highly versatile form of cellulose that is created by certain types of bacteria, particularly Acetobacter xylinum, through the conversion of glucose or other sugar sources and this process results in the formation of a pure and highly crystalline form of cellulose (Amr & Ibrahim, 2023). The production process of bacterial cellulose is ecologically sustainable, necessitating considerably less water and land in comparison to conventional crop cultivation for textile fibers (Mehrotra et al., 2023). Furthermore, it does not require the use of pesticides or fertilizers, hence minimizing its environmental footprint. The manufacture of bacterial cellulose can be considered a type of biofabrication, in which living organisms are employed to create materials with minimal waste and low energy usage (Srivastava & Mathur, 2022). Bacterial cellulose offers distinctive qualities that are significantly esteemed in the field of textiles (see Figure 1). It provides exceptional strength and durability, while also being lightweight and capable of bio-degrading. Due to its absorbency and moldability under wet conditions, it can be easily formed into different shapes and textures, making it ideal for a wide range of applications, including apparel, accessories, and interior design (Elseify et al, 2021). Bacterial cellulose's role in the development of vegan leather offers a biodegradable option that mimics the properties of real leather without the negative environmental impacts of animal farming and chemical processing.

Figure 1. Bacterial cellulose based biofabric fashion collection. Source: Turhan, Çiçek, Özbengi, 2023

Beyond fashion design, the unique properties of bacterial cellulose are also being utilized in medical applications such as wound dressings and tissue engineering scaffolds. Its ability to promote cell growth, combined with its durability and biocompatibility, positions it as a new material for the advancement of regenerative medicine (de Amorim et al., 2022). Despite its potential, the scalability and cost-efficiency of bacterial cellulose production for commercial textile applications remain challenges. However, ongoing research and technological advancements are aimed at optimizing production processes to make bacterial cellulose a more viable alternative in the textile industry.

With the growing concern for circularity and environmental impact in the industry there has been an increasing interest in using biobased materials and biocomposites in architectural design and construction. Considering challenges of the adoption of biobased materials such as scalability, performance, and market acceptance that require a detailed assessment, the transition to sustainable architecture with biopolymers confronts obstacles in even small scale applications. Biopolymers may not always meet the rigorous structural demands of buildings in terms of load-bearing capacity, fire resistance, and weatherproofing so they need modifications based on the desired material properties (Smith & Hashemi, 2006). Extensive testing and certification of materials are often required to establish their suitability in various architectural applications (Efendioglu & Temel, 2023). Another challenge is navigating existing building codes and regulations. These are primarily designed for conventional materials, and biopolymers often require new or revised standards to be established, adding time and complexity to their adoption. The construction industry itself is traditionally cautious towards innovation, favoring established materials and methods with well-documented performance histories (Vagtholm et al. 2023). Biopolymers, as a relatively new material class in architecture, need to overcome this inherent resistance to change. The widespread knowledge and expertise in working with biopolymers within the architectural community is still at the laboratory scale, therefore, it creates challenges in the design, construction, and long-term maintenance of biopolymer structures.

The concept of tensile strength is crucial for both fabric and architectural structures. It is often referred to as ultimate tensile strength (UTS) in mechanics, representing the maximum stress a material can withstand before permanent deformation occurs (Tolani et al., 2006). In fabrics, also referred to as tear strength, tensile strength determines the ability of the material to resist stretching or tearing under tension. Similarly, in architecture, tensile strength is critical for resisting forces that pull on building components. Biopolymers can exhibit varying degrees of tensile strength depending on their composition and processing (George, et al. 2020). Understanding these properties is essential for designing and constructing biopolymer structures that can withstand the necessary loads while offering a lightweight and potentially flexible alternative to traditional materials. This literal analogy between fabric and architecture highlights the importance of considering tensile strength while working with biopolymers for building applications.

This research focuses on the material-wise scalability challenges in order to facilitate a wider adoption of biopolymers for architectural construction. To do that, the material formulation is altered in order to accommodate enhanced structural properties for architectural design and construction. While there is currently a lack of standardization in both the recipe and production methods for these biopolymers, the proposed framework adapted from biotextile engineering could offer a potential solution. This framework is particularly valuable since bacterial cellulose-based biopolymers boast several key properties that make them attractive alternatives to traditional building materials and methods. These properties include high tensile strength, strong structural integrity, excellent water retention capacity, and good thermal insulation, all contributing to a more circular approach to architecture.

3 Experiment Overview

This study follows a comprehensive methodology (see Fig. 2) aimed at exploring the scalability of bacterial cellulose (BC) biofabrics for architectural construction. The process begins with modifying the bacterial cellulose growth culture, an essential step to optimize its structural and mechanical properties for real-world applications. By tailoring the growth medium and introducing reinforcing fibers such as jute, the biofabric is enhanced to meet the necessary tensile strength required for architectural use. Following this, tensile strength tests are conducted to quantitatively assess the material’s capacity to withstand mechanical loads, providing insights into its performance compared to traditional materials.

The methodology further employs computational design and digital fabrication techniques to develop a catenary scaffold that supports the biofabric during its formation. The catenary shape was chosen for its structural efficiency in distributing tension and compression forces, ensuring the biofabric can sustain its form during and after the bioassembly process. The harvested biofilms are then carefully assembled onto the scaffold, allowing them to cure and adhere to the structure, thus transitioning the soft biofabric into a more rigid form capable of bearing loads.

Finally, the biofabric undergoes exposure to various environmental conditions, simulating real-world applications. These observations are key to understanding the material's biodegradation process, its durability under different weather conditions, and its overall sustainability. The integration of these steps provides a holistic assessment of the biofabric’s feasibility for architectural construction, considering both its mechanical properties and its environmental resilience.

3.1 Modification of the bacterial cellulose (BC) growth

Acetobacter xylinum (A. xylinum) was grown within three different growth media for modification that resulted in distinct material properties of the BC biofilms (see Fig. 3). A biofabric recipe for BC is altered by experimenting with the amount of ingredients and integrating additional ones during the cellulose synthesis of A. xylinum. Pectin is used as a gelling agent to provide strength through facial bonds. Jute fibers are used as reinforcements to increase the tensile strength which is justified in tensile strength tests.

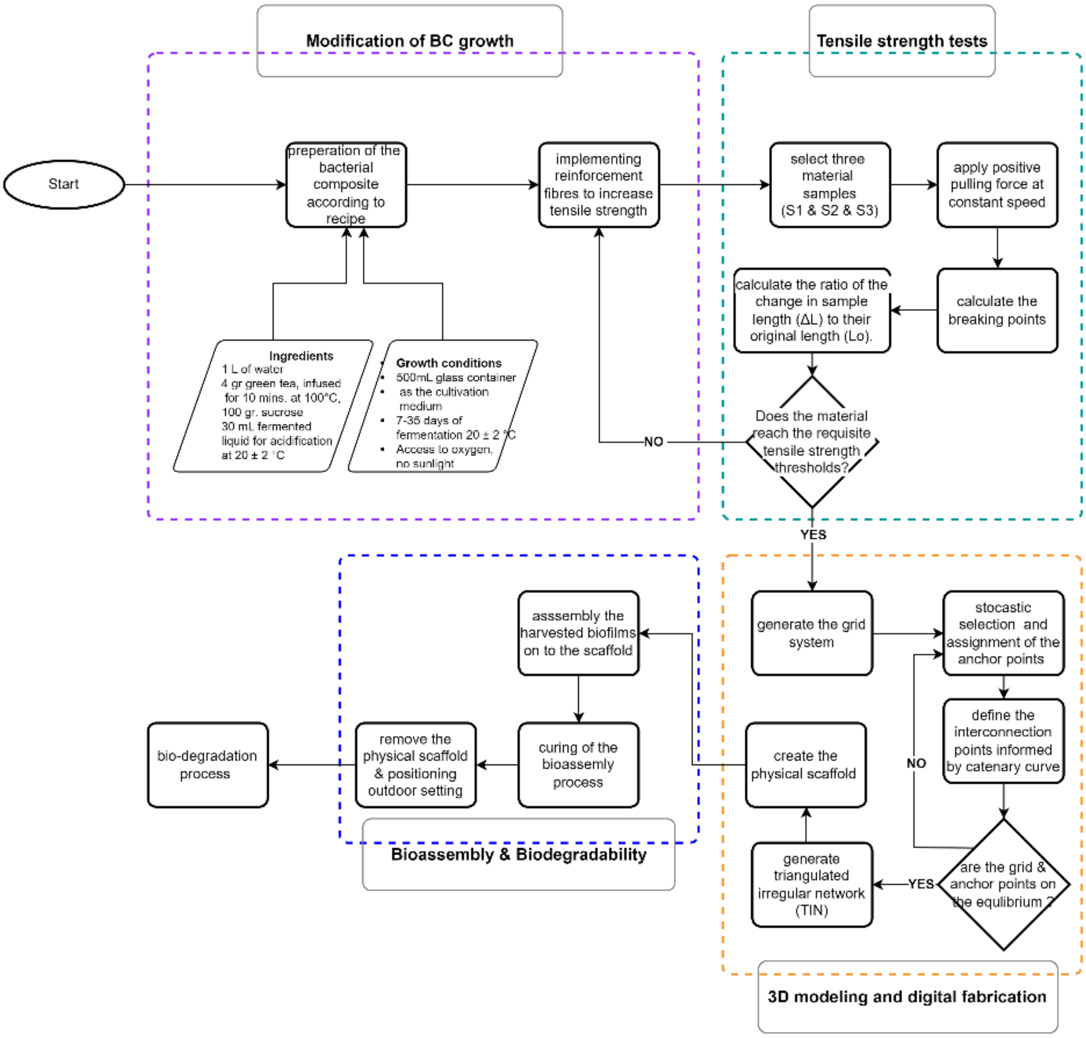

Figure 2. Methodological flowchart. Source: Authors

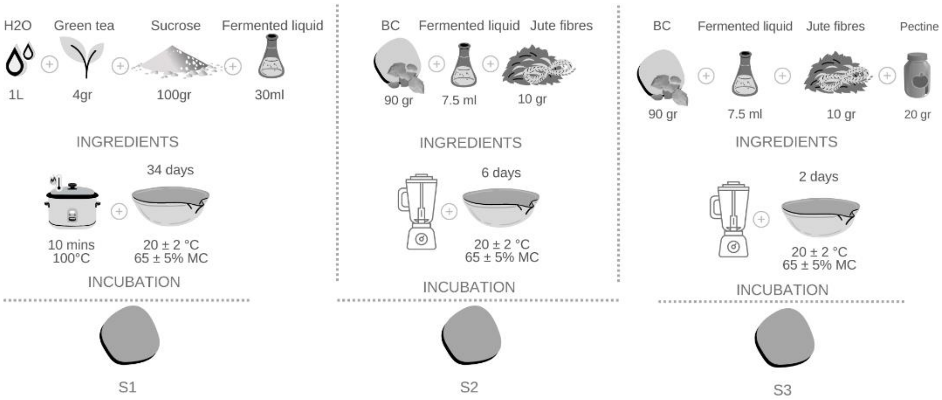

Figure 3. Three different growth media for modification. Source: Authors

3.2 Tensile tests

The specimens are tested against tensile forces using a Texture Analyzer (TA-XTplus, Stable Micro System, UK) with the probe Mini Tensile Grip (A/MTG), and their responses are recorded to measure the stress and strain the specimen experienced under pulling forces (see Fig. 4).

The tests involved testing three material samples, S1, S2 and S3, in triplicate for tensile strength at a controlled temperature (22°C±2°C). These samples are secured between upper and lower clamps and a positive pulling force is then applied to the specimen at a constant speed of 0.5 millimeters per second. The tensile stress at the breaking point (σ) is calculated by dividing the force exerted (F) on the samples by their initial cross-sectional area (Ao). Additionally, the elongation at break (ε) was determined by calculating the ratio of the change in sample length (ΔL) to their original length (Lo).

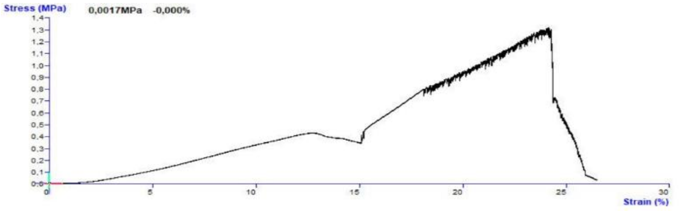

Figure 4. Tensile strength tests (TA-XTplus, Stable Micro System, UK) with the probe Mini Tensile Grip (A/MTG) for S1, S2 and S3. Source: Authors

3.3 3D modeling and digital fabrication of a freeform scaffold

Since the concept of tensile strength is central to this research to provide a literal connection across two disciplines, textile engineering, and architecture, the catenary geometries, which once worked in tension work in compression, were exploited. A catenary geometry is developed as a scaffold, with triangulated irregular network (TIN) panels for bacterial growth (see Fig. 5), consisting of meshes/frameworks of interconnected rods, usually straight, that distribute loads across the entire structure.

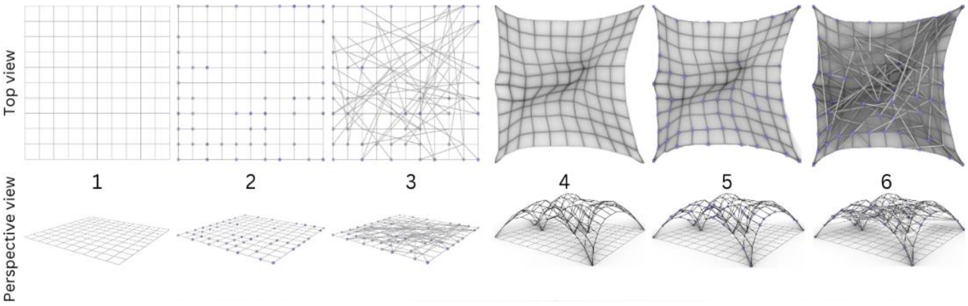

Figure 5. 3D modeling a catenary TIN scaffold (1: grid system, 2: anchor points, 3: interconnected points, 4: grid on equilibrium, 5: anchors on equilibrium, 6: interconnected points on equilibrium). Source: Authors

3.4 Bioassembly and Biodegradation

The harvested biofilms were assembled on a scaffold as a 1:20 scale model (see Fig. 6). After the bioassembly process, the scaffold was removed, and the structure was positioned in an outdoor setting where it experienced different environmental conditions for three weeks, facilitating a presignification for the biodegradation process (see Fig. 7).

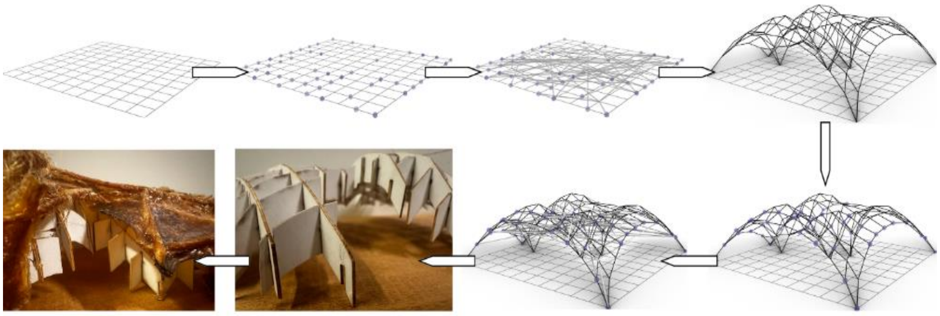

Figure 6. Bioassembly process. Source: Authors

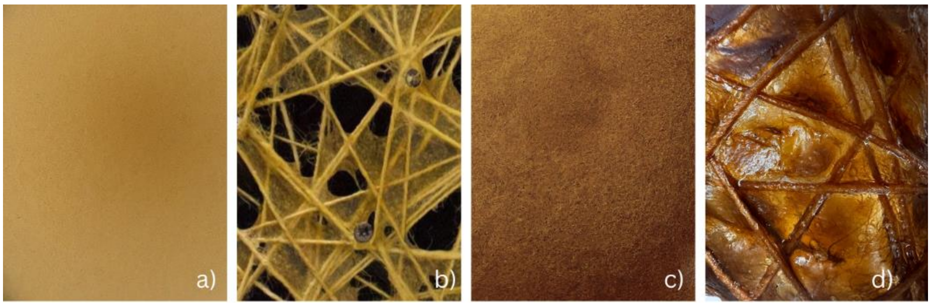

Figure 7. Biodegradation results (a: Initial texture, b: Initial pattern, c: End texture, d: End pattern). Source: Authors

4 Results

The modification stage of the BC growth medium resulted in three samples with different combinations of pure BC biofilm, jute fibers, and pectin. All samples were tested for their tensile strengths. The tensile results showed that the S3 showed 324.6 MPa while the pure BC standed against 48 MPa. Therefore, optimal performance is achieved with the S3, and, S3 formulation is used for scaling up the research. The form of the catenary geometry as the scaffold facilitated an equilibrium condition for the material that can work better in tension. Once the bioassembly process was realized, it could be able to carry its own load under compression. After the removal of the scaffold, the biodegradation process highlighted changes in color, pattern, and texture.

In considering the analogy of replacing concrete in reinforced concrete systems with pure BC, we can draw parallels to the use of jute fibers as reinforcement instead of steel. Just as steel provides strength and stability to concrete structures, jute fibers can serve a similar purpose in enhancing the mechanical properties of pure BC. This analogy highlights the importance of leveraging natural reinforcements to enhance the performance of biofabric materials in architectural applications.

5 Discussion

In general, the formulation of biobased materials enables a fully biodegradable process with no waste generation and a continuous supply, in line with sustainable and circular design concepts. However, the scalability of biopolymers from laboratory to architectural design and construction is a challenging and complex process. The findings demonstrate that it is possible to make alterations in the formulation of biofabrics grown from BC in order to accommodate structural properties for architectural design and construction. Although there is no standardization either in the formulation nor in the manufacturing processes of such materials, the proposed framework, which is adapted from bio-textile engineering, could offer one solution. Properties like tensile strength, structural integrity, water retention capacity, and thermal insulation distinguish bacterial cellulose-based biopolymers as circular substitutes for traditional architectural construction materials and methods. Further studies would involve a full scale (1:1) model for a real life application to further discuss the structural strength. Overall, the results suggest that biopolymers derived from other disciplines such as textile engineering in collaboration with living organisms have the potential to inspire a reassessment of our relationship with nature in architectural practices.

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