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Exploration of Bacterial Cellulose-Based Biofilms for Compliant Mechanisms in Adaptive Façade Applications

Gozde Damla Turhan-Haskara*[1] ,Pinar NESELILER[1] and Yenal AKGUN[a]
1 Faculty of Fine Arts and Design, Department of Architecture, Izmir University of Economics
35330, Izmir, Turkey
*gozde.turhan@izmirekonomi.edu.tr (corresponding author)

a Dokuz Eylül University, Faculty of Architecture, Department of Architecture, 35210, Izmir, Turkey

Abstract
Adaptive façades predominantly employ rigid body mechanics to initiate motion. The manufacture of such systems is costly, susceptible to malfunction, and challenging to maintain, rendering them both economically and environmentally unviable for operational purposes. However, compliant mechanisms are mechanical systems that achieve motion or force transmission through the deformation of flexible materials, rather than traditional rigid joints or linkages. For the development of compliant systems in architectural applications, material technology has been critical, as these systems cannot be considered without materialization due to the need for an elastic capability for the curved crease. State-of-the-art biobased materials can be utilized for compliant mechanisms in the form of lightweight biofilms. These materials are derived from renewable biological resources such as plants and microorganisms, representing a sustainable alternative to traditional, fossil fuel-based materials and reducing dependence on non-renewable resources. This paper explores the use of bacterial cellulose (BC) biofilms for compliant systems to design a biodegradable, lightweight adaptive façade system. The methodology is divided into three steps: production of biofilm, daylight permeability analysis and digital fabrication, and production of BC-based compliant mechanisms. The results have shown that bacterial cellulose-based biofilms have a great potential for the materialization of CLF as a biodegradable and lightweight alternative for developing into an adaptive facade system through the passive actuation method in different environmental conditions.

Keywords: Curved line folding, biobased material, bacterial cellulose, adaptive facade

1. Introduction
Adaptive façades represent a cutting-edge technology that provides reactions, to shifts in conditions such as environmental conditions, which can be seasonal or short-term fluctuations in weather. These specialized building exteriors can change their responses promptly by leveraging a range of materials, components, and systems (Brzezicki et al. [1]). Moreover, the notion of façades goes beyond alterations, in form; it also encompasses modifications to the composition of building enclosures aimed at improving their functionality (Tazikova et al. [2]).

While enhancing the applicability of adaptive façades, the technique of curved line folding offers an opportunity since it consists of compliant systems instead of rigid bodies. Compliant mechanisms are mechanical systems that achieve motion or force transmission through the deformation of flexible materials, rather than traditional rigid joints or linkages. They are designed to be simpler, more reliable, and often lighter than their traditional counterparts, making them useful in various engineering applications, from robotics to aerospace. Through the bending and folding of the geometry, compliant mechanisms gained the attention of architects and designers as well, since it allowed for the building of more flexible, moveable, and complex geometries. Researchers have explored the various applications in different contexts, such as in artworks, products, sculptures, mosaic pattern panels, architectural spaces, shells, and façade installations. The studies have shown that the characteristics of materials and limitations of geometry play an important role in architectural purposes.

This study explores bacterial cellulose (BC) biofilms for mobile components in the CLF system. BC biofilms are known for their high tensile strength, allowing flexible and elastic components to move successfully during their displacement. The capacity to detain high amounts of water due to their hydrophilic nature is also an advantage when outdoor conditions are considered. Moreover, when the transparency of the biofilm is optimized through material formulations, the visual connection from inside to outside can be maintained.

2. THEORETICAL BACKGROUND

2.1 Adaptive Façade Applications

Several applications for adaptive façades showcase the advantages and capabilities of contemporary building envelopes. These façades are essential to improving occupant comfort and performance in complex buildings. Additionally, they can be distinguished by kinetic, engaged, and responsive envelope systems, all of which have a major influence on their overall efficiency (Yitmen et al. [3]). Adaptable façades have been constructed via a variety of strategies, including adaptable nanomaterials, which may be applied to these building envelopes and rely on special material characteristics to optimize energy efficiency (Aziz and Abdelall [4]). Furthermore, the integration of bio-based materials into adaptive building facades is growing as a viable strategy rather than traditional materials, indicating a shift towards environmentally friendly and sustainable building practices (Sandak et al. [5]).

According to Rizi and Jahangiri [6], adaptive façades consider the desires of building occupants during both the design and operation phases. One such application is the integration of bio-inspired building envelopes for energy conservation and improved visual comfort. Another example is the Barcelona Media-TIC building, whose façade was constructed employing a biomimetic technique. A system of inflated pillows is used in the façade mimicking the structure of a plant's stomata to regulate the interior temperature, which opens and closes (Elsakksa et al. [8]). Using a specific material called Ethylene Tetrafluoroethylene (ETFE), the façade of the building improves thermal insulation because of its double membrane, which is willed with nitrogen under vacuum conditions.

Passive material-based actuation systems have been a significant improvement that is cost-effective and simpler than active systems without needing external energy. These materials can be triggered by sun, wind, humidity, electricity, or magnetic differences. Moreover, the use of smart materials, such as shape memory alloys, has been investigated as an option for mechanical actuation in adaptive facades (Hannequart et al. [9]). The applications of the referred materials have been used to align the research and studies involved with the construction of adaptive façades while utilizing advanced materials and innovative technologies to construct a building exterior that responds to its surroundings in real time while being energy-efficient and sustainable. However, advanced and alternative materials are essential because the latter two still account for 40% of carbon dioxide emissions in the building industry due to resource scarcity.

2.2 Curved Line Folding (CLF)

The design method called CLF (Curved Line Folding) has become popular in architecture, focusing on geometric optimization, material choices, and how the structures can move. Architects and researchers have been looking deeply at how folded shapes can be perfected for strength, beauty, and practicality. Curved line folding works on the basis of compliant shell mechanisms, in which the deformation of thin-walled surfaces and their alignment along the fold lines affect the entire kinematics. This folding mechanism abstracts the motion concept of a curved-line folding mechanism from natural structures, such as the underwater carnivorous plant Aldrovanda vesiculosa. The basic ideas behind this folding approach are demonstrated by the geometric mechanics of curved folds, such as an elastic sheet folded along a closed circular curve, which resolves incompatibilities between the folded geometry and mechanical stresses.

They have also been studying which materials work best for CLF designs, taking durability, sustainability, and how they hold up in different environments into account. The most popular material types used in CLF applications are polypropylene sheets, wood composites made of spruce, maple, and other types of timber, GFRP mixed with either polypropylene or elastomer, and wood filaments. The study of a skin-wrinkle-inspired curved-line bending mechanism for elastic-kinetic architectural structures exhibited the potential benefits of curved-line folding in the production of creative architectural elements (Matini & Haghnazar [7]). This research highlights the significance of material properties and behavior for the adaptability and functionality of curved-line folding mechanisms in architectural design.

2.3 Bacterial Cellulose-Based Biofilms

Bacterial cellulose (BC), type of a biopolymer, presents a compelling case for the convergence of microbiology and material science. Unlike its plant-derived counterpart, BC is biosynthesized by specific bacteria, such as *Acetobacter Xylinum (A. xylinum)*, during their metabolic processes (McManus et al. [10]). These bacteria utilize various carbon sources, most commonly glucose, and convert them into long, interwoven chains of highly pure crystalline cellulose fibers without lignin and hemicellulose, which are typically present in plant cellulose (Vasconcelos et al. [11]). The resulting BC-based biofilms exhibit impressive tensile strengths exceeding 300 MPa, rivaling some engineered plastics (Turhan [23]). Additionally, their intricate network of ultrafine nanofibers creates a highly porous structure with unmatched water absorption capabilities, reaching upwards of 98% by weight (Derme et al. [12]).

BC polymers can be tailored to achieve desired material properties for various design applications by crosslinking them or synthetization with suitable gelling agents. While chemical crosslinking, often using aldehydes, offers excellent results, its cytotoxicity raises concerns (Jimtaisong & Saewan [13]). As a result, the focus has shifted towards natural gelling agents and natural cross-linkers and which are becoming increasingly explored for biocomposites (Ma et al. [14]; Turhan [23]). The synergistic interactions and conformational changes arising from the different polymer structures contribute to this improved performance (Altaner et al. [15]; Simoes et al. [16]). One of the strong candidates is pectin (Turhan [23]) a major component of plant cell walls, particularly in citrus fruits. It constitutes nearly two-thirds of the dry weight of these walls, providing structural integrity, strength, and flexibility. Furthermore, pectin contributes to cell structure by forming a matrix with cellulose and hemicellulose (Vanitha [17]). Beyond its biological and physiological functions, pectin's integration to BC biofilms with its complex and diverse structure offers promising opportunities across various fields, from food processing to product design and architecture (Turhan [24]).

Biopolymer matrices of BC can also be reinforced using natural fillers (Turhan [23]). In contrast to chemical fillers, these fillers, typically plant-derived fibers, source of polyphenols that are functionally important molecules dispersed throughout plant tissues and offer a promising alternative to synthetic fillers (Spanic et al. [19]; d'Archivio et al [20]). Natural fibers such as cotton, bamboo, jute, kenaf, and sisal offer several advantages over their synthetic counterparts such as carbon and glass fibers. These advantages include lower density, affordability, and the ability to minimize mechanical processing during production (Karimah et al. [21]). Jute stands out as a promising natural filler due to its exceptional strength surpassing other options such as cotton (Turhan [23]). Furthermore, its high aspect ratio translates to better reinforcement within the composite material, considering its affordability.

This unique combination of strength, flexibility, water retention, biocompatibility and biodegradability, coupled with natural agents and fillers, positions BC as a promising material for various applications (Swingler et al. [22]). Unlike the conventional materials that often struggle with intricate geometries, necessitating complex manufacturing processes and generating significant waste, BC's inherent flexibility and remarkable strength suggest its suitability for creating complex, three-dimensional structures, without waste (Turhan [24]). Furthermore, BC-based biocomposites' biodegradability eliminates concerns about the long-term environmental impact of construction materials. It can be concluded that the BC and its biocomposites are potential game-changers in ecological architectural construction, paving the way for a future where buildings can be both aesthetically pleasing and environmentally responsible.

3. Methodology

The methodology is divided into three steps: Biofilm production, daylight permeability analysis and digital fabrication and production of BC-based compliant mechanism (Figure 1). The first stage involves different formulations, followed by the second stage, daylight permeability analysis, so that the best-performing sample could be scaled up as a prototype, at the last stage.

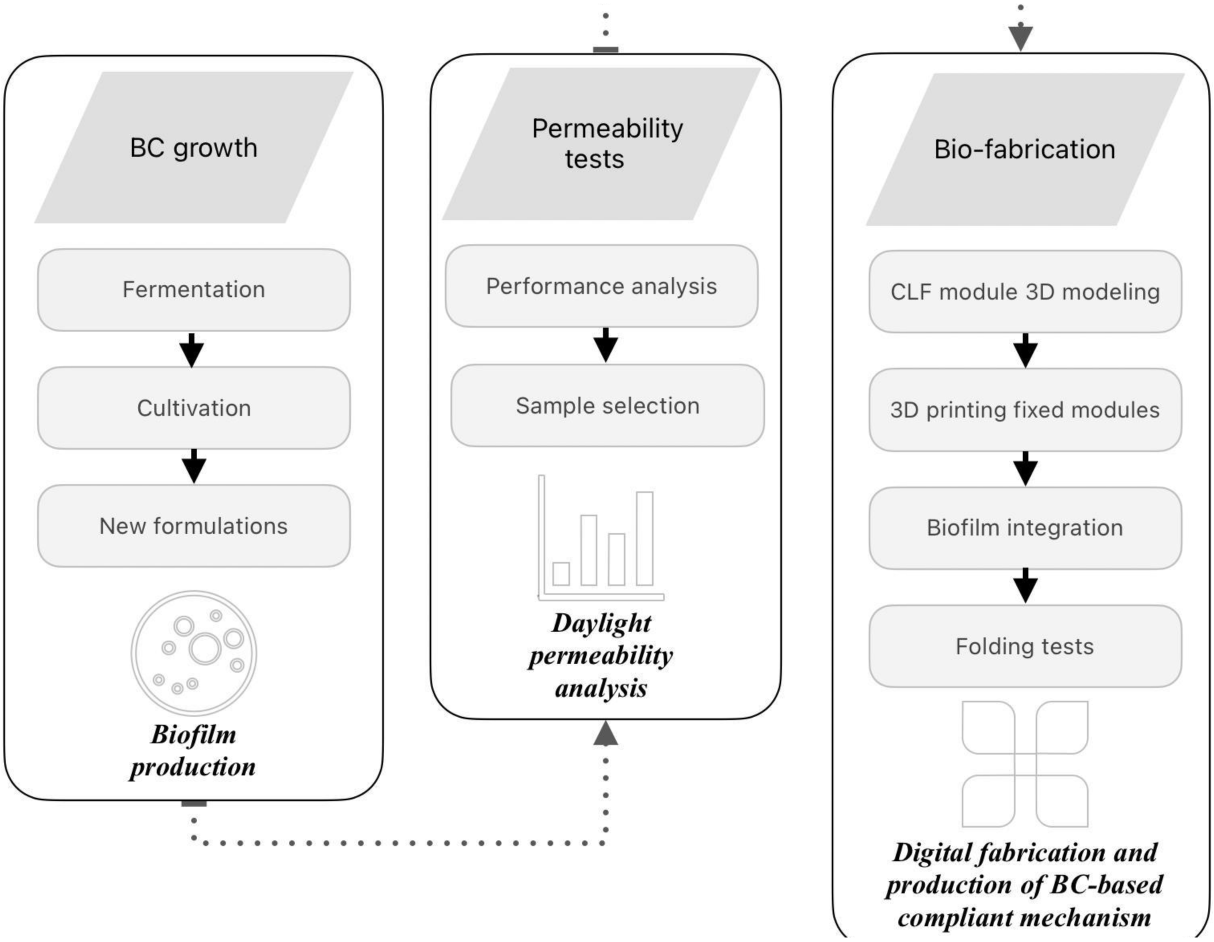

Figure 1. Methodology

3.1. Biofilm production

The production of the BC biofilm was conducted in collaboration with *A. xylinum*. A 1-liter water solution served as the base, in which 4 grams of green tea was infused for 10 minutes at 100°C. To promote bacterial growth, the solution was further supplemented with 100 grams of sucrose and 30 millilitres of fermented liquid for acidification. An existing piece of BC biofilm (90 grams) was introduced to initiate bacterial growth. The entire culture was then incubated under static conditions for 34 days at a controlled temperature of 20 ± 2°C and humidity of 65 ± 5%. After this period, the biofilm formed on the container's surface was harvested and sliced into smaller pieces without any pretreatment to maintain ongoing bacterial activity. 15 grams of the sliced biofilm was reserved for use as inoculum in future fermentations, while the remaining 75 grams were designated for biofabrication. This fermentation procedure was adapted from research previously conducted (Turhan [23]) (Figure 2). In this research, five different recipes were experimented with and tested for workability as well as transparency (Figure 3) with the adjustments of different ingredients (Table 2). The optimal formulation (S2) performed as the best to be incorporated into a larger-scale experiment.

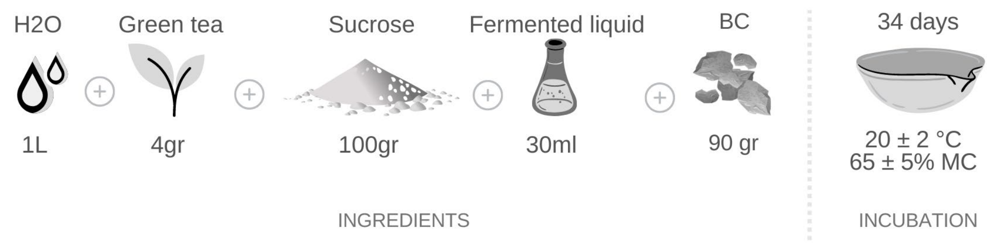

Figure 2. Fermentation process for BC biofilm growth

Figure 3. Five different material formulations explored in the research: S1-5 (left-to-right).

Table 2. Five different material formulation and ingredients

Sample number	BC (gr.)	Jute fibers (gr.)	Pectine (gr.)	Glycerine (gr.)	Oil treatment	Thickness (mm)
S1	30	-	-	-	-	0.05
S2	30	2	15	10	3 days after	0.10
S3	30	2	15	20	3 days after	0.75
S4	30	-	15		3 days after	1.20
S5	30	-	5	10	3 days after	1.75

3.2. Daylight permeability analysis

The daylight permeability analysis (Table 3) is conducted for the North side of an office environment of an educational building located in Izmir, Turkiye by using a lux meter with photoelectric sensing technology, which can represent light intensity through electrical signals, then process the data and display the result on the LCD screen on the Unit UT383 Mini. The existing facade has a double-glazed window system, needing a protection system against the glare in the immediate office environment, while still providing natural light for people to operate. The results showed that although the S4 showed the maximum shading rate (87%), natural light is dimmed drastically. Moreover, although S2 and S5 demonstrated a very similar benchmark value (81%), the thickness of S5 restrained the mechanism for the desired movement in terms of workability (Figure 4). Therefore, the optimum sample S2 is scaled up in the following bio-fabrication stage for a BC-based compliant mechanism.

Table 3: Shading rates of the samples

Sample number	Thickness (mm)	Lux (Izmir, North facade, 08.03.2024, 3:30pm)	Shading rate (%)
-	-	5367 (base condition)	0%
S1	0.05	2555	53%
S2	0.10	1070	81%
S3	0.75	1316	76%
S4	1.20	739	87%
S5	1.75	1022	81%

Figure 4. Incapability of S5 to fold and unfold due to its thickness

3.3. Digital fabrication and production of BC-based compliant mechanism

After the production of BC biofilm from the best sample recipe S2 (Figure 5), the patterns of CLF are drawn through laser cutting on 9x9cm square sheets. To conduct the small-scale prototype of the proposed adaptive façade, one part was modelled, which has four short arms. Each module is fixed from the corner, these are pulled via a fish net. Understanding the fundamentals of cable systems, the fish nets are fastened at one end and threaded through from the opposite corner of the module. When the fish nets are pulled from the centre of the frame, the CLF modules are folded, which leads to an opening of a small-scale device (Figure 6).

Figure 5. S2, scaled up formulation

Figure 6. Scaled overall model of the adaptive shading device, open and closed positions

4. Results and Reflections

The exploration of bacterial cellulose (BC) biofilms for compliant mechanisms in adaptive façade applications yielded promising results. The study successfully demonstrated the potential of BC-based biofilms as a sustainable and lightweight alternative to traditional materials for developing compliant mechanisms using the curved line folding (CLF) technique. The key findings are as follows:

- The fermentation process yielded BC biofilms with varying material formulations. The optimal formulation (S2) exhibited superior workability and transparency, making it suitable for larger-scale experiments.
- The daylight permeability analysis revealed that sample S2 provided an optimal balance between shading rate and natural light transmission, making it a suitable candidate for BC-based compliant mechanisms.
- Digital fabrication methods were employed to produce CLF patterns from the selected BC biofilm. Small-scale prototypes demonstrated the feasibility of BC-based compliant mechanisms in adaptive façade applications.

The use of BC biofilms presents a compelling avenue for sustainable material innovation in architectural design. BC's biodegradable nature, high tensile strength, and water retention capabilities make it an attractive choice for compliant systems in adaptive façades. The study highlighted the importance of material properties in the functionality and adaptability of compliant mechanisms. BC's flexibility and strength offer significant advantages over traditional materials, paving the way for more environmentally responsible building practices. Furthermore, the research underscored the potential of bio-based materials in reducing the carbon footprint of the construction industry. By encouraging the use of renewable biological resources, such as BC, the environmental impact associated with the production and disposal of conventional building materials can be mitigated. Future research could focus on scaling up the prototype to an actual building scale (Figure 7), optimizing material formulations, and exploring integration strategies with other sustainable technologies to advance the field of eco-friendly architectural design.

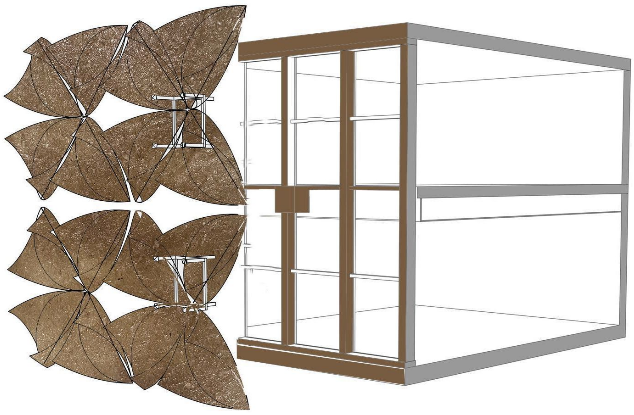

Figure 7. 1:1 scale system proposal

5. Conclusion

The presented model demonstrates how bio-based materials can be offered as an alternative for compliant mechanisms, once the formulation archives enough elasticity and strength. The research provides sustainable and affordable soft material instead of plastics such as polypropylene sheets, glass fibre polymer with elastomer, or polypropylene utilized in current CLF applications. This study is conducted successfully although rather at a small scale, the framework can also be optimized with a cable-driven passive system where the soft components are triggered by humidity or light that does not need external energy in further research.

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Author(s): Gözde Damla Turhan-Haskara[a] Pinar Neseliler[a] and Yenal Akgun[b]

Affiliation(s): [a] Faculty of Fine Arts and Design, Department of Architecture, 35330, Izmir, Turkey.

[b] Faculty of Architecture, Department of Architecture, Dokuz Eylül University, 35210, Izmir, Turkey

Address: Fevzi Cakmak, Sakarya Street, No: 156, 35530/Izmir

Phone: +90 (555) 569 0997

E-mail: gozde.turhan@ieu.edu.tr

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