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Longevity and Biodegradability Assessment of Biobased Lighting Fixture Design for Interiors

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Abstract: Biobased materials are often associated with fast degradation due to their inherent biodegradability, limiting their adoption in long-term applications. This study explores the dual potential of biobased composites, particularly bacterial cellulose-based materials, through the case of lighting fixture design in interior spaces. While these materials naturally degrade under specific environmental conditions, their lifespan can be extended significantly through thoughtful design and controlled usage. The research involves a four stage methodology to focus on developing and testing composite materials by combining bacterial cellulose biofilms with various biobased agents to enhance light transmission and durability. The study then evaluates the performance of these composites in terms of illuminance quality and biodegradation in interior use and composting, comparing them to one of the conventional lighting fixture materials, polypropylene plastic. The results have shown that this study challenges the perception of biobased materials as inherently fast-degrading due to maintenance requirements, by demonstrating their capacity for longevity when utilized in stable indoor environments. The findings contribute to biodesign discourse by showcasing how biobased composites can balance biodegradability and extended usability, offering innovative pathways for a variety of ecological design applications.

Introduction

Biobased materials have gained significant attention in recent years due to their potential to address pressing environmental challenges such as resource depletion, high carbon emissions, and non-biodegradable waste. However, these materials are often criticized for their inherent biodegradability, which limits their use in long-term applications. While rapid degradation is desirable for specific scenarios such as compostable packaging, it poses challenges in contexts requiring material longevity, such as interior product design.

This duality raises a critical question: Can biobased materials offer durability and biodegradability, depending on their intended application and environment? This study explores this question through the lens of lighting fixture design for interiors, a domain where materials must balance energy efficiency, aesthetic quality, and functional durability.

Among biobased materials, bacterial cellulose (BC), also known as microbial cellulose, deposited from bacteria such as *Acetobacter Xylinum* thanks to their metabolic activities, emerges as a promising candidate due to its lightweight nature, excellent mechanical properties, and compatibility with various biobased additives. Despite these advantages, its applicability in products requiring extended usability remains underexplored. This research aims to bridge this gap by developing bacterial cellulose-based composites tailored for interior lighting fixtures. The study investigates how biodesign interventions for different biobased material formulations can extend the lifespan of these biocomposites without compromising their biodegradability under end-of-life conditions.

The paper also addresses the broader perception of biobased materials as inherently short-lived, arguing that through thoughtful design and controlled use, their lifespans can be significantly enhanced. By examining these composites' performance in terms of light transmission through illuminance tests, this study also contributes to the discourse on ecological interior lighting design. It emphasizes the potential of biobased materials to meet contemporary demands for ecological responsibility and product longevity, challenging traditional paradigms in sustainable design.

Theoretical framework

Biodegradability and Longevity Challenges in Biobased Composites

Biobased composites are renowned for their potential to reduce environmental impact due to their renewable nature and inherent biodegradability. However, these same properties often present challenges when considering the material's longevity. One of the primary issues is the degradation of biocomposites when exposed to environmental factors like moisture, ultraviolet (UV) radiation, and microbial activity. These challenges are especially critical for applications requiring durability and extended performance, as uncontrolled degradation can compromise the structural integrity and usability of the material over time (Lepoittevin et al., 2023; Salmén & Gatenholm, 2022).

To address these issues, researchers have focused on modifying biocomposites at both microstructural, chemical and facial bonding levels. Incorporating hydrophobic agents, crosslinkers, UV stabilizers, or reinforcement fillers has been shown to significantly enhance durability. For example, combining bacterial cellulose with bio-based additives, such as lignin or *polyhydroxyalkanoates* (PHA), has improved moisture resistance and mechanical strength while retaining biodegradability under controlled conditions (Gorgieva & Trček, 2023; Nawab et al., 2021). There are also studies that demonstrate the incorporation of calcium, magnesium, iron, sulfate ions could lead to the formation of different material properties such as antibacterial properties or ferroelectric properties etc. (Wang et al., 2024; Zhao et al., 2023).

Advancements in Biocomposites for Durability and Sustainability

Studies exploring the enhancement of biocomposites have yielded promising results in balancing environmental benefits with practical performance. For instance, the addition of nanocellulose as a reinforcement in *polylactic acid* (PLA) matrices has been found to significantly increase tensile strength and thermal stability (Kargarzadeh et al., 2018). Similarly, biocomposites infused with chitosan and tannin have demonstrated resistance to microbial degradation while maintaining biodegradability under composting conditions (Sahoo et al., 2023). These advancements highlight the potential for biobased materials to address longevity concerns without compromising their sustainable credentials.

However, challenges remain, particularly in applications subjected to fluctuating environmental conditions, such as lighting fixtures. Prolonged exposure to heat and UV radiation can accelerate material degradation, necessitating frequent maintenance or replacement. This has spurred research into coatings and treatments that can shield biocomposites from environmental stressors, prolonging their usability in demanding environments (Huang et al., 2023).

Balancing Environmental Benefits with Performance in Sustainable Design

The dual goals of biodegradability and longevity often appear contradictory, but they can coexist with thoughtful material selection and design strategies. In interior applications, such as lighting fixture design, biobased composites can be utilized in controlled environments where factors like moisture and UV exposure are minimized. This strategic use not only extends the material's lifespan but also ensures that its biodegradability is activated only at the end of its functional life cycle (Lee et al., 2023). Sustainable design practices must prioritize materials that offer both ecological benefits and practical performance. The integration of life-cycle assessment (LCA) tools into the material selection process enables designers to evaluate trade-offs between environmental impact and durability, fostering a more holistic approach to sustainable design (Salmén & Gatenholm, 2022). By demonstrating the feasibility of biobased composites in long-term applications, this research aims to shift perceptions of these materials as inherently short-lived, paving the way for broader adoption in interior and architectural design.

Methodology

The methodology followed a four stage framework, consisting of bacterial cellulose cultivation, sterilization, composite formulations, and testing (Figure 1).

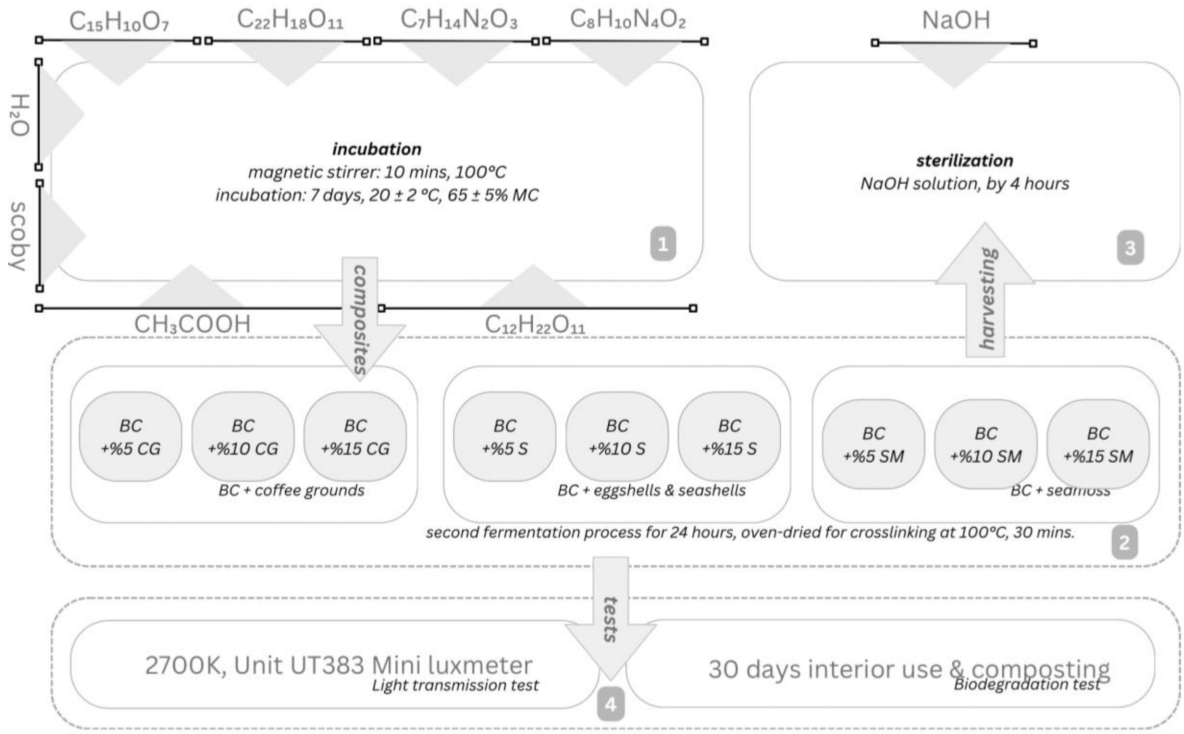

Figure 1. Methodological flowchart.

Bacterial cellulose cultivation

Bacterial cellulose (BC) was cultivated following the methods described in XXX (2022), where *Acetobacter xylinus* was the main collaborator to produce the microbial strain for BC production. The BC cultivation process involved the preparation of a sterile medium, which supported bacterial growth and cellulose synthesis, containing the bacteria and yeast from a piece of scoby, $C_{12}H_{22}O_{11}$ (*sucrose*), $C_2H_4O_2$ (*acetic acid*), *catechins* such as $C_{22}H_{18}O_{11}$ (*Epigallocatechin gallate*), *amino acids* such as $C_7H_{14}N_2O_3$ (*theanine*), $C_8H_{10}N_4O_2$ (*caffeine*), *flavonoids* such as $C_{15}H_{10}O_7$ (*quercetin*), and minerals such as Mg (*magnesium ion*) and Mn (*manganese ion*). The culture was incubated for 7 days (20 ± 2 °C, 65 ± 5% MC), after which the BC biofilms were harvested, distilled in NaOH solution to get rid of the residue.

Composite formulations

To enhance the properties of BC and test the viability of biobased composites for lighting fixture applications, BC biofilms were modified by incorporating a range of biobased agents (Figure 2). The selected agents—coffee grounds, eggshells & seashells, and sea moss—were chosen based on their potential to improve the mechanical properties, durability, and sustainability of the BC composites. These materials are often available as waste products and sustainable resources with potential for positive contributions to biocomposite materials. These agents were ground into fine powders and mixed with the cultivated BC biofilms in varying proportions (5%, 10%, and 15%) to develop composite materials. The mixtures were then subjected to a second fermentation process for 24 hours, ensuring uniform distribution of the additives within the BC matrix. Afterward, the composites were oven-dried at 100°C for a better crosslinking for 30 minutes and then they were soaked into NaOH solution for sterilization, by 4 hours of time intervals, and finally air-dried at room temperature to be tested for light transmission and biodegradability.

Coffee Grounds

Coffee grounds are a rich source of organic compounds, including antioxidants, which can potentially improve the structural integrity and UV resistance of biobased composites. The studies in the literature have explored the incorporation of coffee grounds into various materials, demonstrating their ability to enhance mechanical properties while maintaining biodegradability (Berg, 2019; Jafari et al., 2021).

Eggshells and Seashells mix

Eggshells are primarily composed of calcium carbonate, which has been shown to enhance the mechanical properties of composites. The incorporation of eggshells in biobased materials has been investigated for its potential to improve the rigidity and strength of composites, as well as to contribute to their environmental sustainability (Bach et al., 2020). Eggshells also have a potential antimicrobial effect, which could benefit the longevity of materials used in indoor environments (Li et al., 2021).
Seashells, particularly those rich in calcium carbonate, are often used to enhance the mechanical properties of biocomposites. Studies have demonstrated that seashells can increase the hardness and durability of biocomposites, making them suitable for applications that require higher resistance to wear and environmental stress (Yang et al., 2021; Almeida et al., 2023).

Sea Moss

Sea moss, a type of algae, is known for its unique gelling properties due to its high content of *carrageenan*. Incorporating sea moss into biocomposites could potentially enhance the material's flexibility and moisture resistance, which are important for applications such as lighting fixtures in varying environmental conditions (González et al., 2020; Sharma et al., 2022).

Figure 2. Bacterial cellulose composite biofilms.

Testing

The final BC composites were developed into a minimal lighting fixture, and tested in terms of their light transmission and biodegradability to assess their suitability for interior lighting applications.

Light Transmission

The light transmission of the composites was evaluated by measuring the transmittance of 2700K light through the biofilms using a lux meter equipped with photoelectric sensing technology. This device converts light intensity into electrical signals, processes the data, and displays the results on the Unit UT383 Mini's LCD screen. The percentage of light transmitted through the composites was calculated and compared to one of the standard lighting fixture materials, polypropylene plastic (Figure 3).

Biodegradability

Biodegradation tests were performed where the composites were placed in a controlled interior environment, as well as in an environment with soil to compost and biodegrade. The weight loss and material degradation were monitored over a 30 days period. Damage due to the heat was also observed to evaluate the biodegradability of the composites and their potential for both operational and end-of-life applications.

Results and discussion

This section outlines the findings from the development and testing of bacterial cellulose (BC) composites, mechanically enhanced with various biobased agents, for use in interior lighting fixtures. The materials were tested for light transmission and biodegradability to determine their potential for both longevity and sustainability.

Light Transmission

The light transmission properties of the tested materials varied significantly based on composition and concentration, offering insights into their potential applications in lighting design for interiors (Figure 3). The baseline material, polypropylene plastic, exhibited approximately 80% light transmission, serving as a reference point for comparison. Among the biocomposites, the BC-coffee grounds composite demonstrated the highest light transmission at 89% with 5% concentration, outperforming the baseline plastic. This value dropped to 74% at 10% concentration and further to 61% at 15%, indicating that increased coffee ground content reduces translucency.
The BC-eggshells and seashells composites showed moderate light transmission capabilities, ranging from 59% at 5% concentration to 48% at 10% and 24% at 15%. The reduction in light transmission for these composites can be attributed to the inherent opacity and larger particle sizes of the additive agents, which scatter light more significantly. Meanwhile, the BC-sea moss composites exhibited light transmission values of 62% at 5% concentration, 51% at 10%, and 32% at 15%. Sea moss's gelling properties contributed to light diffusion but with increasing concentration, the overall translucency was diminished.
In the overall case, results indicate that while biocomposites generally have lower light transmission than polypropylene plastic, their ability to diffuse light effectively makes them viable for ambient lighting applications, particularly where sustainability and material innovation are priorities.

Biodegradability

The biodegradability of the composites was assessed through composting tests conducted over a 30 days period (Figure 4). The composites showed varied rates of degradation based on the types of additives incorporated. The BC composite with 15% sea moss demonstrated the most rapid biodegradation, losing approximately 35% of its weight over 30 days. The composites with shells followed closely, with a weight loss of 20–25%. However, coffee grounds exhibited a weight loss of 8-12%.
This result aligns with the findings in the literature on biocomposites, indicating that the biodegradation rate is influenced by the nature of the biobased agents. Organic additives tend to accelerate biodegradation due to their high organic content (González et al., 2020; Jafari et al., 2021), whereas inorganic additives contribute to slower degradation, providing more stability during the material's life cycle (Yang et al., 2021). Nevertheless, the BC

composite with 5% coffee grounds lost dramatically less weight, approximately 8%, in the biodegradation for a given time.

Figure 3. Comparison of shades: Polypropylene plastic vs biocomposites.

Figure 4. Comparison of biodegradation: Composting in soil vs. in use for 30 days.

Conclusion

The findings of this study suggest that biobased BC composites, enhanced with coffee grounds, eggshells, seashells, and sea moss, are promising candidates for sustainable lighting fixture applications, offering a balanced combination of light transmission and biodegradability. Other biobased agents for different composite formulations could be explored to build up a composite profile for a variety of design applications.

The light transmission results suggest that the biobased composites did not match the high translucency of conventional materials such as polypropylene plastic, yet they still offer viable alternatives for diffused lighting applications, especially for calm environments such as bedrooms or cozy interiors. These findings underscore the potential of biobased composites to meet specific design needs, such as diffused lighting, while maintaining a sustainable and environmentally friendly profile. The biodegradation tests hinted that the biobased composites can decompose efficiently at the end of their life cycle, with composites incorporating organic agents showing faster degradation rates. This aligns with the growing trend in materials science toward designing for end-of-life biodegradability, reducing environmental impact after use. The slower degradation observed in the 5% coffee ground composite suggests that this material can be more suitable for longer-lasting applications.

The integration of waste-derived materials such as coffee grounds, eggshells, seashells, and sea moss not only enhances the mechanical and aesthetic properties of the BC composites but also contributes to reduce reliance on non-renewable resources and promote a circular economy in material design. The ability to mold these biocomposites into different forms is only one promising side; utilizing advanced robotic technologies could also open up possibilities for innovative, custom lighting designs that align with ecological design principles.

While the study demonstrates promising results, further optimization of the biobased composite formulations is necessary to achieve a balance between biodegradability and light transmission that meets industry standards. It is essential to highlight that the primary focus was on the functionality and biodegradability of the materials, while durability still remains an area for further investigation, requiring long-term testing (exceeding 30 days) to align with the expected lifespan of an interior lighting fixture. The next steps would also include refining the additives' proportions, observing other agents and exploring additional processing techniques to further enhance the composites' performance and sustainability, offering a novel approach to lighting fixtures that supports both longevity and biodegradability.

Nevertheless, the adaptability of bacterial cellulose (BC) in lighting fixture design is particularly relevant in contexts where semi-durable materials like paper and fabric are traditionally favored, such as pendant lamps, table lampshades, and wall sconces. These applications benefit from BC's translucency, flexibility, and potential for reinforcement through fiber integration, allowing for controlled illuminance and enhanced structural integrity. By varying fiber composition, designers can modulate light diffusion, creating soft ambient lighting or more directional illumination tailored to specific spatial needs. Moreover, the potential of BC composites extends beyond lighting; its acoustic absorption properties and compatibility with digital fabrication techniques open avenues for broader interior applications, such as modular partition panels or decorative wall treatments. These design implications position BC as a viable alternative to conventional materials, offering sustainable and customizable solutions for contemporary interior environments.

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