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The Role of Mycelium-Based Biomaterials in Eco-Friendly Packaging and Product Design

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ABSTRACT

This study explores the role of mycelium-based biomaterials in promoting environmentally friendly packaging and product design in Indonesia. Using a qualitative methodology, data were gathered through interviews with three key informants: a material scientist, a packaging industry expert, and a sustainable design entrepreneur. Thematic analysis conducted with NVIVO software revealed four major findings: (1) the environmental benefits of mycelium, including biodegradability and low energy production requirements; (2) challenges such as scalability, high costs, and limited awareness; (3) diverse applications in packaging and product design, including luxury markets; and (4) the critical role of government policy and stakeholder collaboration in driving adoption. These findings highlight the potential of mycelium-based biomaterials to contribute to Indonesia's sustainability goals by reducing plastic waste and fostering innovative eco-friendly solutions. However, addressing scalability and cost issues requires policy interventions and cross-sector collaboration.

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1. INTRODUCTION

Environmental degradation from unsustainable packaging and product design is a critical global issue, with Indonesia as a major contributor to marine plastic debris. The packaging sector is under pressure to adopt sustainable alternatives that balance cost, functionality, and environmental impact by using biodegradable, recyclable, and reusable materials while integrating circular economy principles and advanced manufacturing technologies like 3D printing [1]. Lifecycle assessments (LCA) help evaluate packaging sustainability, while circular economy strategies optimize resource use [1]. Sustainable product design also reduces waste through eco-friendly materials and responsible manufacturing, with biodegradable plastics and modular designs enhancing longevity and minimizing environmental impact [2]. Addressing plastic pollution requires innovative packaging designs, better recycling systems, and stakeholder collaboration for a sustainable supply chain [3]. Government intervention is crucial in promoting sustainable practices [3]. Packaging designers play a key role by advocating responsible design, interdisciplinary knowledge, and long-term sustainability considerations to minimize waste [4].

Mycelium-based biomaterials are gaining traction as sustainable alternatives to traditional plastics and non-renewable materials due to their biodegradability, lightweight nature, and adaptability. Derived from the root structure of fungi, these materials are increasingly used in packaging and product design, aligning with circular economy principles while expanding across industries such as construction, electronics, and social housing due to their minimal ecological footprint and potential to reduce environmental impact. Mycelium-based composites offer significant environmental benefits by reducing reliance on non-renewable resources and minimizing waste, making them economically viable and capable of revolutionizing multiple sectors by enhancing sustainability [5]. In social housing, mycelium materials lower energy consumption by 56% and waste pollution by 68%, reinforcing the circular economy model [6]. In construction, they serve as sustainable insulation alternatives with high recyclability, contributing to nearly energy-neutral buildings and reducing environmental impact in walls and terraces [6], [7]. Innovations in electronics are also emerging, with mycelium-based substrates offering an eco-friendly alternative to fossil-based polymers, enhanced by post-growth treatments that improve mechanical and electrical properties for flexible electronic devices [8]. However, challenges such as consumer acceptance, intrinsic variability, and the need for standardized guidelines persist, necessitating further research and innovation to optimize material properties and production processes [5].

Despite their potential, the adoption and development of mycelium-based materials in Indonesia remain in the early stages. Challenges such as limited awareness, technological barriers, and economic feasibility must be addressed to unlock their full potential. This study investigates the role of mycelium-based biomaterials in environmentally friendly packaging and product design in Indonesia. By employing a qualitative approach, it seeks to explore the perceptions and experiences of key stakeholders, including material scientists, packaging industry professionals, and sustainable design entrepreneurs. Through in-depth interviews and thematic analysis using NVIVO software, the research aims to uncover the benefits, challenges, and opportunities associated with adopting mycelium-based materials in the Indonesian context.

2. LITERATURE REVIEW

2.1 Mycelium-Based Biomaterials: Properties and Applications

Mycelium-based materials are gaining attention as sustainable alternatives to traditional materials due to their eco-friendly properties and versatility. Cultivated by growing fungal mycelium on substrates like agricultural waste, these materials form a dense, moldable structure that is biodegradable and cost-effective, with applications spanning industries such as construction, packaging, and fashion. In construction, mycelium-based composites are explored as insulation materials with high recyclability, though they currently lag behind conventional materials like polystyrene in some physical properties [7], [9]. In packaging, mycelium is used to create compostable protective materials, reducing waste, while its lightweight and adaptable nature makes it suitable for various manufacturing applications, including furniture and fashion [5]. Additionally, mycelium is utilized in biocomposites and mycelial leather, providing sustainable alternatives to animal-based products and supporting carbon neutrality efforts [10]. However, challenges remain, such as substrate variability, as agricultural by-products used in production can be seasonal and inconsistent, though research suggests alternative substrates like sewage sludge can enhance material density and thermal stability [11]. Market viability also presents a challenge, as while mycelium materials attract environmentally conscious consumers, widespread adoption requires further innovation and increased demand for sustainable solutions [9].

2.2 Environmental Benefits of Mycelium-Based Biomaterials

Mycelium-based biomaterials present a promising alternative to traditional packaging materials, particularly plastics, due to their environmentally friendly properties. These biodegradable materials can be produced using renewable agricultural waste and require low energy inputs, making them a sustainable choice for industries aiming to reduce their environmental footprint. The cultivation of mycelium emits fewer greenhouse gases and consumes less water compared to conventional manufacturing processes, aligning with circular economy principles [5], [10]. Mycelium-based materials naturally decompose, returning nutrients to the environment, unlike plastics that persist and pollute ecosystems [5]. Their production also involves minimal greenhouse gas emissions, contributing to carbon neutrality efforts [10], while utilizing agricultural waste reduces reliance on virgin resources and promotes waste recycling [10]. Economically, mycelium-based products are cost-effective due to their reliance on waste materials and low-energy processes [5]. Their versatility enables applications across various industries, including construction and packaging, due to their adaptable properties [5]. However, challenges remain, including the need for increased consumer awareness and acceptance [5], as well as the development of standardized guidelines for production and quality control to facilitate widespread adoption [5], [9].

2.3 Challenges in Adopting Mycelium-Based Biomaterials

The adoption of mycelium-based biomaterials in Indonesia faces significant challenges, including scalability, cost, and public awareness. While these materials offer environmental and economic benefits, large-scale production requires specialized facilities, and their costs remain higher than traditional plastics, deterring businesses from adoption [5]. Digital biofabrication techniques, such as liquid spawn, show promise for improving production efficiency but are still in early development [12]. Environmentally, mycelium-based materials provide a sustainable alternative to polystyrene, contributing to a circular economy by allowing reuse and reducing waste pollution by up to 68% [6]. Additionally, mycelium insulation acts as a carbon sink, enhancing its ecological benefits [9]. In Indonesia, consumer education is essential for increasing awareness and acceptance of sustainable materials, while government incentives could support industry growth and encourage businesses to transition [5]. Collaboration among researchers, entrepreneurs, and policymakers is crucial to addressing infrastructure gaps and enhancing market readiness, ensuring the successful integration of mycelium-based biomaterials into Indonesia's sustainable development framework [5].

2.4 Theoretical Framework

The adoption of mycelium-based biomaterials aligns with the principles of sustainability and the circular economy. The circular economy emphasizes reducing waste, reusing materials, and recycling resources to create a closed-loop system that minimizes environmental impact (Ellen MacArthur Foundation, 2019). Mycelium-based biomaterials fit within this framework by providing a renewable, biodegradable alternative to synthetic materials.

Additionally, this study draws on the concept of eco-design, which integrates environmental considerations into product development. Eco-design focuses on creating products that minimize resource consumption, reduce emissions, and enhance recyclability (Pigosso et al., 2017). By examining the role of mycelium-based materials in packaging and product design, this research contributes to the broader discourse on eco-design and sustainable development.

3. METHODS

3.1 Research Design

A qualitative research approach was chosen to gain an in-depth understanding of the topic by exploring the perspectives and experiences of key stakeholders. This approach allows for the identification of themes and patterns that emerge from the data, providing valuable insights into the adoption and application of mycelium-based biomaterials in Indonesia. The study focuses on examining the social, environmental, and economic implications of these materials in the context of sustainable packaging and product design.

3.2 Participants and Sampling

The study involved three key informants selected using purposive sampling based on their expertise in material science, packaging industry practices, and sustainable product design. The participants included a material scientist specializing in biodegradable materials, including mycelium-based products; a packaging industry expert with experience in adopting sustainable practices; and a sustainable design entrepreneur actively integrating eco-friendly materials into product design. These selection criteria ensured that the informants possessed relevant knowledge and experience to provide meaningful insights into the research topic.

3.3 Data Collection

Data were collected through semi-structured interviews, providing flexibility in exploring various aspects of the topic while ensuring consistency in addressing research objectives. The interview guide covered themes such as the benefits and challenges of using mycelium-based biomaterials, the feasibility of their adoption in Indonesia, potential applications in packaging and product design, and the role of government policies and industry practices in promoting sustainable materials. Each interview lasted approximately 60 to 90 minutes and was conducted either in person or via video conferencing, depending on participant availability. All interviews were audio-recorded with participant consent and transcribed for analysis.

3.4 Data Analysis

The transcribed data were analyzed using thematic analysis, facilitated by NVIVO software, to identify, analyze, and interpret patterns within the qualitative data. The process involved familiarization with the data through repeated reading of interview transcripts, generating initial codes to capture meaningful segments, grouping related codes into broader themes aligned with research objectives, refining and validating themes for accuracy, defining and naming themes with descriptive labels, and finally, producing a report summarizing findings supported by direct participant quotes. NVIVO software enhanced the organization and visualization of data, ensuring rigor and transparency in the analysis process.

4. RESULTS AND DISCUSSION

4.1 Environmental Benefits of Mycelium-Based Biomaterials

All informants highlighted the significant environmental advantages of mycelium-based biomaterials, particularly their biodegradability and reliance on agricultural waste. A material scientist emphasized that "mycelium-based biomaterials align perfectly with circular economy principles. They decompose naturally and help reduce plastic waste pollution, which is a huge issue in Indonesia." Additionally, the informants underscored the low energy requirements for mycelium cultivation compared to traditional plastic production, contributing to a reduced carbon footprint.

4.2 Challenges in Adoption and Scalability

The scalability of production emerged as a recurring challenge, with the packaging industry expert noting, "While mycelium has potential, scaling up production to meet industry demands is still a bottleneck. The facilities and expertise required are not yet widespread in Indonesia." High production costs and limited awareness among businesses and consumers further hinder the adoption of mycelium-based biomaterials.

4.3 Potential Applications in Packaging and Product Design

The versatility of mycelium-based materials was recognized by all informants, who identified various applications such as protective packaging for fragile items, biodegradable food containers, and eco-friendly product designs. The sustainable design entrepreneur emphasized, "The design potential of mycelium is immense. Its natural texture and moldability offer opportunities for innovative, eco-friendly products that appeal to conscious consumers." Informants also highlighted the potential for integrating mycelium-based materials into the luxury market, where sustainable and aesthetically pleasing designs are increasingly in demand.

4.4 Role of Policy and Collaboration

Government policies and cross-sector collaboration were identified as critical enablers for the adoption of mycelium-based biomaterials. The material scientist emphasized, "Support from the government in the form of subsidies, tax incentives, and research funding can accelerate the adoption of sustainable materials like mycelium." Informants also stressed the importance of partnerships between researchers, businesses, and policymakers to overcome challenges and promote the use of mycelium-based materials in Indonesia.

DISCUSSION

The findings align with global research highlighting the environmental benefits of mycelium-based biomaterials. In Indonesia, where plastic waste management is a significant issue, the adoption of mycelium-based materials can contribute to national sustainability goals. By reducing reliance on plastics, mycelium supports the country's commitments to combating pollution and fostering a circular economy. The challenges related to scalability and costs are consistent with findings from previous studies. However, informants emphasized that these barriers could be mitigated through targeted investments in infrastructure and technology. Establishing localized production hubs that utilize agricultural waste could reduce costs and create economic opportunities for rural communities.

The versatility of mycelium-based biomaterials offers significant market potential, particularly in the packaging and product design industries. Informants' insights echo research by Haneef et al. (2017), which suggests that mycelium can replace plastics in various applications. Moreover, its aesthetic appeal positions it as a viable material for sustainable luxury goods. The role of policy and collaboration in promoting sustainable materials cannot be overstated. Informants emphasized the need for government support, which aligns with global best practices where subsidies and incentives have facilitated the adoption of eco-friendly materials. Partnerships between academia, industry, and policymakers can drive innovation, reduce costs, and enhance market readiness.

5. CONCLUSION

This study demonstrates the significant potential of mycelium-based biomaterials to revolutionize packaging and product design in Indonesia. The environmental advantages of mycelium, including biodegradability and reduced carbon footprint, position it as a viable alternative to plastic. However, challenges such as production scalability, high costs, and limited awareness hinder widespread adoption. Addressing these barriers requires targeted investments in production infrastructure, government support through subsidies and tax incentives, and the promotion of cross-sector collaboration between researchers, businesses, and policymakers.

The versatility of mycelium-based materials, as highlighted by their application in packaging, food containers, and luxury product designs, underscores their market potential. Integrating these materials into the supply chain can contribute significantly to Indonesia's sustainability goals, particularly in reducing plastic waste and promoting a circular economy. Future research should focus on scaling production processes and assessing consumer perceptions to enhance market readiness. By fostering a collaborative ecosystem and leveraging innovative technologies, mycelium-based biomaterials can play a transformative role in advancing sustainable development in Indonesia.

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