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왕겨 4D 프린팅을 활용한 하이그로모픽 키네틱 차양

4D Printing of Rice Husk for Hygromorphic Self-Shaping Building Skin

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Abstract

This study presents an interdisciplinary, biomimetic approach to designing and fabricating adaptive architectural skin by transforming agricultural waste-rice husks (RHs) into a functional, responsive building material. The primary objective was to develop a novel hygromorphic bio-composite and integrate it into a responsive façade system. A bio-composite was fabricated by combining RHs and a bio-based PLA polymer, using a pellet 3D printer to produce humidity-responsive elements. The material's performance was rigorously evaluated through 4D testing to understand how printing parameters and geometries influenced its moisture-responsive deformation. Our results demonstrate a rapid, reversible, and controllable morphing response of RH-based skin prototype.

Keywords : Rice husk; 4D printing; Hygromorphic façade; Kinetic building; Responsive architecture.

1. Introduction

1.1 Research backgrounds

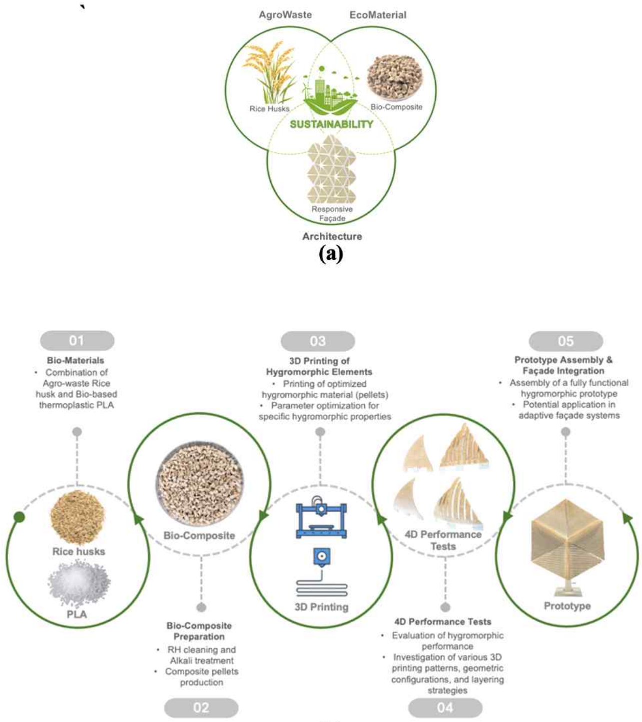
Rice husks (RHs), which account for about 20% of rice grain weight, are generated in vast quantities worldwide-estimated at over 150 million tons annually from the global rice production of 750-780 million tons [1]. Because of their low nutritional value and resistance to biodegradation, RHs are mostly burned or landfilled, causing air and water pollution [2]. Although efforts have been made to repurpose RHs (e.g., silica extraction, thermal insulation, biomass fuel) [3,4], their large-scale industrial use remains limited.

The building sector consumes ~34% of global energy and contributes ~37% of CO_2 emissions, prompting interest in passive, low-energy solutions [5]. Among these, self-shaping building skins employing smart materials and compliant mechanisms offer a promising climate-adaptive strategy to reduce energy demand and enhance indoor comfort while limiting reliance on mechanical systems [6-10].

Hygromorphic composites transform shape with ambient humidity through moisture-driven anisotropic deformation, typically in bilayer or multilayer structures [11,12]. This study leverages the abundance, low thermal conductivity, and moisture responsiveness of rice husks to develop a passive façade system for regulating humidity and daylight, particularly suited to hot, humid climates.

1.2 Study objectives

This study aims to (i) demonstrate the 3D printability of RH pellets and analyze factors affecting hygromorphic performance, (ii) develop reversible RH-PLA bio-composite sheets and validate their humidity-driven actuation through a kinetic shading prototype, and (iii) address research gaps by assessing the feasibility and mechanical properties of RH-based 4D printing for architectural applications.



(b)

Figure 1. Research framework and workflow for hygromorphic façade prototype development. **(a)** Conceptual sustainability framework. **(b)** Research workflow for system development.

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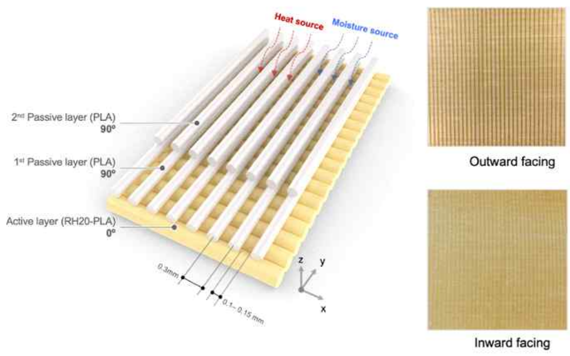
2. Materials and Methods

2.1 Rice husk processing and pellet production

Rice husks were processed into ultrafine (<74 µm) alkali-treated powders to improve printability. A bio-composite (RH20-PLA) was formulated by compounding 20 wt.% RH powder with PLA and extruded into filaments via FGF 3D printing. The filaments were then cut into 3-5 mm granules for subsequent printing.

2.2 Composite design and 3D printing



(a) (b)

Figure 2. Design of 3D-printable RH bilayer composite: (a) layer structure and dimensions; (b) printed surfaces.

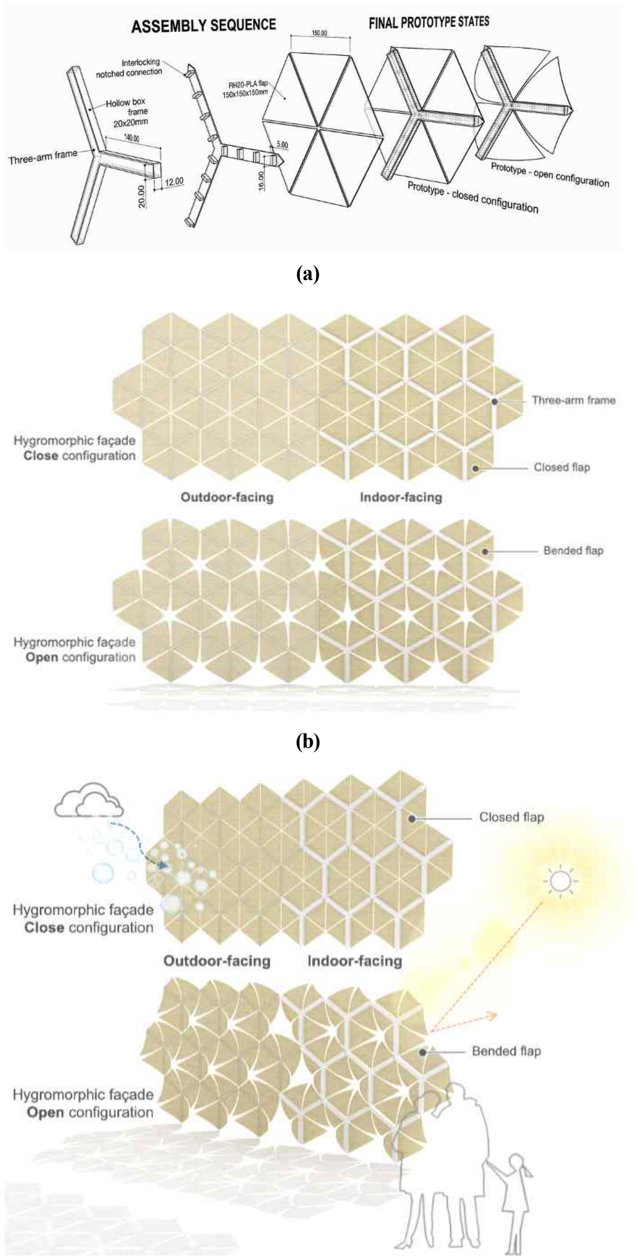
As illustrated in Figure 2, a bilayer composite structure—laminating an active (moisture-responsive) and two passive layers—was designed. The active layer, 0.3 mm thick, was printed using RH20-PLA with a 0° infill angle, while the passive layers, each also 0.3 mm thick, were printed using PLA with a 90° infill angle. Additionally, inter-path gaps of approximately 0.1-0.15 mm were introduced between printed lines in the passive layers. The outward-facing gaps were intentionally designed to enable direct exposure of the RH layer to ambient humidity, thereby activating moisture-induced bending, and vice versa in air-dried conditions. Through iterative preliminary printing tests, printing parameters were configured empirically (Table 1).

Pellet	Infill angle	Nozzle size	Nozzle Temp. (°C)	Bed Temp. (°C)	Printing speed (mm/s)	Fill density (%)
RH20-PLA	0°	2.0	180	80	45	50
PLA	90°	0.8	185	80	45	50

Table 1. FGF 3D Printing Parameters

2.3 4D Printing: Prototyping a hygromorphic building skin system

As illustrated in Figure 3, the responsive building skin prototype comprises six single-flap panels made of 4D-printed RH composites, mounted on a symmetric triangular frame.



(a)

(b)

(c)

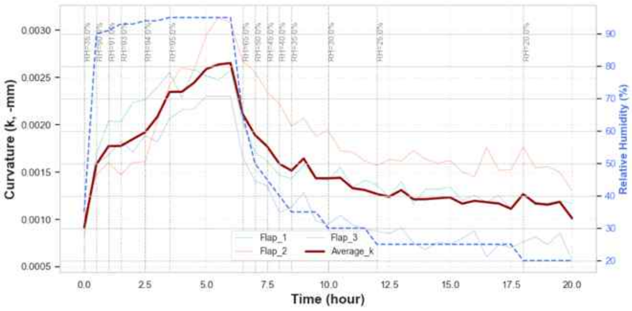
Figure 3. Hygromorphic façade prototype: (a) modular assembly of the hexagonal prototype with a three-arm central frame; (b) Indoor/outdoor views in closed (top) and open (bottom) states; (c) passive ventilation and light control via flap deformation under hygromorphic actuation.

3. Results

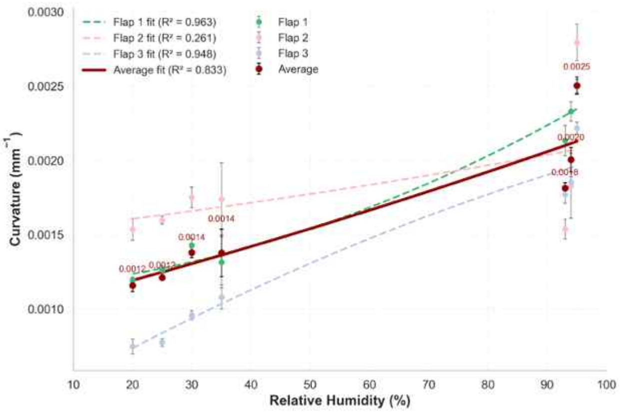
3.1 Hygromorphic performance of flap specimens (n = 3)

The hygromorphic performance of individual flap specimens was systematicallyevaluated, with a particular focus on the average curvature response under controlled humidity variations. During the absorption phase, as relative humidity (relH) was progressively increased from 20% to

95%, the average curvature showed a steady upward trend, indicating effective moisture-induced bending. Conversely, the desorption phase revealed a gradual yet marked reduction in average curvature as relH decreased. The direct relationship between average curvature and relH is further elucidated, where the average fitted curve (R^2 = 0.833) demonstrated a strong positive correlation, with average curvature increasing from approximately 0.0010 mm^{-1} at 20% RH to around 0.0025 mm^{-1} at 95% RH. Despite some individual variations, the overall consistent trend confirms the stable an d reversible hygromorphic actuation of the specimens (Figure 4).



(a)



(b)

Figure 4. Hygromorphic performance of flaps in a single absorption-desorption cycle (n = 3): (a) curvature change at stepwise relH; (b) curvature–relH relationship.

3.2 Building skin module prototype

The façade module prototype was comprehensively tested across varying humidity conditions in the chamber. The prototype consistently exhibited dynamic, adaptive morphological change in response to moisture levels. Under high relative humidity, the individual triangular flaps actuated into open positions, enhancing ventilation and permitting greater ventilation and daylightingress. In contrast, at low humidity, the flaps reverted to a more closed configuration, effectively reducing permeability and improving enclosure. (Figure 5, 6)

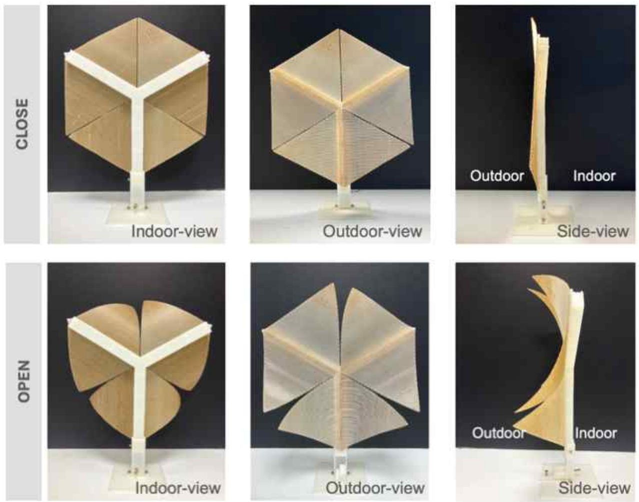


Figure 5. Hygromorphic façade prototype: closed state (dry); Open state (humid).

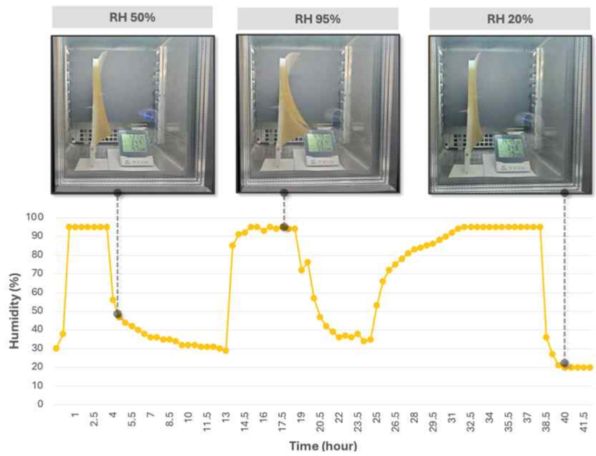


Figure 6. Prototype configurations at different humidity levels in chamber.

4. Discussion and Concluding Remarks

This research presents a compelling framework for transforming agricultural waste into a sustainable and functional architectural material. The core concept revolves around an interdisciplinary approach that links agro-waste, biomaterial, and architectureto foster a more sustainable built environment.

A novel hygromorphic bio-composite material was created by combining agricultural byproducts, specifically rice husks, with a bio-based polymer like PLA. The fabrication of this responsive material marks a methodological advancement, leveraging a FGF 3D printer instead of the conventional filament-based systems or industrial extruders utilized in previous studies [13-16].

The hygromorphic performance of the material was rigorously evaluated. The results confirmed a reversible morphing response that allows the façade to open and close according to predefined criteria. Crucially, this responsive behavior was shown to react quickly to changing moisture conditions. The successful integration of these elements into a functional prototype therefore validates not only the performance but also the material's environmental friendliness and degradability, which are central to the research's sustainability goals. This tangible outcome demonstrates the practical feasibility of using bio-composites to create adaptive building envelopes. Such systems offer significant potential for passively regulating indoor climate, thereby improving energy efficiency and occupant comfort without relying on active mechanical systems.

This work eventually makes a significant contribution to the fields of adaptive architecture by providing a concrete example of circular economy in practice. By transforming a low-value waste product into a high-performance building component, the research offers a pathway toreduce material waste and the environmental footprint of the construction industry.

However, this study is not without limitation. Future research should focus on the quantitative evaluation oflong-term durability, scalability, and cost-effectiveness of these bio-composite façades. Nevertheless, this study provides a solid scientific basis of valorizing agricultural waste by developing a hygromorphic bio-composite from RHs and a tangible proof-of-concept for creating 4D-printed, bio-sourced climate-adaptive building skin.

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