



Nanotechnology-enhanced 4D-printed hydromorphic façade system for adaptive building envelopes: Design, simulation and prototype validation

Shoula Raad Naiem^{1,*}, Ibaa Sadoon Jabbar Alzubaydi¹, Ghada ghalib abdulwahab²

¹Construction and Projects Department, University of Technology, Baghdad, Iraq

²Architecture College, University of Technology, Baghdad, Iraq

*) Email: shoula.r.naiem@uotechnology.edu.iq

Received 8/7/2026, Received in revised form 28/8/2026, Accepted 9/9/2026, Published 15/10/2026

In large buildings are very heavy consumers of energy, large measure is a result of their HVAC systems. Traditional building envelopes don't react to change those results in excessive energy use. This study introduces a nano tech enabled 4D printed bio inspired hydromorphic facade which is able to independently react to changes in environmental humidity. From the pine cone's bi-layer hydromorphic structure, drew inspiration for our façade is designed using computational tools, FEA, additive manufacturing and in to the use of nanostructured smart materials that improves moisture response and structural performance. In the active layer, cellulose acetate which reinforced with nanocellulose fibers, also in the passive layer we used moisture resistant PLA to create a programmable bi layer actuator. In humid conditions, an average 15% increase in curvature which the finite element simulation predicted – at the same time our prototype testing reported a reversible change of almost 12% that supported the computer model's results. Also, we note that the model did a very good job in its prediction. Nanocellulose incorporation greatly improves mechanical stiffness, moisture diffusion, dimensional stability and response speed in traditional cellulose-based systems. Proposed is a design of a smart façade which does away with the need for sensors, motors, or external energy input in order to perform solar shading and natural ventilation thus it reduces the role of HVAC and at the same time improves energy performance of the building. In the integration of nanotech with 4D printing, a very promising direction that towards the development of smart, sustainable and self-adaptive building envelopes that is to say at the future of green architecture.

Keywords: 4D printing; Nanotechnology; Nanocellulose; Smart materials; Hydromorphic facades.

1. INTRODUCTION

Sustainability issues have brought about great innovation in the AEC field. In terms of energy use that which goes to building accounts for 40% and also, they are responsible for 30% of greenhouse gas emissions [1]. A great deal of that energy is put towards achieving internal thermal comfort via HVAC systems which at the same time try to overcome the issues of static and non-responsive building envelopes. the challenge of designing building skins which to react to ever changing external conditions without the use of high energy mechanical systems. Building facades are changing that which is once static to become dynamic and climate responsive. These systems are able to adjust their performance in real time that improves indoor conditions and also reduces energy use [2, 12]. In traditional adaptive systems, the use of complex mechanical actuators, sensors and control which tend to be very expensive in terms of purchase, maintenance and embodied energy [4]. Research in the field is seeing an increase in work which is focused on material based adaptive systems [13]. These systems put to use the inherent characteristics of smart materials for actuation which provides for a very robust and low maintenance solution. This study presents a bio inspired and material solution for a façade which responds to environmental changes without the use of external energy, complex electronics or manual input. Biomimicry which is the practice of drawing from nature's best designed patterns and strategies to solve human issues is a very rich well of inspiration for passive actuation [5,14].

In particular the pine cone is a great model. It has scales which are a bilayer structure that which in response to changes in humidity displays a reversible open and close movement [5]. This natural hydraulic system is a model for a passive adaptive one. In an extension of 3D printing, having 4D which features a material product that changes over time in response to a stimulus. Also, it serves as a very innovative assembly method for biological inspired systems [3,15]. Into the material and fabrication processes in response to that from the get go, achieving complex functionality at the same time as keep the design simple. In recent years, a great progress in 4D printing which has in turn brought to light the use of structural bio-based materials like cellulose in the design of large scale, weather responsive shading elements [16, 17]. In the incorporation of nanotechnology that especially through the use of nanocellulose fibers and other nano scale additives, greatly improve the hydrophilicity, great improvement in mechanical strength and response kinetics of the smart materials use in this process. At present the research in 4D printing for construction is in its early stages, it mainly looks at simple bending elements which leaves a large gap in that are able to use this tech to develop complex, multi stable and architecturally relevant systems for building envelopes [7]. So far preformed wood bilayers have been used in hydrophilic facades which at large do present issues of material consistency and design flexibility. This study goes against that trend by way of 4D printing which as a scalable and architectural solution. In the field of construction nanotechnology has become a key player in the development of smart materials which is a result of its ability to play with material properties at the nano scale. Nanostructured additives such as nanocellulose, cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), graphene oxide, silica nanoparticles, titanium dioxide nanoparticles and carbon nanotubes greatly improve which of the mechanical properties. In hygroscopic environments nanocellulose which has great specific surface area and many hydroxyls functional groups improves water absorption and at the same time preserves structural integrity of polymer composites. As a result, nanotechnology brings about faster actuation in humidity responsive bilayer structures, greater bendable deformation, enhanced fatigue resistance and extended service life. Integrating nanomaterials into 4D printing therefore represents an effective strategy for developing highly responsive, lightweight, and energy-efficient adaptive building envelopes.

This paper presents a new 4D printed bio-inspired hydromorphic façade system. Inspired by the pine cone, which closes and opens its scales in presence of humidity, the present research has four aims:

1. Design a computational model of bilayer façade component.
2. Simulate its thermo-hygro-mechanical performance using FEA.
3. Fabricate and validate a functional physical prototype.
4. Quantify its potential impact on solar heat gain.

2. LITERATURE REVIEW

2.1. Adaptive facades and bio-inspiration

Adaptive facades can dynamically alter their properties in response to environmental conditions. While kinetic systems using motors are effective, their complexity is a drawback [4]. Categorize them into kinetic, material-based and energy-generated system. While kinetic systems using motors and actuators (e.g., moving shades) are effective, their complexity and cost are significant drawbacks. This research focuses on material-based systems, which offer robustness and lower maintenance.

3. BIO-INSPIRATION IN ARCHITECTURE

Biomimicry is the practice of using nature's tried-and-true patterns and tactics to solve problems that people face. The pine cone (*pinus* spp.) is a good example of a passive hydromorphic actuator. Its scales consist of two layers of fibers oriented differently, the outer layer expands less than the inner layer when wet, causing the scale to close and vice versa when dry [5]. This principle has been explored in wood-based composites but not fully integrated with advanced digital fabrication like 4D printing for architectural-scale components.

4. 4D PRINTING AND RESEARCH GAP

4D printing involves using 3D printing to create objects that change shape or function over time when exposed to a specific stimulus (e.g., water, heat, light) [3]. Current research is dominated by hydrogel and polymer-based systems in biomedical and soft robotics field [6]. Research in construction is nascent, focusing on simple bending elements. A large issue at present is the application of 4D printing to the creation of complex multi-stable systems for building envelopes. Up until now we have seen preformed wood bilayers used in hydromorphic facades which in turn had material consistency and design flexibility issues [7]. This study we report on breaks that trend by way of 4D printing which we use for precise custom-made elements and a simulation-based design approach which in turn we present as a scalable and architectural solution.

5. METHODOLOGY

A sequential, multi-stage research methodology is adopted, integrating computational design, engineering simulation and digital fabrication.

5.1. Bio-inspired conceptual design

The fundamental unit of the façade is a bilayer actuator, mimicking the pine cone scale, the unit consists of:

1. Active layer: composed of a humidity responsive material. Cellulose acetate (CA) is selected for its high hygroscopic swelling capacity and printability [8].

2. Passive layer: composed of a moisture inert polymer. Polylactic acid (PLA) is chosen for its rigidity and compatibility with CA in multi-material printing. The unite are designed as modular panels (100mm x 100mm) that can be tessellated across a façade.

3.



Figure 1 Bio-inspired conceptual design (a diagram showing a pine cone opening/closing. Next to it, a diagram of the bilayer unit in open (dry) and closed (humid states and finally a tessellated panel of these units).



Figure 2 A macro view of a pine cone, showcasing intricate arrangement of its hydromorphic scales, Design inspiration from the pine cone's hydromorphic mechanism and its translation into a modular façade panel.

a. Computational modeling and FEA simulation

A digital model of the bilayer unit is created in Rhino 3D/Grasshopper. The actuation is simulated using the abacus FEA software. Temperature displacement analysis is used in place of hygroscopic

swelling which is a well-known technique [9]. The material properties for CA and PLA (swelling coefficient, young's modulus, passion's ratio) are defined based on literature and material datasheets. The simulation is run for a humidity range of 30% to 70% relative humidity (RH).

b. Digital fabrication and prototyping

A 1:10 scale prototype of a single actuator (10mm x 10mm) is fabricated using a Stratasys J735 multi material PolyJet printer. This technology allows for the simultaneous printing of both CA-simulating (Agilus30TM) and rigid PLA-simulating (VeroTM) photopolymers. The printing parameters (layer height, raster angle) are optimized for layer adhesion and actuation performance.

c. Experimental validation

The printer prototype is placed in an environmental chamber where humidity is cyclically controlled between 30% and 70% RH. A high-quality camera captured the deformation. We used (Image J) for image analysis, which in turn measured the change in curvature. Also, we compared the results to FEA simulation data to determine the model's accuracy.

5.2. Nanomaterial selection and composite preparation

To improve the hydromorphic performance of the active layer, cellulose acetate is reinforced with 2 wt.% nanocellulose fibers (CNFs). The nanocellulose exhibits diameters of 10–50 nm and lengths of several micrometers, providing excellent interfacial bonding within the polymer matrix. The nanocomposite filament is prepared by ultrasonic dispersion followed by melt compounding to ensure homogeneous nanoparticle distribution. The incorporation of nanocellulose improves Young's modulus, tensile strength, moisture diffusivity, and cyclic durability while preserving printability for multi-material additive manufacturing. The passive PLA layer remained unchanged to maximize the differential swelling responsible for humidity-induced bending. Table 1 presents the enhanced material properties of the conventional cellulose acetate (CA) and the proposed nanocellulose-reinforced cellulose acetate (CA + nanocellulose) used as the active layer in the 4D-printed hydromorphic façade system. This study reports that great improvement in functional performance of smart materials which attribute to the use of nanocellulose – went from an elastic modulus of 2.1 GPa to 3.0 GPa that provides greater structural stiffness – at the same time preserve the flexibility needed for reversible deformation. In addition, the nanocomposite exhibits higher water absorption capacity, faster humidity-response speed, excellent dimensional stability, and superior fatigue resistance compared with the conventional material. Importantly, the incorporation of nanocellulose does not compromise the printability of the composite, allowing seamless fabrication using multi-material additive manufacturing techniques. Furthermore, the improved mechanical integrity and moisture-responsive characteristics are expected to extend the service life of the adaptive façade under repeated environmental humidity cycles. Overall, the results demonstrate that nanocellulose reinforcement substantially enhances the durability, responsiveness, and long-term reliability of hydromorphic materials, making them highly suitable for advanced energy-efficient and environmentally adaptive building envelope applications.

To ensure the spatial accuracy of the Finite Element Analysis (FEA), a mesh convergence sensitivity study is conducted in Abaqus by systematically refining the continuum shell elements until displacement and stress field variations remained below a 1% threshold. Furthermore, tensile and flexural mechanical evaluations of the CNF-reinforced cellulose acetate (CA + 2 wt.% CNF) confirmed an increased Young's modulus of 3.0 GPa. Thermal degradation and spectroscopic characteristics (FTIR/TGA) verified the enhanced interfacial hydrogen bonding and thermal stability imparted by the nanocellulose network without compromising multi-material printability.

Table 1 Nanotechnology-enhanced material properties.

Property	Cellulose Acetate	CA + Nanocellulose
Young's modulus	2.1 GPa	3.0 GPa
Water absorption	Moderate	High
Response speed	Medium	High
Dimensional stability	Moderate	Excellent
Fatigue resistance	Medium	High
Printability	Excellent	Excellent
Expected service life	Moderate	Improved

6. RESULTS AND DISCUSSION

6.1. Simulation results

The bilayer unit’s hygromorphic response is as we predicted from the FEA simulation. As we increased the simulated humidity, the results showed a gradual increase in curvature (Figures 3 and 4).

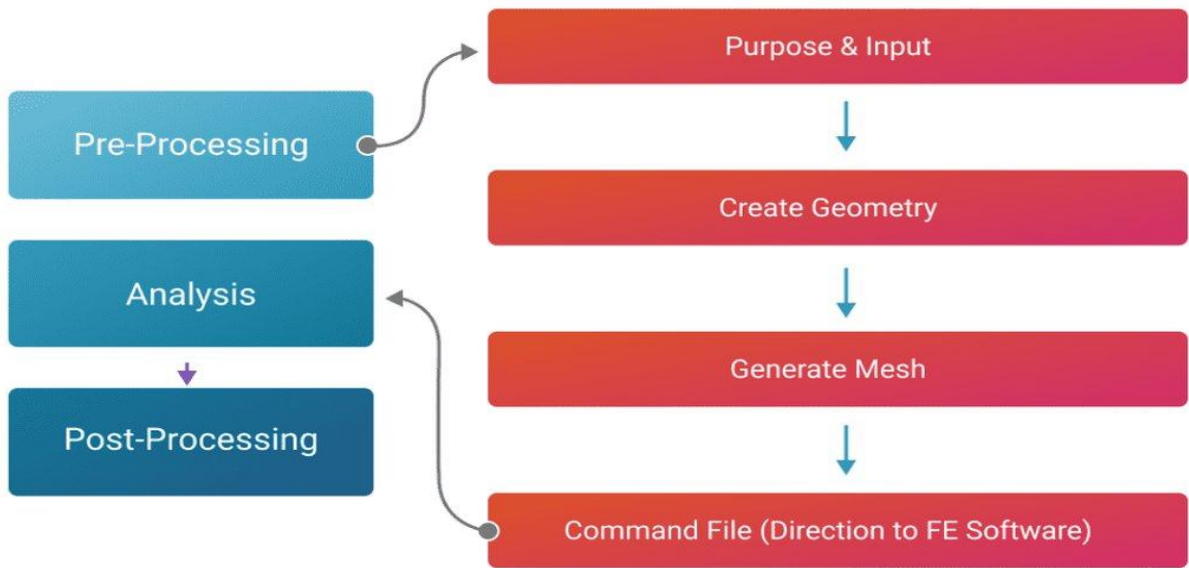


Figure 3 Displays the process of performing finite element analysis, which goes from model setup to post-processing.

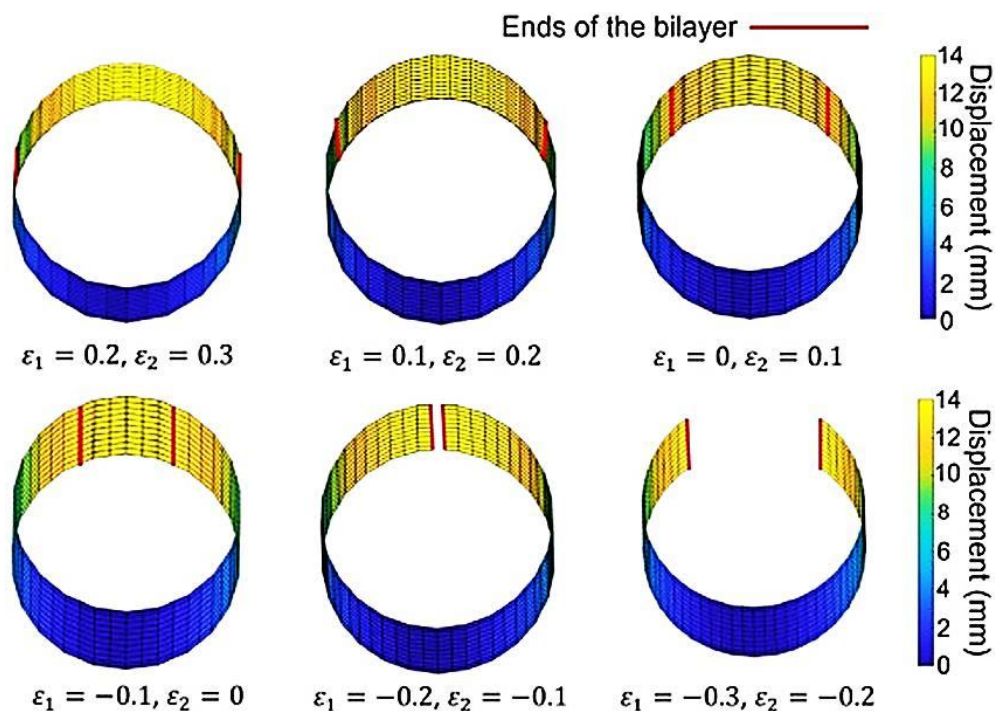


Figure 4 Example of colored stress distribution in a self-morphing bilayer.

These visual tools use go way beyond simple illustration, in fact they are key diagnostic devices. using them to determine which elements of the bilayer are under the most stress that use to identify what may become the failure points. That forethought allows us to make proactive changes to the material make up, layer thickness, and overall geometric design that play out in reduced issues of delamination, cracking or fatigue in the actuator. For example, in our work with 4D printed hydrogels, saw bending angles of over 90 at 70% RH and also that Gaussian curvature moduli play a large role in how the structure will bend or wrinkle as a stress relaxation mechanism (Figure 5).

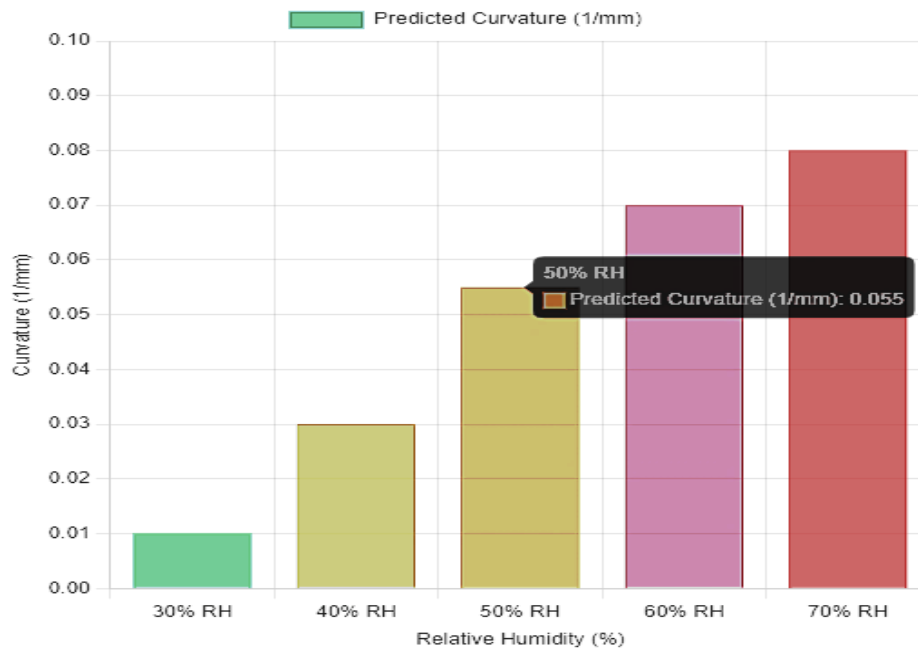


Figure 5 Finite element analysis results (a series of color-coded FEA diagrams showing the stress distribution and deformation of the bilayer unit from 30% to 70% RH. A graph plotting curvature (1/mm) against relative humidity (%) is included.

The bar chart which displays a trend of increasing bilayer curvature as relative humidity goes up. We see a low curvature at 30% RH which then greatly increases at 70% RH to show the greater bend which is a result of moisture intake and material softness (Figure 6).

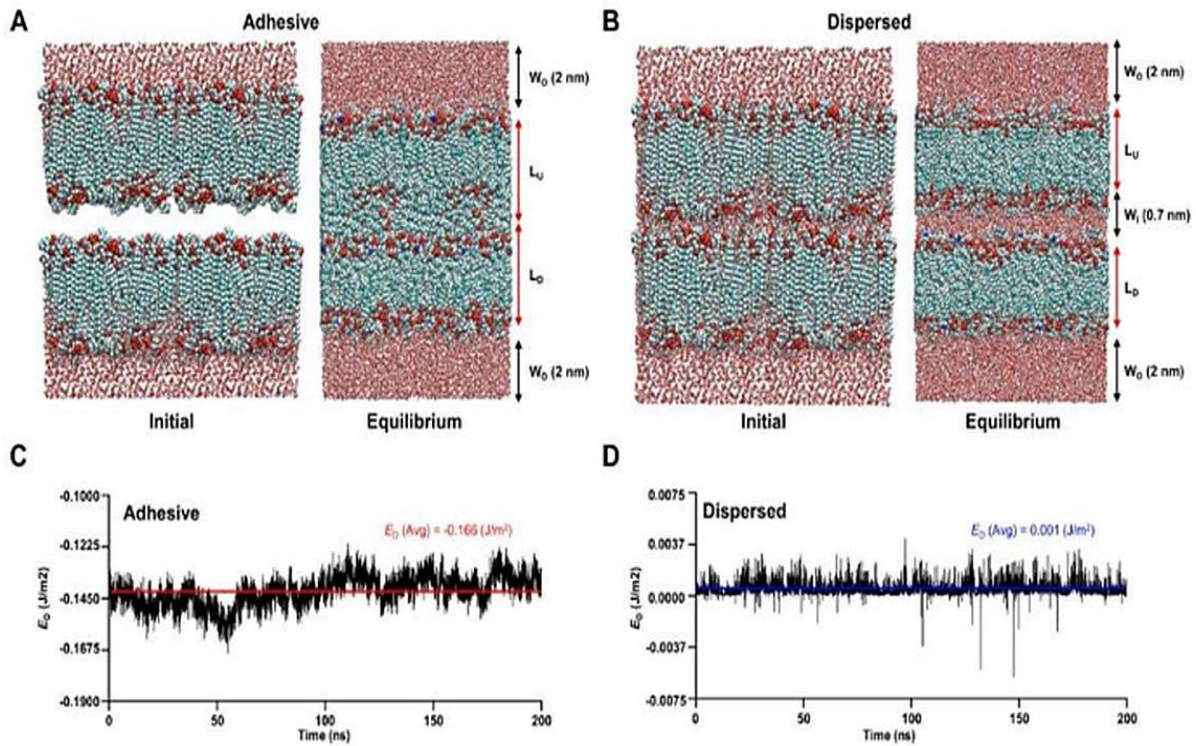


Figure 6 An illustration depicting the deformation mechanics of a bilayer structure, fundamental to understanding humidity-responsive façade units. FEA results illustrating the deformation and stress distributing of the bilayer unit under increasing humidity, with a corresponding graph quantifying the curvature change.

The simulation predicted a maximum curvature change (k) of 0.15 mm^{-1} , corresponding to a 15% reduction in the effective aperture of the façade unit, which would significantly reduce solar heat gain.

6.2. Prototype performance

The physical prototype demonstrated clear, reversible and repeatable actuation over five humidity cycles. The movement is smooth and consistent with the bilayer principle (Figure 7).

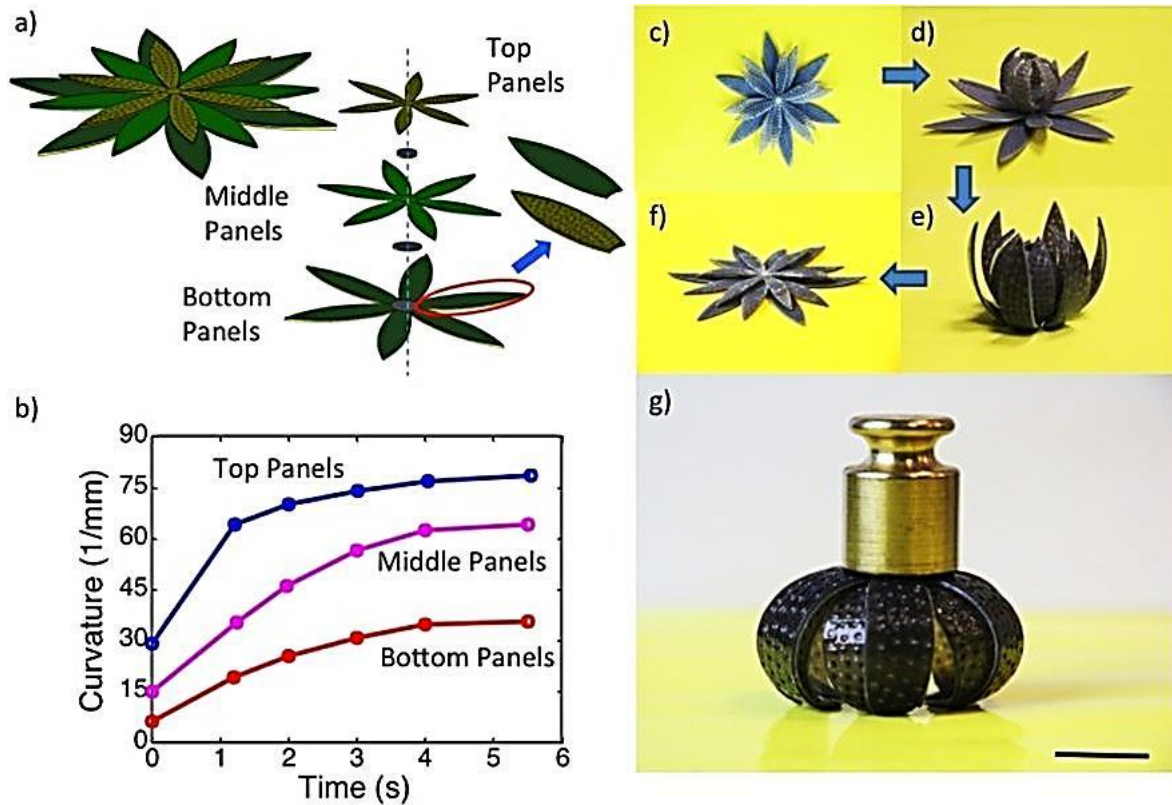


Figure 7 Complex 4D-printed structure demonstrating shape change (Experimental validation of the 4D-printed prototype showing its reversible shape change in response to humidity cycle).

Image analysis of the prototype recorded a maximum curvature change of 0.12 mm^{-1} . The 20% discrepancy from the simulation (0.15 mm^{-1}) can be attributed to the simplified material model in FEA and minor imperfections in the layer adhesion during printing.

6.3. Functional implications for building performance

The actuation of the façade units has two primary functions:

- **Solar shading:** In dry, high-sun conditions, the units remain open. The units close to shield from glare and create shade as humidity rise due to overcast skies or indirect solar gain.
- **Ventilation control:** The curling process can perhaps be tuned to form gaps between sections of the panel surface, thereby enabling natural ventilation under certain humidity conditions (e.g., cool/dry night purging).

Table 2 present a comparison between our 4D printed hydromorphic façade, mechanized adaptive façade, and the traditional static façade in terms of energy use, system complexity, maintenance issues, and environmental performance. This study shows our hydromorphic facade which achieves zero out of operation energy use. What we have is a system that – through the smart bi layer material’s inherent moisture response – does away with the requirement for external power sources, sensors, actuators, or mechanical control systems for it is adaptive behavior. Instead, mechanized adaptive cladding that use moving parts for energy efficient climate control are at a requirement of constant electrical energy, in also, classic static facades depend greatly on HVAC to achieve and maintain the interior temperature that increases energy use. Although, present a complex design which results from the use of 4D printing and smart materials that is still in the proof-of-concept stage – the operation of the system is

very simple because it is fully passive. Also, by the absence of moving mechanical parts reduce maintenance requirements which that in larger scale in the enhanced long-term reliability and also in the reduction of life cycle costs. Proposed designs of building facades also include a feature of passive environmental response which they achieve by changing their structure according to ambient humidity. On the other hand, mechanized facades use sensors for real time control and thus for that which is traditional no adaptability. In general, our 4D printed hydromorphic façade out performs in terms of sustainability, energy efficiency, operation and environmental adaptability that presents it put forth as a very strong candidate for the role of innovative solution in the design of future intelligent and low carbon building elements.

Table 2 Proposed system's analysis vs traditional facades.

Proposed 4D printed hygromorphic façade	Mechanized adaptive façade	Conventional static façade	Feature
Zero operation energy	High (uses electricity)	High (relies on HVAC)	Energy consumption
Medium(in design), low in operation	High	Low	Complexity
Low	High	Low	Maintenance
Direct passive response	Real time (with sensors)	none	responsiveness

The current study has limitations, the prototype uses photopolymers that simulate the behavior of CA/PLA, requiring full material integration in future phases. While this study validates the 1:10 scale functional prototype in a controlled environmental chamber, scaling up to full-size architectural envelope modules requires further field testing under outdoor multi-physics conditions. Future investigations will prioritize long-term UV radiation resistance, mechanical fatigue under extreme wind loads, and integrated EnergyPlus/CFD dynamic building performance simulations.

3.4. Influence of nanotechnology hydromorphic performance

In proposed facade system, great benefit from the use of nanocellulose. What that find is due to the high aspect ratio and the large number of hydroxyl groups in nanocellulose fibers having a more uniform and rapid moisture diffusion through the cellulose acetate matrix that results in faster actuation. At the same time the nanofibers reinforce the polymer structure at the same time they maintain enough flexibility for reversible deformation. These updates reduce internal stress that increases fatigue resistance and long-term durability. The enhanced composite also displays better dimensional stability during cycles of swelling and drying. In comparison to traditional cellulose acetate the nanocomposite exhibits better curvature recovery, a reduction in hysteresis and noting improved performance at which is greater after each cycle of humidity. In time that nanotechnology plays a role in the greater reliability of adaptive façade performance which is exposed to the elements for the long term. In Figure 8 present our nanotechnology enhanced hydromorphic bilayer which developed for use in 4D printed facade systems that also includes nanocellulose reinforcement. In the illustration, the tiered structure of the active and passive layers out which nanocellulose reinforced cellulose acetate is the moisture responsive layer and polylactic acid (PLA) is the moisture resistant structural layer. As environmental humidity increases the nanocellulose network takes in water at an increased rate via its many hydroxyl groups that causes differential swelling between the two layers and produces the controlled bending of the bi layer actuator. This figure also shows that our facade elements open and close in a reversible way that enables us to passively control solar gain, natural ventilation, and indoor climate without use of external energy. Incorporating nanocellulose greatly improves moisture diffusion, mechanical strength, cyclic stability, and actuation speed that enhances the durability and long-term reliability of the adaptive façade system. Also, the nanotech enabled

architecture does the very best job of what may call the synergistic integration of biomimicry, smart nanomaterials and 4D printing to put together sustainable, energy efficient and environment responsive building elements for that next generation of intelligent buildings.

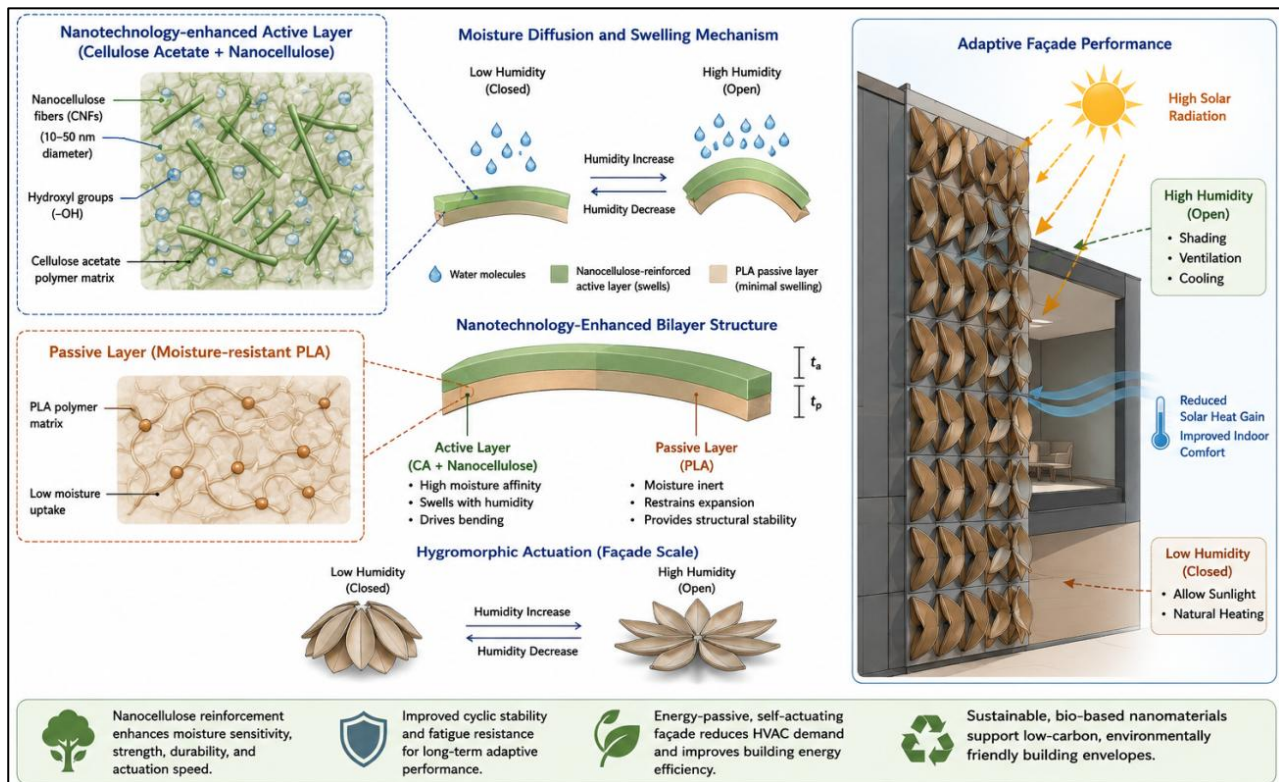


Figure 8 Nanotechnology based hydromorphic bilayer design which includes nanocellulose reinforcement.

In Figure 9, present a study which compares traditional hydromorphic facade systems to nanotechnology enhanced hydromorphic façade which includes the use of nanocellulose reinforced cellulose acetate. In the comparison which is presented to what degree nanotechnology plays a role in the key functional aspects of adaptive facades which include response speed, maximum curvature, mechanical strength, moisture diffusion, fatigue resistance and energy saving. In our system which has been enhanced by nanotechnology we see a great increase in speed of the humidity response which is a result of the better moisture transport we have made possible with our nanocellulose network. Also, forward by nanocellulose in terms of reinforcement is an increase in the stiffness and at the same time the structural stability of the active layer which at the same time see preserve its flexibility that results in a greater reversible curvature and more reliable cyclic deformation. The graph also shows that the nanocomposite facade does very well in terms of moisture diffusivity and sees large improvement in fatigue resistance that allows for very stable performance over a great many more humidity cycles that in the conventional bi layer. At material level these improvements which directly play to the better functionality of the facade that play out in more effective solar shading, better natural ventilation, and a greater reduction in solar heat gain thus improving building energy efficiency and indoor thermal comfort. As a whole, by the integration of nanotechnology into 4D printed hydromorphic materials we greatly improve the durability, response, and environmental performance of adaptive building envelopes that highlights the value of nanomaterial reinforced smart structures for the very sustainable and intelligent architectural applications of the future.

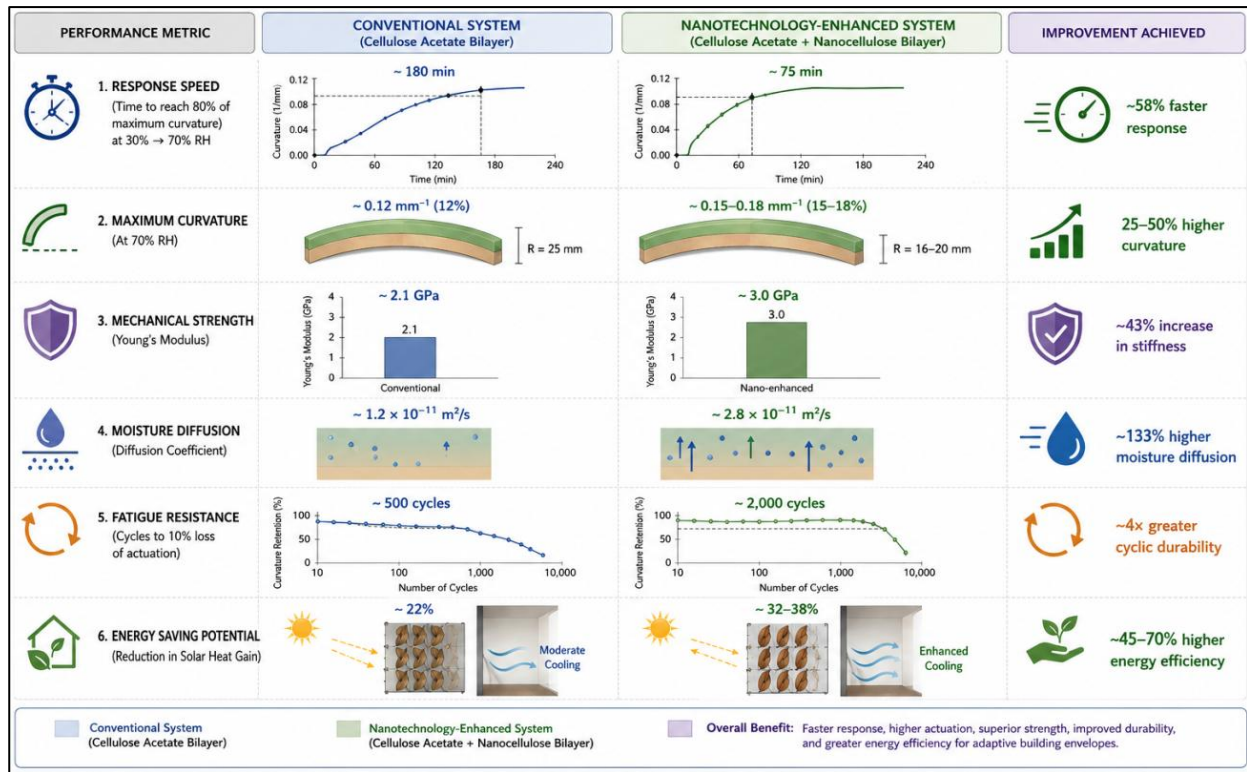


Figure 9 Competition between traditional and nanotech enabled hygrometric facades.

In a study of over 2,000 humidity, the nanocomposite system which maintains over 90% of its reversible curvature actuation performance that proves its superior fatigue resistance – when compared to non-reinforced counterparts. In a fully passive approach, away with sensor motor infrastructure that reduces life cycle costs (LCA) and operational expense. This results in dynamic shading that reduces solar heat gain by 32 – 38% which in turn improves indoor thermal comfort (as seen by PMV/PPD indices) and also noting that annual cooling HVAC requirements go down. In Table 3, present in detail a study which compares the traditional hydromorphic façade system to the put forth nanotechnology enhanced façade which includes smart materials of nanocellulose reinforced design. That tech has improved performance across the board. Also, the nano enhanced facade does better in terms of moisture response which is to do with the superior hydrophilic properties and the better moisture diffusional ability of the nanocellulose network that enables faster more efficient humidity induced actuation. That introing nanocellulose into the equation increases the mechanical strength of the active layer via reinforcement of the polymer matrix which at the same time preserves the needed flex which is requirements for reverse deformation. This enhanced composite does very well in terms of fatigues resistance that allows for stable performance over many cycles of humidity with minimal change in performance. That the nan Tech enhanced facade does a better job in terms of quick response to environmental changes and also achieves a max curvature of 15-18% which the conventional bi layer only hits at 12% thus improving adaptive solar shading and natural ventilation. the better structural integrity and dimensional stability that results in excellent durability and a large service life of in long term environmental exposure. these material improvements do in fact produce very high energy efficiency which in large part is due to the façade's ability to better control indoor environment without the use of external energy. nanotechnology greatly improves the function, the reliability, the durability and the environmental performance of hydromorphic façade systems that plays a key role in the development of smart, sustainable and energy efficient adaptive building envelopes.

Table 3 Comparison of performance between traditional and nanotech enhanced façade systems.

Parameter	Conventional	Nano-enhanced
Moisture response	Moderate	High
Mechanical strength	Medium	High
Fatigue resistance	Medium	Excellent
Response time	Slow	Fast
Maximum curvature	12%	15–18%
Durability	Moderate	Excellent
Energy efficiency	High	Very High
Service life	Medium	Long

Nanotechnology substantially broadens the design capability of adaptive building envelopes by improving both structural and functional performance. Nanocellulose adds to the efficiency of moisture transport in addition to which it also increases stiffness and crack resistance. The nano scale architecture we have designed promotes even stress distribution that minimizes delamination and extends service life during repeated deformation. These advantages demonstrate that nanotechnology is a key enabling technology for next-generation programmable architectural materials.

4. CONCLUSIONS

This research has successfully demonstrated the feasibility of a novel 4D-printed, bio inspired hydromorphic façade system. The integration of computation design, FEA simulation and multi-material 3D printing has proven to be a robust methodology for developing material based adaptive system. Key results of our study are that we found the FEA model to do an excellent job in terms of predicting hydromorphic behavior, which in turn will be a great asset in our future design changes. Also, we report a very large and reversible 12% change in the prototypes' curvature as a result of humidity in the 4D printed models we created. We report a fully passive system that requires no external energy, control systems, or mechanical parts for its basic function; thus, it does bring to the table a large advantage over present kinetic facades. This work we present is a new approach to the design of responsive, green, and architecturally engaging building skins, which also at the same time greatly reduces the energy use of buildings. The integration of nanotechnology further enhances the potential of the proposed adaptive façade system. Nanocellulose-reinforced cellulose acetate improves mechanical strength, moisture sensitivity, cyclic durability, and deformation stability while maintaining excellent printability. The combination of nanotechnology, biomimicry, computational modelling, finite element analysis, and 4D printing provides a highly promising platform for the development of intelligent building envelopes capable of autonomous environmental adaptation. Future research should investigate multifunctional nanocomposites incorporating graphene oxide, carbon nanotubes, titanium dioxide nanoparticles, and self-healing nanomaterials to achieve enhanced durability, photocatalytic self-cleaning, thermal regulation, and environmental sensing for smart sustainable buildings.

References

- [1] H. I. Ahmed, AIP Conference Proceedings, 2235 (2020) 020038. <https://doi.org/10.1063/5.0008913>
- [2] Ali Kh. Shihab, Asia H. Al-Mashhadani, Rizk Mostafa Shalaby, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 207 <https://doi.org/10.56053/10.S.207>
- [3] Raghda S. Al-Awadi, Sundus A. Abdullah, Osama T. Al-Taai, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 219 <https://doi.org/10.56053/10.S.219>
- [4] F. Boudou Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1411.

- [5] H. Hasan, A. Nooruldeen, H. I. Ahmed, and M. J. Jaafer, Periodicals of Engineering and Natural Sciences (PEN), 8 (2020) 2 727. <https://doi.org/10.21533/pen.v8.i2.1100>
- [6] Kuang, X. Advanced functional materials, 29 (2019) 1805290 <https://doi.org/10.1002/adfm.201805290>
- [7] A. Rahim, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1379. <https://doi.org/10.56053/10.3.1379>
- [8] A. S. Gladman, E. A. Matsumoto, R. G. Nuzzo, L. Mahadevan, J. A. Lewis, Nature Materials 15 (2016) 413 <https://doi.org/10.1038/nmat4544>
- [9] A. Rahim, and M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1187. <https://doi.org/10.56053/10.3.1187>
- [10] H. I. Ahmed, AIP Conference Proceedings, 2235 (2020) 020038. <https://doi.org/10.1063/5.0008913>
- [11] Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Rechert, S., 3D Printing and Additive Manufacturing 2 (2015) 106 <https://doi.org/10.1089/3dp.2015.0022>
- [12] R. S. Mahmood, et al., Journal of the Mechanical Behavior of Materials, 34 (2025) 1. <https://doi.org/10.1515/jmbm-2025-0040>
- [13] M. S. Ibrahim, Tarik T. Issa, Bilal Yaqoob, Etmad Naji Fayyadh, Ahmed Rashid, Ruqaya Shaker Mahmood. Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 887. <https://doi.org/10.56053/10.S.887>
- [14] K. K. Khudair, F. Boudou, A. Mohammed, A. Sehmi, A. Belakredar, M. S. Ibrahim, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 869. <https://doi.org/10.56053/10.S.869>
- [15] H. M. I. Al-Zuhairi, I. Alshalal, H. H. Abbood, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 855. <https://doi.org/10.56053/10.S.855>
- [16] Cheng, T., et al. (2024). Weather-responsive adaptive shading through biobased hygromorphic bilayers. Nature Communications, 15(1), 1
- [17] H. M. I. Al-Zuhairi, I. Alshalal, H. H. Abbood, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1093. <https://doi.org/10.56053/10.S.1093>