Evaluating Alginate-Xanthan Biofilm Encapsulation for Perovskite Photovoltaic Cells: A Comparative Methodology Against Silicon Panels

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Literature Review

As the global energy transition accelerates, photovoltaic (PV) technology has emerged as the dominant mechanism for renewable electricity generation. Solar energy now comprises 63% of United States electricity generation capacity, representing an 800% increase over the past decade, with PV cells accounting for 99% of all solar energy production (U.S. Energy Information Administration, 2024). Despite this rapid proliferation, conventional silicon-based photovoltaic cells remain constrained by fundamental material limitations: current commercial systems harvest only approximately 20% of incident sunlight, lack the mechanical flexibility needed to conform to diverse installation surfaces, and degrade at rates that substantially shorten their operational lifespans (Green et al., 2023; Shockley & Queisser, 1961). These deficiencies generate 6 million metric tons of electronic waste annually as failed panels are replaced and discarded (Weckend et al., 2016).

The economic barriers associated with current PV technology have further constrained adoption, particularly among small and medium-sized enterprises. Retail electricity prices ranging from $0.06 to $0.10 per kilowatt-hour and high upfront panel costs have prevented many organizations from realizing the benefits of solar energy (Martinez, 2023). The Inflation Reduction Act of 2022 introduced significant incentives for PV adoption, yet rapid degradation and replacement cycles continue to limit the economic feasibility of solar deployment for a substantial share of potential adopters (Parker, 2021; U.S. Department of Energy, 2022). Mid-to-small businesses consume nearly 89,000 kilowatt-hours annually, approaching the consumption levels of large enterprises, making this segment a critical but underserved deployment context for photovoltaic technology (Parker, 2021).

Perovskite-based photovoltaics have emerged as a promising next-generation approach to solar energy conversion. As a class of crystalline materials defined by their ABX_3 lattice structure, perovskites demonstrate exceptionally high light absorption coefficients, tunable bandgaps, and theoretical power conversion efficiencies exceeding 53%, far surpassing the 29.4% Shockley-Queisser limit of silicon single-junction cells (Shockley & Queisser, 1961; NREL, 2024). Inkjet-printed thin-film deposition techniques have enabled perovskite layers to be deposited uniformly onto flexible substrates, opening pathways to conformable, lightweight photovoltaic systems suitable for a broad range of installation environments (Pendyala et al., 2023). Research has specifically validated the DMF/NMP solvent system as producing perovskite films of superior long-term crystalline stability compared to alternative formulations, confirmed through scanning electron microscopy (SEM) and ISOS accelerated aging protocols (Jiao et al., 2023; Ahn & Choi, 2023).

Despite these performance advantages, perovskite photovoltaic systems have faced persistent commercialization challenges rooted in their susceptibility to environmental degradation. Moisture ingress, ultraviolet radiation, and thermal cycling destabilize the perovskite crystal lattice, inducing rapid performance loss under operational conditions (Ahn & Choi, 2023). Existing protective approaches, including synthetic encapsulants and anti-reflective coatings, impose additional fabrication costs and introduce non-biodegradable materials that compound the environmental concerns associated with PV waste streams (Weckend et al., 2016; Weiß et al., 2022). Furthermore, these approaches have shown limited efficacy against combined moisture-UV-thermal stressors, leaving a critical gap in the development of a durable, environmentally compatible encapsulation methodology for flexible perovskite cells (Ahn & Choi, 2023).

Biopolymer-based materials have increasingly attracted attention as sustainable functional coatings across multiple industries. Alginate, a natural polysaccharide extracted from brown seaweed, exhibits strong moisture-barrier properties, UV-absorbing capacity, and compatibility with cross-linking agents such as calcium chloride and xanthan gum, enabling the formation of mechanically robust biofilms (Marchi et al., 2022; Xie et al., 2024). Research has demonstrated that sodium alginate substrates can enhance charge transport in organic photovoltaic devices, suggesting that alginate-based encapsulation may simultaneously improve

both the stability and efficiency of solar cells (Marchi et al., 2022). Sargassum, a genus of invasive brown macroalgae, represents a particularly compelling alginate source: since 2011, sargassum blooms have caused an estimated $48 billion in economic losses affecting 30 million people in Caribbean coastal communities (Garrison et al., 2021; Mohammed et al., 2020). Alginate extraction from sargassum waste therefore offers the dual benefit of producing a high-value feedstock while directly addressing an ongoing environmental crisis.

Existing literature on perovskite stabilization has explored self-assembled monolayers, ionic liquid additives, and polymer encapsulants, yet none have investigated the application of a biological alginate-xanthan composite film as a multifunctional protective layer (Ahn & Choi, 2023; Jiao et al., 2023). Furthermore, no prior studies have examined the integration of such a biofilm with the P-I-N roll-to-roll fabrication architecture, nor evaluated its performance across flexible thin-film form factors at different application scales. This gap underscores the need for focused research to determine whether alginate-xanthan biofilm encapsulation constitutes a practical, scalable, and environmentally superior methodology relative to conventional silicon-based photovoltaic systems. This study proposes and evaluates a biofilm-encapsulated perovskite photovoltaic system as a conceptual model rather than a commercially deployed product. The central research question is: Does alginate-xanthan biofilm encapsulation improve the performance, durability, and environmental sustainability of perovskite photovoltaic cells relative to conventional silicon photovoltaic panels?

The scope of this research evaluates biofilm-encapsulated perovskite photovoltaic cells—fabricated using a P-I-N roll-to-roll inkjet deposition methodology on PET flexible substrates—against benchmark silicon PV panels across performance, durability, flexibility, and end-of-life dimensions. This includes evaluation of power conversion efficiency, degradation rate under accelerated aging protocols, mechanical flexibility, water vapor transmission resistance, and compostability (Ahn & Choi, 2023; Weiß et al., 2022; Volk et al., 2024). Two cell size configurations are assessed to evaluate performance across different application scales: a larger format (12” × 8”) and a smaller format (4” × 2”). Life-cycle cost comparisons are incorporated to assess economic feasibility relative to silicon panel benchmarks. By establishing the functional, economic, and environmental viability of biofilm-encapsulated perovskite cells, this study aims

to demonstrate that this encapsulation methodology represents a compelling next-generation approach for photovoltaic applications.

Experimental Methods

3.1 Justification

The experimental approach is the most appropriate methodology for this research because it enables direct, controlled comparison of performance variables between biofilm-encapsulated perovskite photovoltaic cells and silicon benchmark panels under identical testing conditions. Practicality is operationalized through measurable criteria established by regulatory bodies and industry standards, including power conversion efficiency, degradation rate, mechanical flexibility, water vapor transmission resistance, and thermal stability, in alignment with IEC 61215 performance testing standards and IEC 61730 safety requirements (IEC, 2021a; IEC, 2021b). Compostability and end-of-life environmental impact are additionally incorporated as dependent variables. The experimental methodology designates encapsulation type (biofilm-encapsulated perovskite cell versus uncoated silicon panel) as the independent variable, with each performance metric constituting a dependent variable assessed under controlled conditions. Control groups consist of commercially available monocrystalline silicon panels; experimental groups consist of biofilm-encapsulated perovskite cells fabricated through the P-I-N roll-to-roll methodology. Hypotheses are formulated prior to each testing phase, predicting that biofilm-encapsulated cells will demonstrate equivalent or superior performance across efficiency and durability metrics while exhibiting substantially improved environmental outcomes.

3.2 Cell fabrication and P-I-N assembly

Prior to testing, experimental photovoltaic cells are fabricated using a five-layer P-I-N roll-to-roll inkjet deposition methodology. The substrate layer is formed from polyethylene terephthalate (PET) polymer treated to enhance UV barrier performance. PEDOT:PSS is deposited as the transparent conductive electrode (TCE) layer, followed by a poly(triarylamine) (PTAA) hole transport layer (HTL). Perovskite crystals in the DMF/NMP formulation are deposited as the active layer, with uniformity verified through scanning electron microscopy (SEM) imaging at 200x magnification. Carbon-based electron transport layers (ETL) and

ITO/FTO flexible electrodes complete the core cell architecture. Fabricated cells are inspected in real time using a convolutional neural network (CNN) quality control system integrated with a LiDAR imaging feed to identify and reject cells exhibiting deposition defects prior to biofilm application. Eight large-format and eight small-format cells are fabricated for testing, with four cells per size configuration allocated to each test condition.

3.3 Alginate-xanthan biofilm preparation and application

The alginate-xanthan biofilm is prepared by extracting sodium alginate from dried Sargassum natans biomass through alkaline extraction and acid precipitation, following the optimized methodology of Mohammed et al. (2020). The extracted alginate is dissolved at a 1% (w/v) concentration in deionized water, combined with xanthan gum at a 0.5% (w/v) ratio, and cross-linked through the dropwise addition of 0.1 M calcium chloride solution to induce gelation. The biofilm precursor is spread uniformly across the upper surface of each fabricated cell using a doctor-blade coating technique and dried at room temperature for 48 hours to produce a coherent, adherent protective film. Film thickness is verified using profilometry to a target of 50 μm (±5 μm). Silicon benchmark panels receive no additional surface coating, serving as unmodified controls across all subsequent testing phases.

3.4 Power conversion efficiency testing

Power conversion efficiency (PCE) is measured for all experimental cells and silicon benchmark panels using a solar simulator calibrated to AM 1.5G irradiance (100 mW/cm²) at 25°C, in accordance with IEC 60904-1 standards (IEC, 2019). Current-voltage (J-V) sweep measurements are recorded from open circuit to short circuit at a scan rate of 50 mV/s, with both forward and reverse scans performed to detect hysteresis. Open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and PCE are extracted from J-V curves using standardized software analysis. Measurements are repeated three times per cell and mean PCE values with standard deviations are reported. Biofilm-encapsulated perovskite cells are hypothesized to demonstrate PCE values exceeding 25%, consistent with published DMF/NMP perovskite formulations, compared to a benchmark silicon PCE of 20.1% representing current commercial monocrystalline averages (Green et al., 2023).

3.5 Accelerated degradation and ISOS testing

To evaluate long-term stability and degradation rate, experimental cells and silicon panels are subjected to ISOS-D-2 damp heat aging protocols: 1,000 hours of continuous exposure at 85°C and 85% relative humidity (RH), consistent with IEC 61215 certification requirements (IEC, 2021a; Ahn & Choi, 2023). PCE is remeasured at 250-hour intervals throughout the exposure period to generate degradation curves. Degradation rate is calculated as percent efficiency loss per hour and annualized for comparative reporting. Biofilm-encapsulated cells are hypothesized to exhibit a degradation rate of 0.014% (±0.0003%), compared to industry-standard silicon panel degradation rates of 0.5-1.0% per year (Weiß et al., 2022). UV exposure stability is additionally assessed under ISOS-L-2 protocols using a UV aging chamber (365 nm, 1 mW/cm²) for 500 hours, with PCE remeasured at 100-hour intervals.

3.6 Water vapor transmission and moisture resistance testing

Water vapor transmission rate (WVTR) is assessed using a modified ASTM E96 gravimetric approach. Each cell or panel is mounted over a sealed dish containing calcium chloride desiccant and placed in a controlled-humidity chamber at 50% RH and 23°C. The mass of each assembly is recorded at 10-minute intervals over a 60-minute period. WVTR is calculated as the rate of mass change per unit area per unit time (g/m²/day). A parallel qualitative assessment examines biofilm surface integrity after moisture exposure through optical microscopy at 100x magnification. Biofilm-encapsulated cells are hypothesized to demonstrate significantly lower WVTR values than uncoated perovskite cells, attributable to the moisture-sequestering properties of the alginate-xanthan matrix (Xie et al., 2024), while approaching the WVTR resistance of encapsulated silicon panels.

3.7 Mechanical flexibility testing

The mechanical flexibility of experimental cells is assessed through repeated bending cycling using a custom-built mandrel bending apparatus. Cells are bent to radii of 30 mm, 15 mm, and 5 mm for 1,000 bending cycles at each radius, with PCE remeasured after each 250-cycle increment to assess electro-mechanical degradation. Bending direction alternates between convex and concave orientations to simulate real-world installation conditions on non-planar surfaces. Silicon benchmark panels, which are rigid, are excluded from bending cycle testing and serve as flat-installation controls for efficiency comparison. Biofilm-encapsulated cells are hypothesized to retain greater than 90% of initial PCE following 1,000 bending cycles

at a 15 mm radius, consistent with benchmarks established for flexible perovskite systems by Pendyala et al. (2023).

3.8 End-of-life compostability testing

To assess environmental end-of-life outcomes, one large-format experimental cell and one silicon panel fragment of equivalent surface area are placed in a controlled indoor composting vessel containing decomposed mixed leaf litter and dried foliage at 21°C with an internal compost temperature of 22°C, following the conditions established by Volk et al. (2024). The dry mass of each specimen is recorded daily for 30 days to calculate percent decomposition over time. Silicon panel fragments are expected to show no measurable mass reduction over the 30-day period, consistent with the non-biodegradable nature of silicon and glass encapsulants. Biofilm-encapsulated cells, which incorporate a biodegradable PET-alginate architecture, are hypothesized to demonstrate measurable decomposition within the observation window, providing quantitative evidence supporting the end-of-life sustainability advantages of the biofilm encapsulation approach.

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